I. Arnon

Mineral Nutrition of Maize

International Potash Institute Bern/Switzerland 1975

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Printed by: Werder AG, Bern/Switzerland
Layout: H. R. Schafroth, Bern/Switzerland

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Foreword

Much of the older literature on the fertilizer requirements of maize is no longer relevant for areas with progressive agriculture.

The adoption of hybrid maize varieties, new cultural practices and their interrelationships with nutrient supply have resulted in the application of ever increasing amounts of fertilizers. More fertilizers is probably used for maize than for any other annual crop, and this in turn has given rise to new basic problems not considered previously. Because of its considerable economic importance and its high yield potential, the maize plant has been subjected to more research than most other crop plants. The relatively small number of plants per unit area, as compared with most other cereals, facilitates the study of the individual plant and makes this study more rewarding. The enormous research effort expended on maize, in particular in relation to its mineral nutrition, has many implications for other crops, too.

Whilst it is reasonable to expect that a book sponsored by the *International Potash Institute, Berne/Switzerland* and entitled «*The Mineral Nutrition of Maize*» should have fertilizer use as its central theme, it would be futile to attempt to isolate plant nutrition from other relevant aspects of crop management. Incidentally, some of the most significant advances in recent years in our knowledge of nutrient supply to crops in general, and to maize in particular, have been concerned with the changes that have occurred in management practices and their interrelationships with fertilizer use. Hence, it was found necessary to devote the first chapters in this work to a description of the methods used for maize production in the world, and in particular to review the changes that have occurred in these methods, some of which are very far-reaching. Maize has been a pioneering crop for many new practices, such as a new concept of monoculture, in which mineral fertilizers replace the role traditionally assigned to fertility-building crops, like the legumes, and in which crop residues, reinforced with appropriate fertilizers, replace farmyard manure. It is with maize that the newer concepts of minimum tillage were first investigated and adopted in crop production and that new approaches to herbicide use were developed.

It is not surprising that dramatic changes in crop production methods have marked effects on fertilizer practice, and a large part of this book is therefore devoted to these interrelationships.

Agriculture has a major role to play in raising the standards of living in the developing countries. Maize is an important food crop in many of these countries, and fertilizer use is not only a means of increasing yields, but is also a «lead» practice in the introduction of other improved methods of production. The 1970's are bound to be a decade of agricultural development in the underdeveloped nations, and it was therefore felt to be appropriate and necessary to review some of the problems attendant on the adoption of improved agricultural practices in general, and of fertilization, in particular, in developing countries.

In advanced countries, the farmer who wishes to achieve and maintain an acceptable standard of living, must produce high yields and must do so efficiently and economically. For this purpose, he has at his disposal an increasingly sophisticated array of inputs: plants with very high yield potentials, precision machinery for all phases of production and a large number of chemicals for feeding the plants, controlling their growth, preventing competition by weeds and combating diseases and pests. A high professional standard is required to make proper and efficient use of these inputs. For fertilizers, no diagnostic methods have as yet been devised which can tell the farmer the right amounts of nutrients to apply in any one of the innumerable and changing combinations of soil, environment, past management, economic climate and crop, with which he is faced. Soil and plant analyses may provide the farmer with guidelines in making his decisions, but in the final analysis these will depend on his experience, knowledge and judgement. The latter, in turn, require an understanding of the plant's requirement, its physiological processes, the role and effects of different fertilizers, the most efficient methods of applying them, etc. To provide this understanding is the basic justification for the enormous effort invested in agricultural research in this field.

It has been the objective of this book to give an up-to-date and comprehensive review of the present knowledge on mineral nutrition of maize. A considerable amount of literature was perused in the preparation of the text, and a synthesis of the results of research and available information was attempted in the light of the author's own experience in the field. It is hoped that the book is timely and will fulfil a real need by contributing to an understanding of maize production in general, and its mineral nutrition in particular.

Acknowledgements

It is a pleasure to acknowledge gratefully the critical and constructive comments made by Professor *Dr. K. Mengel,* who read the manuscript with painstaking care; and those of *Dr. N. Friedgut,* Economist, who read the chapter on the «Economics of Fertiliser Use».

I also wish to express my warm thanks to the *Directors* of the International Potash Institute, whose initiative and support made the publishing of this book possible.

I. Arnon, Bet-Dagan, December 1974
The Volcani Institute of Agricultural Research

1. Background information

1.1 Origin

There are a number of theories regarding the origin of maize. A detailed discussion of these theories is not within the scope of this book.

The tripartite theory proposed by *Mangelsdorf (1965)* is based on archeological evidence, hybridisation experiments, and genetical analysis. He suggests that the ancestor of maize was a primitive form of pod corn, a type in which the individual kernels are enclosed in glumes, so that their dispersal after maturity is possible, in contrast to cultivated maize, in which the entire ear is firmly enclosed by husks.

As a result of hybridisation of the ancestral maize with its relatives teosinte *(Euchlaena mexicana)* and Tripsacum, maize became highly heterozygous. As a result of natural selection, acting in a man-make environment, maize evolved into a number of domesticated forms, each highly adapted to a specific ecological environment. The teosinte contributed genes for hardness and toughness that increased the strength of the maize stalk, making it capable of carrying a large ear.

Introgression from Euchlaena and Tripsacum also increased the mutability of maize, and made it one of the most heterotic plants propagated by seed, in which the heterosis is not due to allopolyploidy (ibid.).

The earliest evidence of the cultivation of maize is a primitive, small-eared type which appears, somewhere betwen 3000 and 2000 BC, in the incipient farming centred in the semi-arid hill country of Tamanlipas. From there, village farming spread northwards to Mexico and southwards as far as Peru, with the maize plant as the vital element, complemented by beans and pumpkins *(Willey [1960])*. By 700 BC, a relatively well developed type of maize appeared also at Huaca Prieta in Peru.

The role of maize in the economy of the Incas, Mayas and Aztecs was so considerable that it achieved religious significance.

Maize was brought to Europe by Columbus, at the end of the 15th century. It was first grown in Spain, and from there spread to other parts of Europe and to Asia.The early settlers in America learned to grow maize (Indian corn) from the native Indians, and it soon became the principal grain crop of the country.

1.2 Economic Importance

1.2.1 Production

Maize is the basic food plant of the New World, and is also widely grown on all other continents. On a world scale, maize comes third in area sown and quantity produced, after wheat and rice. The area sown has increased in the last two decades – from 1948 to 1968 – by 20 per cent (from 88 to 106 million ha),whilst production during the same period has increased by 80 per cent (from 139 to 251 million tons (**Figure 1**), *(FAO [1969])*. These figures also reflect the steep increase in yields per unit area due to the widespread use of hybrids and to improved crop management practices. As a result, maize production in the major producing countries is breaking all records.

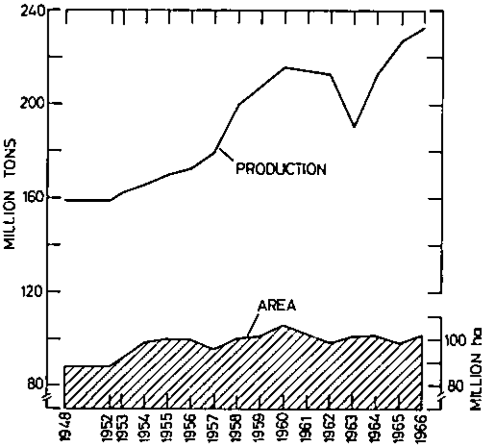

Fig. 1 World production trends of maize during the period 1948 to 1966 *(Based on data from FAO [1969])*.

Though maize had its origin in a semi-arid area, it is not a reliable crop for growing under dryland conditions with limited or erratic rainfall; under these conditions it generally cannot compete with sorghum or millets. However, with adequate rainfall it is one of the most important crops in many temperate, subtropical and tropical regions; and under irrigation, maize is supreme as a grain crop for the dry regions, with a yield potential higher than that of any other cereal. Though limited to warm climates, it is grown under a wider range of conditions than either wheat or rice.

Maize production figures for the main regions of the world are given in Table 1.

Table 1. Production of maize in the regions of the world in 1968 *(FAO, [1969])*

	Area (million ha)	Production (million tons)
Europe	11.2	32.7
North America	23.0	113.6
Latin America	25.9	34.0
Near East	1.9	4.1
Far East*	14.5	15.5
Africa	16.4	16.0
Oceania	0.1	0.2
USSR	3.3	8.8

* Excluding the People's Republic of China, for which official figures are not available.

1.2.2 Europe

By the end of the 17th Century maize was widely grown in countries of central and southern Europe.

The introduction of American hybrid maize varieties into Europe, mainly after World War II, was very successful; the average yield increase of grain for 13 countries was 60 per cent as compared with the best available open-pollinated varieties previously grown *(Jugenheimer and Silow [1951])*.

The main centres of production in Europe are the Danubian countries (mainly Rumania and Yugoslavia, and small, but still important, areas in Hungary and Bulgaria), as well as the other southern European countries: France (mainly the south-western regions), Italy (the Po Valley), Spain, and Portugal.

Data on the principal maize-producing countries in Europe are given in Table 2.

Table 2. Principal maize-producing countries in Europe *(FAO [1969])*

Country	Area (million ha)	Production (million tons)
Rumania	3.3	7.1
Yugoslavia	2.5	6.8
France	1.0	5.4
Italy	1.0	4.0
Hungary	1.3	3.8
Bulgaria	0.6	1.8
Spain	0.5	1.5
Portugal	0.4	0.5

The development in recent years of hybrid varieties of maize which are tolerant to cold, wet spring weather has encouraged an increase in the areas sown to maize in north-western Europe *(Hall [1968])*. Sizeable areas have been sown in the last decade in northern and north-western France, England and Germany.

Maize is becoming increasingly popular in central European agriculture as a replacement for certain crops, such as sugar beets, which require a relatively large amount of labour. All phases of maize production can now be mechanised, even thinning is no longer necessary with the new precision drills now available. Contract work for most cultural operations is also generally available.

Further advantages of maize in these regions are that (a) the yields are at least comparable to those of barley, whilst the nutrient value of the maize is higher, and (b) there is an almost complete absence of pest and disease problems, as compared with other cereals, even after growing the crop continuously for a number of years.

However, a further expansion in areas is limited by uncertainties about the reliability of the yield level, the difficulties of harvesting in certain seasons and the high costs of drying *(Gunn [1968])*.

1.2.3 USSR

In the Soviet Union, maize is not a major crop. There was a large increase in area during the period from 1960 to 1964 followed by a rapid decline in 1965 and the following years. The areas sown declined from 7.1 million ha in 1961 to 3.4 million ha in

1968 and a parallel decrease in production during the same period from 17.1 million tons to 8.8 million tons *(FAO [1969])*. The main areas of production are in the southern humid regions: Bessarabia, southwestern Ukraine, Georgia, the north Caucasian area, and Turkestan *(Berger [1962])*.

1.2.4 Near East

Maize is not a major crop in the near East and can be grown successfully only under irrigation. The total area sown in 1968 was 1.9 million ha, with a total production of 4.1 million tons. The only country with relatively large areas of maize is Turkey; in 1968, 655 000 ha were sown with a production of 1 million tons *(FAO [1969])*.

In many parts of Asia, maize cultivation is assuming increasing importance, in particular in regions in which rice production is not particularly successful.

1.2.5 Far East

The principal maize producing country in Asia is the People's Republic of China. The estimated area devoted to maize is between 10 and 15 million ha, almost as much as all the other Asian countries combined. The principal production areas are in the Hwong Ho Plains of northern China, western Honan, northern Kiangsu, and western Szechuan *(Berger [1962])*.

In India, the second important maize producing country in Asia, areas devoted to this crop have increased from 3.3 million ha in 1948–52 to 5.7 million ha in 1968, with a corresponding increase in production from 2.1 million tons to 5.7 million tons *(FAO [1969])*.

In India, the growing of maize is confined mainly to the states of Uttar Pradesh, Bihar, Punjab and Rajasthan *(Singh et al. [1965])*.

Maize is an important crop in Indonesia, which has increased the areas devoted to maize from 2.0 million ha in the period 1948/52 to 3.3 million in 1968, with corresponding increases in production from 1.5 million tons in 1948–52 to 3.1 million tons in 1968 *(FAO [1969])*.

Other important maize producing countries in Asia are the Philippines, North Korea, and Nepal.

Data on the principal maize-producing countries in the Far East are given in Table 3.

Table 3. Principal areas of maize production in the Far East in 1968 *(FAO [1969])*

Country	Area (million ha)	Production (million tons)
India	5.7	5.7
Indonesia	3.3	3.1
Philippines	2.1	1.5
Korea (North)	1.0	1.7
Pakistan	0.6	0.6
Nepal	0.4	0.9

1.2.6 Africa

The most important maize producing country on the African continent is the Republic of South Africa, with an area of 5.6 million ha, producing 5.3 million tons. The highest yields are produced under irrigation in the U.A.R., which harvests 2.3 million tons from 0.7 million ha *(FAO [1969])*.

Maize is probably the most widely grown of the starchy staple food crops in tropical Africa. Only millets and sorghums and manioc (cassava) are greater contributors of calories in this continent. In a number of regions (most of Kenya, Malawi and Rhodesia, as well as considerable areas of Angola, Zambia, Tanganyika, Mozambique, Cameroun, Dahomey, Togo and Ghana) it is the main starchy-staple food. The only areas in which little maize is grown are the wet tropical forest region of the Congo Basin, in which manioc is the main source of calories, and the dry savanna regions bordering the Sahara and Kalahari deserts, where millets and sorghums predominate because of their drought resistance *(Miracle [1966])*.

Data on the principal areas of production on the African continent are given in Table 4.

Table 4. Principal areas of maize production in Africa *(FAO [1969])*

Country	Area (million ha)	Production (million tons)
Republic of South Africa	5.6	5.3
Nigeria	1.2	1.2
Kenya	1.0	1.2
Malawi	1.0	1.1
Tanzania	1.0	1.0
Ethiopia	0.8	0.8
Rhodesia	0.7	1.0
U. A. R.	0.7	2.3

1.2.7 North America

Over 98 per cent of the area sown to maize in North America is in the United States, where this crop holds a unique position and is the most widely grown crop. It is grown in every state, and about 25 per cent of the total cropland of the country is devoted to maize. About three-quarters of the annual harvest is produced in the Corn Belt in the north central states *(Leonard and Martin [1963])*. The area under maize has actually decreased, from 29.8 million ha in 1948–52 to 22.6 million ha in 1968, but the actual production has increased, from 74.3 million tons to 111.6 million tons, reflecting the enormous progress in crop technology that has taken place in the last two decades *(FAO [1969])*.

Whilst more than 75 per cent of the maize crop is fed to livestock, maize contributes more to the diet of the population in the United States than any other crop, directly as processed foods and indirectly in meat, poultry and dairy products.

1.2.8 Latin America

Of all the world major regions Latin America has the largest area of maize (25.9 million ha in 1968). However, average yields are low, so that the total annual production (34 million tons in 1968) is less than one third of that of North America *(FAO [1969])*.

Data on the principal centres of production are given in Table 5.

Table 5. The principal areas of maize production in Latin America in 1968 *(FAO [1969])*

Country	Area (million ha)	Production (million tons)
Brazil	9.6	12.8
Mexico	7.8	9.4
Argentina	3.4	6.6
Colombia	0.8	0.9
Guatemala	0.8	0.7

In many of the Latin America countries maize, prepared in a variety of ways, forms an important part of the human diet.

1.2.9 Yields of maize

Maize is potentially a highly productive plant, when adapted varieties are grown under favourable environmental and cultural conditions. The yield potential increased steeply with the advent of hybrid maize.

The average yield of maize in the USA during the period 1934–38, when almost the entire area devoted to maize was sown with open-pollinated varieties, was 1510 kg/ha. This average yield was obtained in a country in which maize growing had achieved a high degree of know-how and efficiency. During the period 1967–68, when hybrid maize had completely replaced the traditional varieties, average countre-wide yields had risen to 4930 kg/ha *(FAO [1969]).*

The upward trend in yield is not limited to the United States, but is also evident in the production figures for North America as a whole, Europe and the Near East, whilst yield levels have remained practically unchanged in Latin America, the Far East and Africa (Table 6).

Table 6. Average maize yields according to geographical regions *(FAO [1949 and [1969])* (in kg/ha)

Region	1934/38	1948/52	1952/56	1964	1966	1968
Europe	1480	1240	1560	2540	3000	2920
North America	1500	2490	2650	3960	4550	4940
Latin America	1300	1080	1070	1200	1300	1320
Near East	1250	1510	1600	1910	2210	2170
Far East	1190	820	880	1100	1040	1070
Africa	810	800	880	930	1020	980
Oceania	1480	1800	1880	2150	2470	2750
World average	1340	1590	1700	2140	2320	2370

The average world-wide yield of maize in 1968 was 2370 kg/ha (ibid), but this figure does not reflect the enormous variation in yields recorded within different regions. The data in Table 7, give some idea of the range of variations encountered in different areas.

Canada had the highest average yield in 1968, 5320 kg/ha, whilst the lowest average yield, 380 kg/ha, was recorded in Namibia.

Table 7. Highest and lowest average yields of maize according to continent in 1968 *(FAO [1969])* (in kg/ha)

Continent	Average yield	
	Highest	Lowest
Europe	5410 (Austria)	1250 (Portugal)
North and Central America	5320 (Canada)	750 (Haiti)
South America	3620 (Chile)	430 (Uruguay)
Asia	4100 (Israel)	430 (Burma)
Africa	3520 (U. A. R.)	380 (Namibia)
Oceania	6120 (New Zealand)	1770 (New Caledonia)

The highest yield of maize ever recorded was 19300 kg/ha *(Mangelsdorf [1966])*. The yields obtained in farming practice, even by farmers using the most advanced technology, are still far lower than this record yield, which, however, can serve as an indication of the enormous potential for production inherent in maize hybrids, grown under favourable environmental conditions, with improved cultural practices and in particular an adequate supply of nutrients.

Not in all countries is the yield potential of maize exploited to the same degree, either because of unfavourable climate, or because of backward cultural techniques. Both sets of factors may of course operate simultaneously.

Figure 2 shows the average yield trends during the period from 1934 to 1968 in a

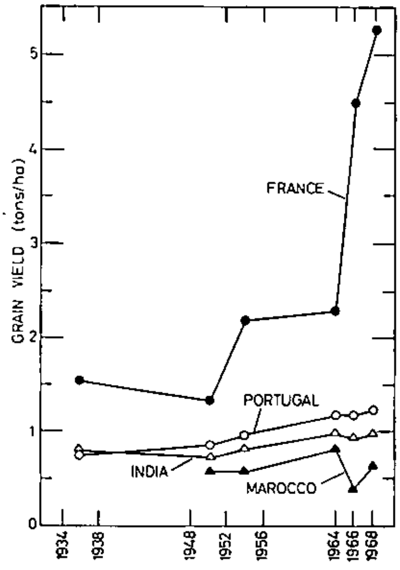

Fig. 2 Average yield trends of maize during the period from 1934 to 1968, in a number of selected countries *(Based on data from FAO [1949]), FAO [1969])*.

number of selected countries. There is no doubt that in France the spectacular increase in yields is due to the higher genetic potential of hybrids and improved cultural techniques generally adopted in recent years. For the other countries shown in the figure, Portugal, Morocco and India, it is more difficult to indicate whether unfavourable climate, backward production techniques, or both concurrently, were responsible for the low yield and lack of marked progress in improving yield levels.

In Table 8 comparative figures are given for average yields on commercial farms and village farms in a number of countries in Africa. Presumably, climatic conditions were similar for commercial farms and village farms and the figures are therefore a fair representation of the possibility of improving yield levels under given conditions of climate.

Table 8. Comparative average yields of maize on farms and villages in four countries of Africa *(FAO [1969])* (in kg/ha)

		1948–52	1952–56	1964	1966	1968
Kenya	Farms	1690	1400	1880	2510	4320
	Villages	1210	1320	1030	1080	1080
Rhodesia	Farms	1170	1710	2630	3310	3300
	Villages	490	700	640	690	800
South Africa	Farms	790	950	940	1040	970
	Villages	500	530	500	500	480
Zambia	Farms	1180	1400	3550	4510	3920
	Villages	750	950	1140	1390	1040

One of the principal limiting factors in maize production is moisture supply. Under irrigation, a good farmer can expect a yield of 9000 to 10 000 kg/ha. However, irrigation *per se,* even of fertile soils, does not ensure such yield levels.

Maize is grown in Egypt under irrigation, on between one quarter and one third of the cultivable area. Yields of maize range from 1400 kg to 3800 kg/ha, with an average of about 2000 kg/ha. Salinity, lack of proper drainage, too low fertilization rates, and attacks by corn borers and the cotton leaf worm are the main reasons for these low yields in irrigated agriculture *(Kaddah and Ghowail [1964]).*

From the foregoing, it is clear that the range of yields that the individual farmer can expect is enormous, depending mainly on environment and cultural level.

Neither average yields for the country nor record yields can serve the individual farmer for estimating his fertilizer requirements. He must make a realistic appraisal of the conditions under which he is operating, taking into account the yields normally obtained in his region, the cropping history of his own fields, the uncertainties of weather, etc. The higher the standard of farming, the more essential it is to ensure that *nutrient supply should not be a limiting factor* and that the farmer should therefore calculate his fertilizer needs on the basis of somewhat higher yields than he expects to obtain.

1.2.10 Utilization

Maize grain is an important animal feed and is also used for human consumption in a variety of ways. In countries with advanced technology, it is also a raw material for major processing industries.

– *Human consumption*
Only the seeds are important for human nutrition. Because immature maize can be eaten roasted or boiled, direct from the cob, maize can be harvested over a relatively long period, and eaten during the season as a vegetable and afterwards as dry grain. The kernel consists mainly of starch (about 60 per cent), protein (about 10 per cent), and oil (about 4 per cent). These main constituents are not uniformly distributed in the kernel. The endosperm, which accounts for over 80 per cent of the weight of the kernel, contains most of the starch and about two thirds of the protein. The germ, which constitutes about 12 per cent of the kernel, contains most of the oil, considerable protein and a relatively large amount of minerals.
The starch of maize is composed of about 80 per cent amylopectin and 20 per cent amylose. In waxy corn the starch consists entirely of the amylopectin. The principal protein of the endosperm, zein, is biologically not well balanced, being deficient in the two essential amino acids, lysine and tryptophane.
Differences in amino acid composition are ascribed largely to the increasing proportion of zeins in the proteins as the total protein increases. Research has shown that hybrid maize usually has a lower protein content than the open-pollinated varieties. The maize kernel contains significant quantities of nicotinic acid, amide riboflavin, pantothenic acid and vitamin E. Yellow maize also contains provitamin A, which is almost entirely absent in white maize.
Maize has, however, a low niacin content; a shortage of niacin, together with a low tryptophane content, is associated with pellagra, which frequently occurs in endemic proportions among maize-eating populations *(FAO [1953])*.
The nutritive value of maize, as compared with that of rice and wheat is given in Table 9.
Maize has higher values than rice for protein and fat, and practically the same caloric value. However, it is inferior to both rice and wheat in the biological value of its protein, having a lower amino acid content of tryptophane and lysine *(Cunard [1967])*.
During milling operations, the endosperm is separated from the grain and the hulls. Oil is extracted from the germ and is used as a cooking and salad oil. The corneous part of the endosperm serves for the preparation of grits and coarse meal. From the floury part of the endosperm a fine flour is produced. The proteins of maize do not form a glutenous substance, as in the case of wheat; for this reason it is not possible to bake leavened bread from maize flour.
Hydrolysis of the starch of maize enables the production of a variety of food products, such as maize starch, syrup and dextrose. Dried starch is used for food, laundry and industrial purposes.
Maize grain is also used as a raw material by brewers and distillers.

– *Animal feed*
The grain is an excellent high-energy animal feed. It is used as the basis for high-

Table 9. Representative values of selected constituents per 100 g edible portion *(Platt [1945])*

	Maize (whole, yellow)	Rice (parboiled, milled)	Wheat (whole)
Water (g)	6–12	11–13	—
Calories	349	352	316
Protein (g)	10	7.5	11.5
Fat (g)	4.5	1.5	2.4
Carbohydrates (g)	67	77	62
Ca (g)	12	8	30
Fe (g)	5	1	3.5
Vitamins A (I.U.)	100	—	—
Aneurin (mg)	0.33	0.21	0.40
Riboflavin (mg)	0.13	0.10	0.17
Nicotinic acid (mg)	1.5	4	5

energy rations for «broiler» production; it is also widely used for fattening cattle and lambs. Maize contains less fibre, less protein (and of a lower biological value) and less minerals than most other cereal grains. It has, however, a higher net energy content, being highly digestible *(Schneider [1955])*.

By-products from the industrial use of maize are also used for livestock: gluten meal, dried distillers' and brewers' grains, oil cake, oil meal and molasses. Industrial uses of various constituents of the grain include the production of adhesives, explosives, textile sizing, plastics, chemicals, paints and other products.

The entire plant is also used on a world-wide scale for forage, either fed as fresh forage or ensiled.

Maize growing for forage in general, and for silage in particular, has increased considerably in recent years in the northern areas of the USSR, USA, Canada, Germany, Poland, etc., where maize was previously only a minor crop. The main factors responsible for this development are the increasing importance of animal husbandry, the improved techniques of maize production – requiring less manual labour – and the production of new early hybrids adapted to the colder areas *(Fellner and Pap [1960])*. For these reasons, maize has been able to replace fodder beet, for example: the labour costs involved in producing silage maize have been shown in Germany to be 25–50 per cent less, and dry matter yields about 15 per cent higher, than those of fodder beet, taken over a period of eight years *[ibid.]*.

1.3 Adaptation

Maize has an extremely wide range of adaptation, and can be grown successfully between latitudes 58°N and 35–40°S.

1.3.1 Temperature

Maize is a warm-weather crop, and is not widely grown where the mean summer temperature is less than 19°C, and the average night temperature during the summer months falls below 13°C *(Shaw [1955])*. However, it can be grown at lower temperatures.

– *Air temperatures*

A warm spring makes possible early sowing with its attendant advantages, permits rapid and uniform emergence, promotes early growth, and is therefore conducive to higher yields.

Warm weather in autumn is beneficial because it ensures early and even maturity of the crop.

Sprague [1955] states that maize production is limited to those areas in the world with an isotherm for July of at least 21–26°C. A minimum average July temperature of 21°C would mean that the northern limit for maize production in Europe would pass through southern France, Switzerland, Austria and Hungary *(Torssell et al. [1959])*. However, since World War II, maize has been produced for seed in Europe as far north as the Netherlands and the middle of Germany, whilst maize for silage has been grown as far north as southern Norway and central Sweden, indicating that the northern limit for growing silage maize is 59°49'N *[ibid.]*.

In central Europe, the lowest mean temperature during the growing season suitable for maize for silage is considered to be 13.0–13.5°C. For grain, 14.5–15.0°C is considered the lower limit, 15–16°C intermediate and over 16°C as favourable. However, these figures may require modification depending on the number of hours of sunshine *(Zscheischler and Gross [1966])*.

The closest correlation between the rate of development of maize and air temperatures is between 10°C and 20°C. Below 10°C, both development and growth are virtually halted. At average daily temperatures above 20°C, the rate of development increases relatively more slowly with rising temperature *(Chirkov [1965])*.

The shoot-to-root ratio of the maize plant increases with increasing temperatures, up to the optimum temperature.

Apparently, at the higher temperatures, roots are more efficient and a smaller root system is capable of supplying adequate nutrients and water, enabling vigourous top growth **(Figure 3)**, *(Anderson and Kemper [1964])*.

– *Frosts*

The growing season is usually defined as the interval between the last killing frost in spring and the first killing frost in autumn. In general, the height of the plants, the weight and number of leaves are correlated with the length of the growing season required for maturity *(Harper [1955])*.

Young plants of maize can withstand night temperatures of down to -3°C. The young leaves will usually die, but the protected growing point will not be affected and remains capable of producing new growth *(Rossman and Cook [1966])*. Yield reductions of 10–15 per cent may however be expected as a result of this set-back.

Early frosts in autumn may cause the premature death of the plants. However, if the grain has already reached a dry-matter content of 60 per cent, yields will not be adversely affected. If the dry matter content of the grain is lower, it is desirable to harvest frost damaged maize as rapidly as possible for ensiling.

Varieties differ in frost resistance, certain strains being killed at temperatures of 7°C whilst others can withstand exposure to 0°C for a few hours *(Harper [1955])*.

– *Excessively high temperatures*

According to *Thompson [1966]*, 26°C may be the critical temperature affecting high yields of maize. During years of high yields in the Corn Belt, temperatures over 26°C were rare during July or August.

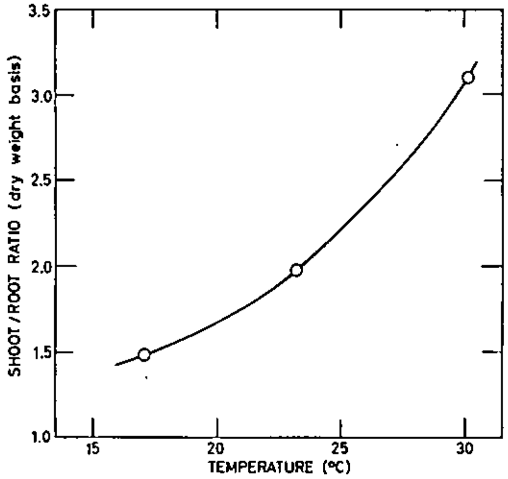

Fig. 3 Shoot to root ratio of maize plants as affected by temperature *(Anderson and Kemper [1964])*. By courtesy of the American Society of Agronomy.

Schaal and Blair [1967], who made weekly comparisons of air and soil temperatures, also showed that the highest maize yields in the Corn Belt occurred in years when the temperature was above normal during the establishment period and below normal during the main growth and reproduction periods (14 June–15 August).

Air temperatures above 30–35°C were found to cause a significant reduction in nitrate reductase activity of maize seedlings, and hence disturbed nitrogen metabolism. As a result, protein content was lowered and changes in protein composition occurred *(Heyne and Laude [1940])*.

Excessively high temperatures and low air humidity at the time of pollination have adverse effects on pollination and fertilization and cause reduced seed-set. If, in addition, soil moisture is low at the time, the exertion of the silks is delayed and seed-set is still further reduced. The critical temperature affecting yields appears to be around 32°C *(Thompson [1966])*.

– *Effect of heterosis on heat resistance*

Maize seedlings normally become increasingly susceptible to high temperatures as they become older *(Heyne and Laude [1940])*. It has been observed that when inbreds and hybrids are grown at high temperatures, the growth of the hybrids remains normal at temperatures at which the inbreds show evidence of high temperature lesions, or even fail to survive. Thus, the hybrids show a far greater phenotypic stability over a wider temperature range than the inbreds *(McWilliam and Griffing [1965])*.

The biochemical basis for this phenomenon may stem from the accumulation of random sets of genes sensitive to high temperatures in the homozygous inbreds. These genes produce a temperature-unstable enzyme, whilst in the hybrid the effect of dominance produces a thermostable enzyme at the same locus *(Langridge [1963])*. One of the advantages of hybrid maize would therefore be a greater degree of heat resistance.

– *Soil temperatures*

The effect of soil temperatures on maize, as a member of the grass family, Gramineae, will probably differ from that on other plant families, because the shoot apex of the maize plant is located in the top layer of the soil during a major part of the vegetative stage *(Grobbelaar [1963])*.

Maize growth increases as soil temperature rises, up to an optimum and then decreases. The optimum soil temperatures for maize are generally lower than the optimum air temperatures; the optimum soil temperature for shoot growth is approximately 5°C higher than that for root growth *(Grobbelaar [1963])*.

The minimum temperature for germination is 8–10°C; however, at low temperatures germination and emergence are protracted, e.g. 3–4 weeks at an average soil temperature of 10–12°C. The germinating seed and seedlings are extremely susceptible to soil-borne pathogens, in particular Pythium species. Insects and birds can also cause considerable damage to the stand.

Emergence is far more rapid and uniform at soil temperatures of 16–18°C (10–12 days); at 20°C, maize usually emerges 5–6 days after sowing.

Corn growth early in the season has been shown to increase linearly with soil temperatures from 15° to 27°C and to decrease with higher temperatures at the 10-cm depth. An increase from 19° to 21°C in the average 10-cm depth doubled the top-growth of six-week-old maize plants **(Figure 4)** *(Allmaras et al. [1964])*.

The yield of maize grain with different nutrient treatments in a temperature-controlled soil, increased with increments in temperature from 5° to 27°C *(Nielsen et al. [1961])*.

The length of the growing season can be prolonged by breeding strains that are capable of germination and of growth at lower temperatures *(Harper [1955])*.

1.3.2 Precipitation

A desirable climate for maize is considered to be one in which precipitation is sufficient to wet the soil to field capacity down to root depth before the sowing season, and a rainfall of at least 375 mm during the growing season.

For example, in Germany, a minimum of 300 to 400 mm from May to September is considered necessary, of which 150 to 170 mm should occur from mid-June to mid-August. In regions that tend to drought, a low rainfall in May – which forces the young plants to develop a deep root system – is considered desirable *(Zscheischler and Gross [1966])*.

Because of its high water requirements, rain-fed maize is grown mostly in the humid regions (over 600 mm average annual rainfall) with sufficiently high temperatures in the range of 20 to 32°C, and a growing season of over 130 days.

Thompson [1966] studied the relation of average rainfall to maize yields for each summer month in the Corn Belt. The optimum amounts were found to be about 100 mm in June, 175 mm in July, and 100 mm in August.

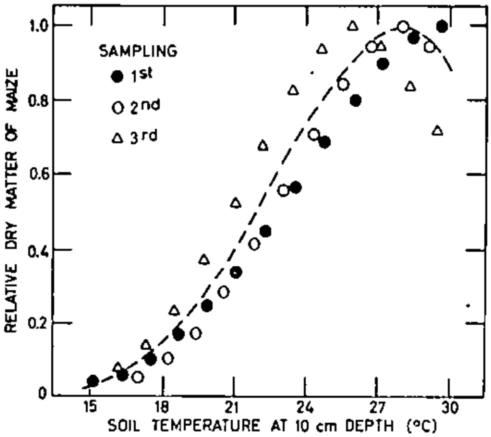

Fig. 4 Relative dry matter production of maize in relation to the soil temperature at a depth of 10 cm *(Allmaras et al. [1964])*. Growth measurements were taken from 13 to 38 days, 22 to 54 days, and 41 to 67 days respectively, for the first, second, and third samplings. By courtesy of Soil Science Society of America.

Large areas of maize are, however, sown in areas in which moisture supply is generally below optimum for maximum maize production. Under these conditions, about 86 per cent of the total variation in yield of forage and 71 per cent of the total variation in grain yield were found to be due to variations in moisture supply. Forage and grain yields were linearly related to stored soil moisture at sowing plus precipitation during the growing period. Total available water had to exceed 150 mm before any grain could be expected. About 0.73 ton ha of silage and 300 kg/ha of grain could be expected for each additional 25 mm of available water *(Alessi and Power [1965])*.

In all regions in which rainfall during the growing season of maize may be deficient, water stored in the root zone during the autumn and winter preceding the sowing of maize, is generally a primary factor in ensuring the success of the crop *(Shaw and Burrows [1966])*.

On the basis of a six-year study in dry to subhumid parts of Minnesota and South Dakota, *Holt et al. [1964]* found that with nearly normal rainfall, a direct relationship could be established between maize yields and the amount of moisture stored in the soil at the time of sowing (**Figure 5**). They found that 150 mm was the minimum reserve necessary to produce about 4500 kg/ha with normal rainfall.

According to *Thompson [1966]*, preseason precipitation must provide about half the moisture needs of maize grown anywhere in the Corn Belt. The optimum preseason precipitation for this region is 650 mm (**Figure 6**).

Even in the humid regions peak water requirements are often in excess of precipitation and irrigation is frequently practiced and economically justified *[ibid.]* **(Figure 7).** In the drier regions of the lower latitudes the combined effect of high temperatures and low precipitation is a major factor in limiting the areas devoted to rain-fed maize production.

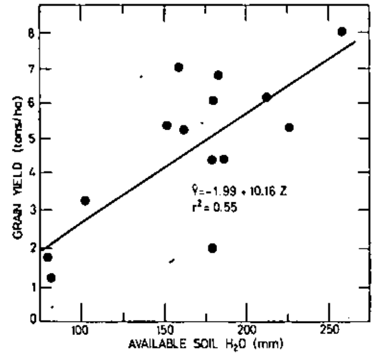

Fig. 5 Relationship between stored soil moisture (available moisture in surface 150 cm) and maize yields *(Holt et al. [1964])*. Averages for 14 locations, in a season with below-average rainfall during the critical period July 1 to August 15. By courtesy of the American Society of Agronomy.

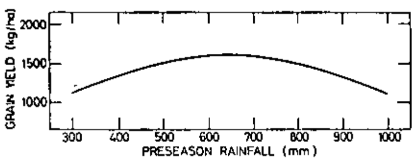

Fig. 6 The relationship between preseason rainfall (September–May) to maize yield in the corn belt of the United States *(Thompson [1966])*. The graph indicates that the optimum preseason precipitation is about 650 mm. By courtesy of Iowa State University Press.

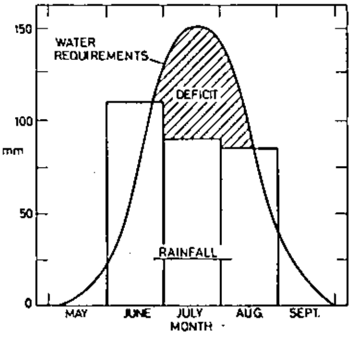

Fig. 7 Water requirement curve for maize in relation to summer rainfall in five states of the corn belt *(Thompson [1966])*. By courtesy of the Iowa State University Press.

The stomata in older leaves of maize are markedly affected by severe drought lasting a week or more, and do not recover their apparent normal behaviour after a favourable moisture regime is restored and leaves have regained their turgidity and normal appearance.

Maize is apparently more drought resistant in the early stages of growth than when full developed. Severely wilted young maize leaves, which unfold when soil moisture improves, recover completely and assimilate CO_2 normally, whilst maize submitted to drought at a later stage does not recover completely. This may explain why the practice of sowing maize early, common in drought areas in East Africa, is desirable, notwithstanding the danger of wilting during periods between light showers which precede the rainy season. Early-sown maize has the advantage of a longer growing season than later sown maize, though the latter is sown under more favourable conditions of moisture *(Glover [1959])*.

The opposite situation, of excess moisture, may occur for maize growing on heavy soils in high rainfall region. For example, *Rintelen [1959]* in Germany has demonstrated that there exists a significant correlation between yields of maize growing on a heavy clay soil, and the average rainfall during the period from May to September: the higher the rainfall, the lower the yields.

Under irrigation, maize has the highest grain-producing potential of all the cereals in dry regions of the low latitudes. In the higher latitudes, temperatures early in the season are too cool and the growing is too short for successful maize production for grain.

1.3.3 Interactions between temperature and rainfall

As a general rule, higher than normal rainfall is associated with cooler than normal temperatures in the Corn Belt *(Thompson [1966])*. This relationship probably holds true in most temperate regions. For this reason there are high correlations between yields and either temperature or rainfall for each of the summer months. The variables that have the greatest influence on yields are June temperature, July rainfall and August temperature *[ibid.]*.

Runge [1968] has also shown that maximum temperature and rainfall are interrelated and together affect maize yield during the growing season. The main effect of this interaction is on evapotranspiration.

Maximum temperature and rainfall influence maize yield mainly during the period from 25 days before to 15 days after anthesis, the maximum effect occurring approximately one week before anthesis and remaining at a high level one week to either side of the maximum.

A period of one or two weeks with temperatures above 26°C, particularly after mid-July, may cause moisture deficiencies during the day even when soil moisture is adequate *(Thompson [1966])*.

In the hotter regions, temperature effects may well overshadow summer rainfall effects on the yields of maize.

Carlès [1959] has shown graphically how the combined effects of temperature and cumulative rainfall of the months of July and August affect the yields of maize in France (**Figure 8**). The marked effects shown are mainly due to the coincidence of the dry period in these regions with the stage of growth of the maize at which the plant is most sensitive to moisture stress.

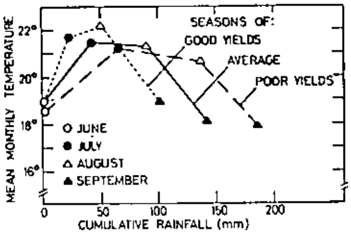

Fig. 8 Combined effects of temperature and cumulative rainfall of the months of July, August, and September on the yields of maize in France *(Carlès [1959])*. By courtesy of «Engrais de France».

In the northern Great Plains of the United States, variability in maize yields was found to be most closely associated with variability in July average maximum temperatures. However, summer temperatures are intimately linked with rainfall. The lower temperature which accompanies a rain may, on occasion, be as beneficial as the rain itself *(Moldenhauer and Westin [1959])*.

During stress periods due to the combined effect of low soil moisture supply and high temperatures, the nitrate reductase activity in maize plants was found to be immediately reduced, even before moisture content of the plants was decreased. Enzyme activity therefore appears to be influenced by changes in stress even too small to be measured by relative turgidity. As a result, the quantity of nitrate per plant increased consistently with exposure to stress (**Figure 9**, *Mattas and Pauli [1965]*).

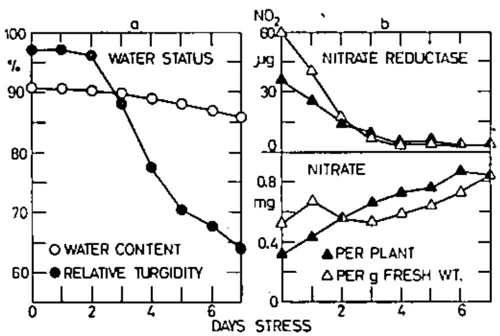

Fig. 9 Combined effects of heat and moisture stress on (a) water status of the plants (b) nitrate reductase activity *(Mattas and Pauli [1965])*. By courtesy of the Science Society of America.

Temperature increases, even in the absence of moisture stress, are associated with significant reductions in nitrate reductase activity, with resultant nitrate accumulation and a reduced accumulation of total nitrogen *(Younis et al. [1965])*.

Experiments in Kentucky during a 14-year period showed that the total rainfall in June and July had the greatest beneficial effect on maximum maize yields, whilst the maximum daily temperature for June, July and August had the most detrimental effect. There was a highly significant negative correlation between these two climate variables *(Engelstad and Doll [1961])*.

As a rule, the highest yields of maize in the Corn Belt, during a 37-year period (1930 to 1967), were associated with below-average temperatures in July and August and above-average rainfall in July. Average June temperature and average precipitation from September through June appeared to be generally optimum for maize *(Thompson [1969])*.

1.3.4 Flooding

The effect of flooding at different stages of development on the growth, yield and quality of maize was studied in India. Plant population, vegetative growth, and yield and protein content of grain were reduced by flooding, while the number of barren stalks was increased. These effects increased with increasing duration of flooding, but for a given flooding time decreased with increasing plant age. Mean grain yields were 22 per cent higher on ridged plots than on level ones *(Joshi and Dastane [1966])*.

1.3.5 Light

Maize is one of the most responsive crops to light, and this is one of the reasons for its high potential productivity (**Figure 10**; *Waggoner et al. [1963]*).

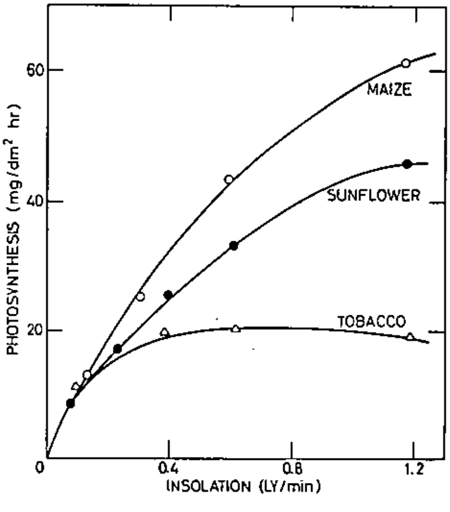

Fig. 10 The effect of light intensity on photosynthesis in three plant species *(Waggoner et a.. [1963])*. By courtesy of the American Society of Agronomy.

The maize crop is most sensitive to shading, the effect of which was studied by *Miller, [1955]*. A 90 per cent reduction of incident light for a brief period (3–6 days) of the reproductive stage, was found to cause a far greater reduction in grain yield than comparable shading at other phases of development *(McIlrath and Earley [1961])*. Light intensity also influences the length of the growing period. A reduction in light intensity of 30 to 40 per cent was found to cause a delay in maturity of 5 or 6 days. Late varieties were the most susceptible to reduced light intensity *(Barbat and Puja [1957])*.

1.3.6 Day length

Maize is a short-day plant; long days increase the duration of the vegetative stage, the number of leaves and the size of the plant.

1.3.7 Wind

Hot winds may cause incomplete pollination of maize, which may be one of the greatest hazards of maize production in certain regions. The death of the entire tassel, or of the pollen grains after they are shed, may be cuased by high temperatures, extreme desiccation, or a combination of the two.

1.3.8 Soils

The ideal soil for maize is a deep, medium-textured, well-drained soil with a high water-holding capacity. Maize is, however, grown on a wide variety of soils and will give good yields if the crops are well managed. In regions with relatively light rainfall, the heavier soils which are capable of storing more water are preferred. In cooler and more humid regions, lighter soils, which warm up more rapidly and are better drained, are more advantageous than heavy soils.

Maize grows well on a fairly wide range of pH, from 5.5 to 8.0. The optimum pH is slightly acid to neutral.

1.3.9 Salinity

Maize is quite tolerant of salt during germination; increasing salinity delays germination but, up to a point, has no marked detrimental effect on the percentage of emergence *(Kaddah and Ghowail [1964])*. However, maize belongs to the group of crops that is considered to be relatively sensitive to salinity and is not suited for growing on saline soils or for irrigation with saline waters (**Figure 11**; *Bernstein [1964])*

In the USSR, it was found that 0.51 per cent total soluble salts in the soil or 15.3 g salts/l in the soil solution suppressed the development of maize plants, and 1.14 per cent or 43.8 g/l, respectively, caused their death. Maize yielded 4270 kg grain/ha on slightly saline soil and 2000 kg/ha on strongly saline soil containing over 0.5 per cent salts *(Burdygina and Kuzin [1965])*.

The degree of yield reduction due to salinity depends on many factors, such as stage of growth, character and concentration of the salt in the root zone, duration of the time that roots are exposed to harmful concentrations of salts, and the extent of the root system salinized.

In experiments carried out in the greenhouse, by *Bingham and Garber [1970]* it was found that salinizing one-third of the root system of maize actually tended to increase plant growth rather than to restrict it. Extending salinization to two-thirds of the root system led to a reduction in growth of approximately 10 per cent; when the entire root system was salinized, the growth reduction was 30 per cent. The uppermost zone of the roots appeared to be the most sensitive to salinization.

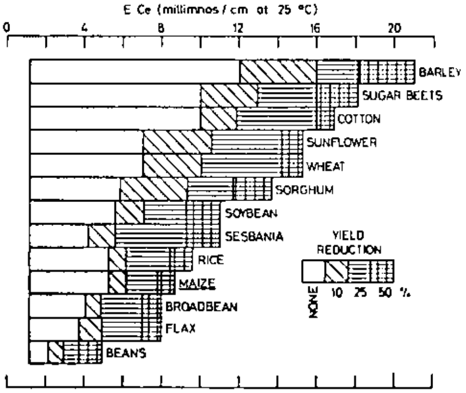

Fig. 11 Salt tolerance of maize as compared to a number of field crops *(Bernstein [1964])*. By courtesy of the U.S. Department of Agriculture.

Root development was more directly affected by salinization than was shoot growth. The degree of reduction was proportional to the portion of the root system subjected to saline conditions. Salinization of the entire root system curtailed root growth by 50 per cent *[ibid.]*.

The retarding effect of salinity on root development appears to be due chiefly to moisture stress. Thus, the roots of maize fail to proliferate in soil containing 0.20 per cent NaCl and a residual osmotic pressure of the soil solution of 10.5 to 11.5 atmospheres *(Wadleigh et al. [1947])*.

1.3.10 Boron content

Experiments with different levels of boron applied in the irrigation water have shown that maize plants are damaged by soil solution levels of 20 meq B/l or greater, and that the degree of injury is a function of the concentration of B in the soil solution and of the proportion of the root system in contact with the soil containing boron **(Figure 12)**. *(Bingham and Garber [1970])*.

1.4 Plant characteristics of agronomic significance

1.4.1 Roots

The root system of the maize plant consists of 3–5 seminal roots, secondary roots that develop from a node just under the soil surface, and aerial roots.

The radicale or primary root and the seminal roots, which arise at the upper region of the scutellar node, form the temporary root system. Subsequently, nodal roots arise from the stem at nodes 5–7 cm below the soil surface, and occasionally, somewhat later, at nodes above the soil. The nodal roots provide the permanent and principal root system of the plant. The aerial roots grow from the nodes above the ground and help to anchor the plant firmly whilst also contributing to the uptake of water and nutrients.

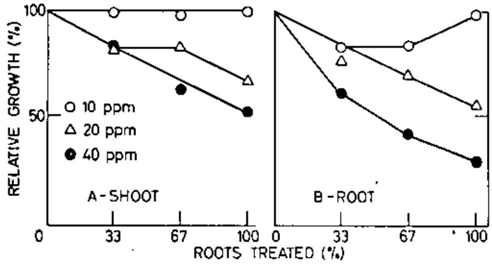

Fig. 12 Effect of boron concentrations in the soil solution on root growth of maize *(Bingham and Garber [1970])*. The graphs represent relative shoot (A) and root growth (B) of maize plants in relation to the percentage of the root system exposed to soil solution concentrations of 10, 20, and 40 ppm B, respectively. By courtesy of the Soil Science Society of America.

The roots of the young plant develop rapidly; when the seedling is still less than 10 cm high, roots have already penetrated to a depth of 30 cm. Most of the fully developed roots are found in the soil layer to a depth of 70–75 cm; single roots penetrate to a depth of 200 cm and more. Lateral spread under favourable conditions is within a radius of 100 cm. The depth of the root zone of mature maize plants must be considered as at least 200 cm. At maturity only 2 per cent (by weight) of the roots occur below a depth of 60 cm *(Foth [1962])*. In the average maize plant, the dry matter of the roots amounts to only 30 grams *(Sayre [1955])*.

1.4.2 Stems

The stems are filled with pith, and have from 8 to 21 internodes. Most varieties of maize do not tend to tiller like other cereals; this is probably the result of selection for large ears *(Mangelsdorf [1965])*. The plants can, however, develop a limited number of low tillers from the lower nodes. These tillers do not carry ears. Though they develop an independent root system, they remain connected to the vascular system of the main stalk. It was assumed in the past that the tillers are always parasitic on the main stem, hence the popular name of 'suckers'.

Tillers and main stalks have, however, been shown to interchange water, nutrients and assimilates. When photosynthetic activity of the tillers of maize plants was prevented, both main stalks and tillers developed poorly and their growth was reduced by approximately 50 per cent. Early removal of tillers resulted in a reduction of 10 per cent in the dry matter production by the stalks *(Rosenquist [1941])*.

Under conditions of deficient soil moisture, excessive tillering may have detrimental effects. Occasionally, there is even a movement of nutrients from the main stalk to the tillers */ibid./*.

In more recent work by *Kovács [1970]*, it has been established that the reciprocal roles of main stem and tillers in the transfer of nutrients change as the plant develops. At tillering, 33–34 per cent of the absorbed ^{32}P was transferred by the main stalk to the tiller, which had not yet developed an independent root system. One month later, P-transfer from the main stalk to the tiller was about equal to that from tiller to stalk. At flowering, ten times more ^{32}P isotope moved from the tiller to the main stalk than *vice versa*. At seedsetting, if the tiller also carried an ear, the ^{32}P transfer from the tiller to the main stalk decreased, but was still greater than the transfer in the opposite direction. By contrast, a tiller that carried no ear, transferred 71 per cent of the ^{32}P isotope to the main stalk, while only 5 per cent of the P absorbed by the main stalk, moved in the opposite direction.

In brief, after the tiller had developed an independent root system, it contributed phosphorus to the main stalk, always at a greater intensity than P-transfer in the opposite direction (**Figure 13**). There is reason to assume that the same might hold true for other nutrients too.

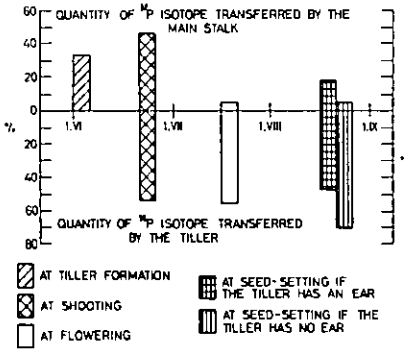

Fig. 13 P-transfer between main stalk and tiller at different stages of growth *(Kovács [1970])*. By courtesy of the Hungarian Academy of Sciences.

1.4.3 Leaves

A leaf develops at each node of the stem. Each leaf consists of a sheath which envelops the stem and a broad, large blade. Leaf number in maize is a fairly constant varietal character; the number ranges from 8 to 48 and is little influenced by environmental factors. Highly significant positive correlations have been found between the number of leaves on the main stalk and the length of the growing period of maize *(Nozzolini [1963])*.

1.4.4 Inflorescences **(Figure 14)**

Maize is unique among the grain cereals in the nature of its inflorescences *(Weatherwax [1955]*. The terminal inflorescence or tassel is a much branched panicle that normally bears only male spikelets, each of which contains two florets with three anthers each. Each tassel may produce around 5 million pollen grains. The amount of pollen produced is a varietal characteristic.

The lower end of the peduncle of the tassel ruptures easily when the tassel is pulled sharply upwards; this characteristic has great practical importance because it makes the task of detasseling, which is necessary in the production of hybrid maize seed, relatively easy and not demanding of much labour.

The lateral inflorescences or ears develop near the middle portion of the stem. The ear is borne on a short lateral branch or shank; it is a spike whose thick axis (cob) carries 8–30 longitudinal rows of paired spikelets. Each spikelet contains two florets, of which usually only one is fertile. Each floret has a single ovary, terminating in a long style or 'silk' which is covered with fine sticky hairs to which the pollen grains adhere.

The ear is covered and protected by husks which are modified leaf sheaths. The kernels are held so tightly on the cob, and covered so tightly by the husks, that maize is no longer capable of dispersing its seeds and therefore cannot survive in nature without man's intervention *(Mangelsdorf [1965])*. The number of kernels in a single ear usually varies between 300 and 1000.

No other cereal is capable of carrying an ear that weighs as much as that of maize; this is mainly possible because the ear is not carried at the top of the stem, as in other cereals, but near, and even somewhat below, the middle of the stem.

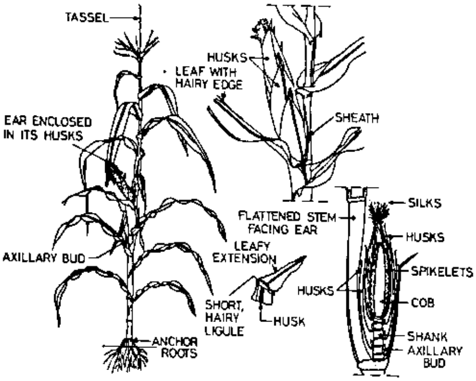

Fig. 14 The maize plant and its inflorescences. By courtesy of «Engrais de France».

1.4.5 Kernels

The kernels are one-seeded fruits (caryopsis) **(Figure 15;** *Barloy [1970])*. The endosperm, consisting mainly of cells filled with starch, constitutes about 85 per cent of the grain. The large embryo and the scutellum together account for 10 per cent and the remaining 5 per cent is composed of the pericarp and remnants of the seed coats, nucellus and pedicel *(Kiesselbach [1951])*.

Most commercial varieties have white or yellow kernels; the yellow kernels indicate a high level of cryptoxanthin with high vitamin A potency. Occasionally, kernels are red, black or purple. The starch of the endosperm usually consists of a mixture of about two-thirds amylopectin and one-third amylose. The kernels have a high oil content – up to 7 per cent –, of which more than 80 per cent is concentrated in the germ.

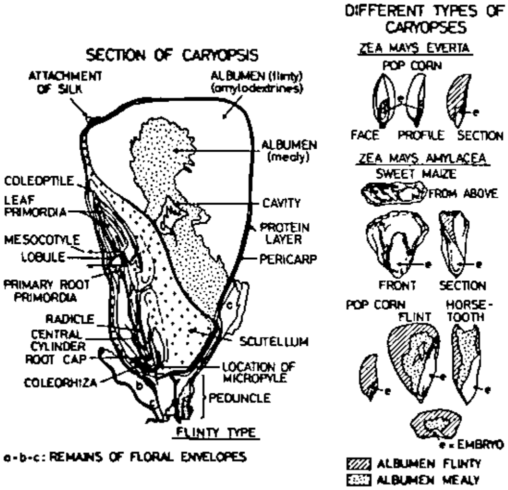

Fig. 15 Maize grain. By courtesy of «Engrais de France».

1.5 Growth and development

1.5.1 Germination, emergence and early vegetative growth

Under warm, moist conditions, emergence occurs within 4 or 5 days of sowing; when temperatures are less than optimal, 14 days or more may be required. A seedbed deficient in moisture also delays emergence. When maize is sown at the proper depth – 5 to 7 cm – the mesocotyl will elongate about half the distance to the surface and the lengthening of the coleoptile brings the leafy parts of the seedling the rest of the distance to the soil surface. The first two true leaves develop as soon as the coleoptile emerges. The next leaves unfold out of the whorl at the rate of one leaf every three days, when growing conditions are favourable. At this stage, the root system is still relatively undeveloped; for this reason high concentrations of fertilizers, placed in a band in the vicinity of the primary roots, are particulary effective in supplying nutrients to the young plants. At the age of two weeks, the seedling has 5 or 6 unfolded leaves and a well-developed primary root system, so that it no longer depends on the food reserves in the kernel *(Aldrich and Leng [1966])*. From then on there is a period of rapid leaf growth.

1.5.2 Development of the root system

Root growth in maize consists of a series of overlapping stages which are associated with stages of top growth. Early root growth is mainly in a downward – diagonal direction.

About three weeks after emergence, the nodal roots already form the major part of the root system. The roots are well distributed in the soil, so that an increasing proportion of nutrients is taken up outside the fertilizer band, from available soil nutrients and from fertilizer that has been applied broadcast and ploughed in. Nutrient requirements increase rapidly.

The early downward diagonal growth of the roots is followed by extensive lateral growth in the 0 to 30–35 cm soil layer, which is completed a week or two before tassel emergence (**Figure 16**). With the cessation of lateral growth, the brace roots make their appearance. Near tasseling time, extensive root growth begins below 35 cm. Grain development occurs largely after root growth has ceased *(Foth [1962])*.

The relative root activity in the surface horizon (7 to 10 cm depth) and the subsurface horizon (20 cm depth) respectively, is shown in **Figure 17** *(Hall et al. [1953])*.

In a study of the root systems of several maize varieties differing in maturity, it was found that the areas of root surface reached a maximum at tasselling. Nutrient supply up to the 15-leaf stage was mainly through primary roots, and thereafter through nodal roots. Injury to the primary roots at the 3 to 4-leaf stage, and to the nodal roots

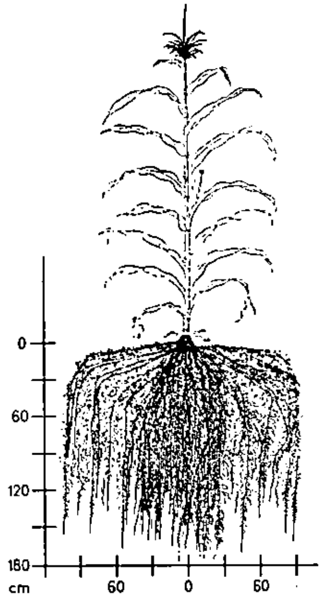

Fig. 16 Root system of fully developed maize plant. By courtesy of the John Deare Company.

at tasseling, markedly reduced dry matter production and the number and weight of grains per cob *(Bondarenko and Artyukh [1968])*.

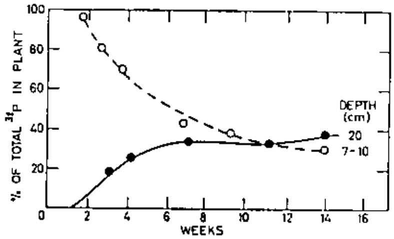

Fig. 17 A comparison of root activity of maize in the surface horizon (7 to 10 cm) and the subsurface horizon (20 cm depth) as measured by uptake of radioactive P *(Hall et al. [1953])*. By courtesy of the N. Carolina Agricultural Experiment Station.

1.5.3 Tassel initiation

Tassel initiation starts at the top of the stem, approximately when the collar of the fourth leaf becomes visible, about two weeks after emergence. After a few days, the differentiation of leaf initials comes to an end, and the number of leaves that will develop on the plant has already been finally determined by genetic factors, day length and other environmental conditions. This occurs about 3 weeks after emergence, when the plant is about 35 to 45 cm high; at this time the growing point is at, or a few centimetres above, the soil surface. The appearance and function of the growing point change, and after a few days the embryonic tassel can be recognised *(Hanway [1963])*.

1.5.4 Ear initiation

About 7 to 10 days after the tassel has been initiated, the embryonic ear begins to form on the side of the growing point.

1.5.5 Vegetative growth from flower initiation to tasseling

Shortly after flower initiation, the plants have their full complement of leaves; the stem starts elongating rapidly and the rate of nutrient uptake increases steeply. The leaf area increases from five – to ten-fold and the stem from 50 – to 100-fold *(Shaw [1955])*.

Approximately five weeks after emergence, over 85 per cent of the final leaf weight has been produced. *Hanway [1962]* considers this to be the critical stage in leaf development, when nutrient deficiencies might seriously reduce the final weight of leaves. By the time all the leaves have attained their full area the first three or four leaves may have ceased to be functional. The tassel at this stage is fully developed, but is still enclosed in the whorl of the leaves. At about this time, the number of ovules on the main ear is determined.

1.5.6 Reproduction

About five weeks after tassel initiation, the top internodes elongate rapidly, the tassels emerge and after a few days shed their pollen. Two or three days later, the silks emerge and start to elongate until they are pollinated. This is the most critical stage in the life of the plant, with peak requirements for moisture and nutrients, during which period any deficiencies will delay silking and have a serious effect on yield.

1.5.7 Pollination

The pollen usually matures and is shed 2–3 days before the ovules on the same plant are receptive, thereby promoting cross-fertilization. Although many insects visit the inflorescences, most of the pollen is wind-borne. The pollen adheres to the silks with which it comes into contact; each pollen grain is capable of germinating at any point on the silk. Pollination may continue for 14 days or more. A limited amount of self-pollination occurs, usually not more than 3 to 5 per cent. In the hot, dry climates of the dry regions, the period of pollination is usually short, not more than a few days. Delays in silking may result in imperfect pollination. During pollination, moisture stress or nutrient deficiencies may cause poor pollination and reduce the number of ovules that will be fertilized.

1.5.8 Grain production

After pollination, all vegetative growth ceases and the ear grows rapidly for about 3 weeks. The husks of the uppermost ear appear first and begin rapid growth. The ear within the husks is at first about 25 mm long, but begins to develop rapidly. An ear shoot can be found at each node, but in single-eared hybrids it will not, as a rule, develop sufficiently to be pollinated; it therefore does not mature. In prolific hybrids, more than one ear develops.

The three week period following silking marks the transition from embryo development to starch deposition. The size of the kernels and the number of them that will fill are determined at this stage *(Deihl [1969])*.

There follows a period of rapid dry matter accumulation in the kernels, which begin to increase rapidly in weight. Potassium deficiencies during this period of rapid increase in grain weight will result in poorly filled kernels. Uptake of nitrogen and phosphorus is still important, at the same time migration of these elements from the vegetative parts to the grain has started. Dry matter accumulation continues at a practically constant daily rate until about 60 days after silking, when the plants are physiologically mature and dry matter accumulation ceases. Then follows a period of water loss, during which the grain ripens and the rest of the plant dries out and dies. The development of the above-ground parts of the maize plant are shown in **Figure 18** *(Gisiger [1965])*.

1.6 Varieties

All varieties of maize belong to a single species, *Zea mays*, but the number of varieties adapted to the most varied environmental conditions is legion. Early maturing varieties are known that do not grow taller than 70 cm, and which mature their grain about 50 days after sowing; at the other extreme are varieties that grow 7 metres tall, and whose growing period exceeds 300 days.

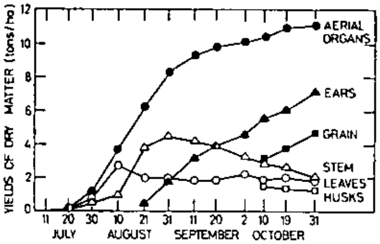

Fig. 18 Development of the above-ground parts of the maize plant *(Gisiger [1963])*. By courtesy of «Die Grüne» Switzerland.

1.6.1 Groups

Maize varieties can be classified into six main groups, which are fully interfertile; the differences among them are due to a few genetic factors.

Dent or Horse-tooth maize (Z. indentata) is characterised by the dent in the crown of the mature kernel. The endosperm consists of about equal proportions of soft and mealy, and of hard and vitreous starch. The dent in the crown of the kernel is caused by the greater shrinkage of the soft starch, which is located at the base of the kernel, whilst the vitreous starch – which is located at the sides of the kernel – shrinks less.

Flint maize (Z. mays indurata). Flint maize is characterised by a rounded kernel. The endosperm consists mainly of vitreous starch, with a small core of mealy starch in the centre of the kernel. Flint maize generally has earlier plant vigour, a greater tendency to tiller, and earlier maturity than dent maize.

In the northern areas of Europe, flint varieties were exclusively grown in the past. These were subsequently replaced by flint x dent hybrids combining the earliness and local adaptation of the European flints with the high yielding potential and lodging resistance of the American dents *(Becker [1956])*.

Flour maize (Z. mays amylacea). Flour maize has an endosperm which consists almost entirely of mealy starch. The layer of hard starch at the sides is very thin. It is one of the older types of cultivated maize.

Sweet maize (Z. mays saccharata). Sweet maize has an endosperm with a large proportion of sugar to starch; when the endosperm dries during grain maturation, the kernel shrinks and wrinkles. This type is harvested immature for table use or canning.

Pop maize (Z. mays everta). Pop maize has kernels which are small and pointed, and their starch is almost entirely vitreous. On heating, the kernels 'pop', and their volume is increased up to thirty-fold.

Waxy maize (Z. mays ceratina). The endosperm starch of this group consists entirely of amylopectin and has special properties, similar to those of tapioca starch.

Most of the cultivated varieties belong to the first two groups; horse-tooth and dent maize. The horse-tooth varieties are those with the greatest yield potential; the dent varieties are better adapted to adverse growing conditions.

1.6.2 Hybrid maize

The methods of producing maize hybrids and their considerable superiority over the traditional open-pollinated varieties are too well known to require elaboration here. Top-crosses and double-crosses are the main forms used in agricultural practice. The single-crosses are potentially more productive and uniform than the others, but their seed is much more expensive to produce. Single-crosses are usually advantageous for growing under irrigation, whilst the double-crosses are widely used in rain-fed cropping.

Successful hybrid maize varieties are characterised by their deeper and more extensive root system, which enables them to draw more efficiently on the nutrients and moisture in the soil.

In view of the importance of making the maximum use of the available growing period and of ensuring that the maize crop is harvested before frost damages the crop or protracted rainfall makes harvesting impossible, hybrid varieties are classified according to the length of the growing period, with a range from 70 to over 150 days.

In general, it can be stated that the earlier-maturing the variety or hybrid, the smaller is the plant; the number of leaves, height and size of ear are thereby reduced. The yield per plant is therefore smaller than that of later-maturing types grown under the same conditions, and this can only be partly overcome by increasing the plant population density. The practical conclusion is to give preference to the varieties or hybrids with the least precocity, that are capable of reaching maturity before the normal date of the first frosts.

The higher yield potential of the hybrids is of value only if environmental conditions make it possible to exploit this advantage; when the crops are grown with primitive methods or under adverse growing conditions, hybrids may be inferior to well-adapted open-pollinated varieties, and single or double-crosses inferior to top-crosses. When pollination coincides with unfavourable climatic conditions such as hot dry winds and deficient soil moisture, the very uniformity of the single – and double-crosses is a disadvantage. Open-pollinated varieties and, to a lesser extent, top-crosses, being more heterogeneous, continue producing pollen for a longer period. The prospect that at least part of this period will have more favourable conditions is greater than that for the hybrid, which completes fertilization within a few days. In brief, the use of hybrid maize must be tied up with improved cultural techniques and a favourable, or controlled moisture regime.

– *Prolific hybrids*

In the past, single-eared maize was preferred because of the popular emphasis on ear size and the greater ease of harvesting when hand harvesting was the rule.

Multi-eared hybrids have been developed from crosses between maize and teosinte.

The grain of these hybrids usually averages 12 to 14 per cent protein, because the teosinte has about twice as much protein as maize.

– *Compact hybrids*
A semi-dwarf mutant, called compact, is characterised by a proportionate reduction in size of the hole plant. Under high levels of fertility and with a controlled moisture supply, the compact inbreds show a higher yielding ability at their optimum population than do their normal counterparts. Much higher population levels are possible with the compact types; few compact plants are barren at population levels at which over half of their normal counterparts produce no ears.
In the early stages of development it is difficult to distinguish between compact and normal plants; at maturity, the former are half as tall as the latter. During flowering, vegetative growth of compact plants is extremely limited, so that more photosynthates can be used for ear shoot initiation and development *(Sowell et al. [1961])*.
Compact types that produce a number of ear-bearing tillers as well as prolific, single-stalked types, are being developed.

– *Male-sterility*
Cytoplasmic male sterility and genes for pollen restoration have been incorporated in many inbred lines in order to eliminate the need for detasseling in the production of hybrid seed.

– *Improved open-pollinated varieties*
For developing countries, that do not have the professional competence required for the breeding of adapted hybrids, nor the necessary infrastructure for the maintenance and large-scale production of hybrid seed, a special approach has been developed by the *International Maize and Wheat Improvement Centre in Mexico.*
The basic purpose is to develop high-yielding, disease-resistant and widely adapted open-pollinated varieties of maize. In order to achieve this aim, gene pools are formed that are highly variable with respect to genes for disease, insect and drought resistance, protein quantity and quality, and insensitivity to daylength. These flexible gene pools provide basic raw materials from which national breeders around the world can develop superior varieties for specific conditions.
Regional programmes have been established to help national breeders work together in the development of high yielding varieties adapted for several countries with similar problems and climates. The international centre supplies breeding materials, information and technical assistance.
Most of the outstanding varieties in the tropics today have been, or are being, formed from a broad-based gene pool that involves five main Latin American germ plasm complexes. These five complexes have been put together in different proportions for different areas to form varieties with yield potentials substantially above the varieties formed from local materials. Outstanding varieties have been developed from this racial intermixture in India, Pakistan, South-east Asia, West Africa, Mexico, Central America, and the lowland tropical areas of South America. The centre itself has formed several widely adapted varieties from this complex; these are proving especially useful in countries that do not have the skills for the adaptive breeding work required to develop improved varieties *(Anonymous [1968])*.

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2. Cropping systems and rotations

2.1 Are crop rotations obsolescent?

Crop rotations were once considered the essential basis of a stable agriculture. They were the only available means of preventing the deterioration of soil fertility and the achievement of relatively high and stable yields. By contrast, monoculture of row crops, such as maize, was considered the epitome of backward, self-defeating farming methods, which resulted in an exhausted and usually eroded soil.

Hopkins et al. [1968] reviewed the results of 30 years of crop rotation at the *Illinois Experiment Station*. They found that after 12 years of continuous maize, yields declined steeply from 4500 to 2200 kg ha; the effects of the monoculture then tended to level off, and dropped by only another 500 kg ha over the following 16 years. Maize yields in a maize-clover rotation were reduced by only 250 kg ha in the first 10 years, and by an additional 500 kg in the following 16 years. *Hopkins* concluded that «The fertility of the soil can be maintained or even increased by a proper system of grain farming including a legume in the rotation.» Similar conclusions were drawn from many other experiments. For example, over a period of 52 years, yields in the famous Morrow Plots at the *Illinois Experiment Station* decreased with continuous maize and in a maize-oats rotation, while they increased in a maize-oats-clover rotation *(Illinois, University of. [1957])*. The declining maize yields were generally attributed to losses of nitrogen and of organic matter. In Ohio, after 33 years, soils under continuous maize lost one-third of their original organic matter and 59 per cent of their nitrogen. Such losses did not occur under rotations including a legume *(Salter et al. [1936])*.

2.2 Technological innovations

Technological innovations in agriculture justify a re-appraisal of the need for and justifications of soil rotation.

a) Soil fertility: At a time when chemical fertilizers were nonexistent, or very expensive, nitrogen fixation, and the application of farmyard manures, were the only ways of ensuring a high level of soil fertility and providing essential nutrients to the crops. At present, chemical fertilizers are generally plentiful and inexpensive; by contrast, the costs of growing legumes and handling farmyard manure have increased steeply. By applying adequate amounts of fertilizers to maize, it has been found possible to reduce the effects of the preceding crops on the yield of maize by 54 to 70 per cent *(Kos [1966])*. Heavy applications of fertilizers also increase the amounts of organic residues that can be returned to the soil.

b) Preventing the build-up of soil-borne diseases, pests and weeds
The increasing array of fungicides, pesticides and herbicides available to the farmer has provided him with tools for protecting his crops which are far more effective than the simple rotation of crops. There are a number of serious soil-borne diseases for which crop rotation never was effective.

c) Control of soil-erosion
Minimum tillage, stubble-mulch farming and sowing on the contour make it possible to prevent soil-erosion, even in monoculture.

d) Ensure a balanced programme of work throughout the year
This was one of the great advantages of crop rotation when most farm operations were carried out with animal power and manual labour. With the mechanisation of agriculture and the use of increasingly specialised, sophisticated and expensive machinery, only the farmer who grows one or at the most two crops, can afford the expense of purchasing and maintaining the equipment required to grow a crop economically. Furthermore, the farmer growing only one or two crops becomes a specialist in them, with a high level of know-how and competence. In these respects the farmer growing a number of crops in rotation is at a disadvantage.

As a result of recent innovations in agricultural technology, mentioned above, the historical view that a planned rotation of crops is essential for the maintenance of soil fertility and efficient water use is no longer generally accepted. The new attitude is summarised by *Pendleton [1966]* as follows: 'The trend towards monoculture has not resulted in great losses of water, soil and yields predicted not too many years ago. To a large degree, this may be attributable to technological advancement. This new era of "crop specialisation" has resulted in more total food or fibre from a given farm, and therefore more efficient use of water.'

2.3 Limitations of monoculture

Before rotations can be abandoned as an essential element in good farming, a number of limitations must still be overcome.

There is a great attraction for many farmers to specialise in the growing of a single crop, such as maize. With modern machinery, labour requirements are low, risks are minimal, high yields can be achieved, the crop is easy to store or market, and a stable income is assured.

Continuous cropping to maize is therefore a frequently adopted practice. Provided ample fertilizers are applied and appropriate cultural practices are followed, continuous cropping has less adverse effects on maize than on many other crops.

In investigations carried out on a wide range of soil types in Iowa, it was established that high yields of maize, of 6000 to 7500 kg/ha, could be obtained under a wide range of cropping systems, provided erosion was no problem and 220 kg N/ha were applied to the maize. Maximum maize yields averaged about the same for the four cropping systems studied:

maize – oats – ley – ley; maize – maize – ley – ley; maize – maize – oats – ley; and continuous maize *(Shrader et al. [1962])*.

In field experiments in Ohio, carried out over a six-year period, maize in monoculture, to which 220 kg N/ha were applied, averaged only 11 per cent less than yields from a maize – wheat – lucerne rotation receiving the same amounts of nitrogen **(Figure 19)** *(Triplett [1962])*.

The major factors considered important to sustaining yields in maize monoculture are nitrogen on light-textured soils and soil structure in heavier soils *(Triplett [1962])*.

Results over 12 years from a maize rotation experiment in Rhodesia (not irrigated) have consistently shown that, provided an adequate level of plant nutrients is maintained in the soil, maize grown continuously and with its stover ploughed in, is the most economic rotation *(Henderson Research Station [1969])*.

However, there are a number of limitations to maize monoculture as the following examples will show.

In Queensland, maize has been grown on red loam soils for up to 70 years, mostly in monoculture. A decline in average yield over a long time has been recognized. A number of factors are considered responsible for this decline. Of these, the following are relevant to monoculture: (a) increase in the incidence of diseases, particularly those due to *Diplodia zeae*; (b) deterioration in soil structure and associated loss of top soil by erosion; and (c) depletion of plant foods by continuous cropping to maize over a long period. From an analysis of yields over a period of 36 years, the decline in yields which could be attributed to time-nitrogen regression, soil structure deterioration, and erosion loss was estimated as 8.48 kg/ha/year *(Van Haeringen [1965])*.

In rotation experiments in Colombia, it was found that yields of maize grown continuously without application of nitrogen declined with each successive crop; when a second crop of unfertilized maize was grown after soybeans, yields were similar to those of unfertilized continuous maize. Nitrogen applications to maize grown after soybeans increased yields markedly *(Gómez [1968])*.

In field trials in Rumania 1959–67, yields of maize grown continuously for more than 4–5 years, were shown to be lower than when they were grown in crop rotations of 2–4 years. Fertilizer efficiency was higher in rotations than in monoculture *(Stratula et al. [1968])*.

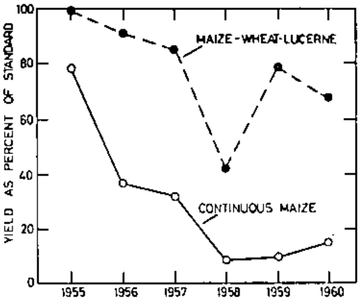

Fig. 19 Maize yields in monoculture compared with those obtained in a 3-course rotation – all without nitrogen *(Triplett [1962])*. The yields are expressed as percentages of the same treatments receiving 220 kg N/ha. By courtesy of the American Society of Agronomy.

2.3.1 *Build-up of diseases, pests, and weeds*

Under continuous maize, there is a simultaneous build-up of diseases, pests and weeds, and a breakdown of the soil structure. Whilst many effective fungicides, pesticides, and herbicides are available, none of these has yet enabled full control of the diseases, insects and weeds encountered in the fields. Their maximum effectiveness is achieved only when they are integrated in a system of crop management which includes crop rotation.

The germination on soil taken from fields cropped continuously with maize has been found to be poorer than on that taken from fields cropped in rotation, indicating that the number and virulence of microorganisms attacking the germinating seed is increased by continuous maize cropping *(Hooks and Zuber [1963])*.

In field studies in Illinois it was found that the more frequently maize was grown in the rotation, the lower the yields and the greater the damage from *Diplodia* ear rot. The yields decreased and the incidence of *Diplodia* ear rot increased with each consecutive year that maize was grown in the rotation *(Koehler [1959])*.

The efficacity of crop rotation in reducing the severity of a number of soil-borne diseases is ascribed not only to the 'starvation' of the pathogen in the absence of a suitable host, but also to the stimulation of antagonistic properties of the soil microflora, by the non-hosts and their residues *(Patrick and Tousson [1965])*.

An example of the role of rotation in the control of weeds is provided by witchweed *(Striga asiatica)*. Catch or trap crops have been found effective in reducing witchweed to levels which make maize cultivation practicable. Soybeans, field peas and sorghum had to be grown for at least three years before acceptable yields of maize could be obtained. Complete eradication of witchweed was not achieved by any crop within a 5-year period *(Robinson and Dowler [1966])*.

2.3.2 *Deterioration of soil structure*

The breakdown of soil structure is one of the main problems of maize production on heavy soils. The heavy lacustrine soils of northwestern Ohio, for example, when properly drained, were among the most productive soils of the Corn Belt of the United States. After two to three decades of cultivation, the soils tended to become compacted and to drain with more difficulty. An extensive series of experiments was carried out in Ohio, comparing the long-term effects of different crop rotations with maize upon the physical characteristics of the soil *(Page and Willard [1946])*.

The average yields of maize for 4 years, and the response to fertilizer, on one site, are shown in Table 10.

The low yields of continuous maize are striking, with little apparent difference whether the residues were left in or removed. Fertilizer increased yields somewhat, but not to very high levels. The low yields of the continuous maize plants are paralleled by the sharp reduction in the degree of soil aggregation. By contrast, in rotations in which soil improving crops were included and liberal amounts of organic matter have been returned to the soil, far more favourable soil structure has been maintained and higher yields achieved **(Figure 20).**

Table 10. Average yields of maize for 4 years, and response to fertilizers in different cropping systems and physical condition of the soil in Paulding, Ohio *(Page and Willard [1946])*

Rotation	Average yield (kg/ha) *Unfertilized*	*Fertilized*	*Degree of aggregation* %
Maize – oats – lucerne – lucerne	4 121	4 438	47.0
Maize – oats – lucerne – grass – lucerne – grass	4 337	4 692	54.2
Maize – oats – lucerne	3 166	4 165	53.0
Maize – oats – sweet clover	3 790	3 556	52.2
Maize – soybeans – oats – sweet clover	3 191	3 492	49.0
Maize – oats (residues turned under)	2 914	3 206	43.7
Maize – oats (residues removed)	1 974	2 882	40.1
Maize continuous (stalks returned)	1 149	1 546	23.4
Maize continuous (stalks removed)	1 200	1 765	23.4

2.3.3 Decline in soil fertility

On the basis of a 39-year record of maize yields from crop rotation experiments initiated in 1915 on a silt loam soil in Ohio, there was no evidence to show long-term cumulative trend effects of the commonly used Corn-Belt rotations on soil productivity. Almost all of the cropping systems, excepting continuous maize, were capable of maintaining the crop producing capacity of the soil, provided soil erosion was prevented. The yield levels characteristic of a given rotation were generally reached as soon as the rotation had completed the first cycle, but with no pronounced trends thereafter. In general, the yield levels of maize were associated with soil nitrogen level. Continuous cropping to maize resulted in a long-term downward trend in apparent soil productivity *(Haynes and Thatcher [1955])*.

The most dramatic effects of fertilizers were recorded in maize monoculture. In 1955, the Morrow Plots at Illinois were modified and started to receive large amounts of nitrogen, phosphorus and potassium. Phenomenal yield increases were obtained in the old plots that had been under continuous maize since 1915. Following these

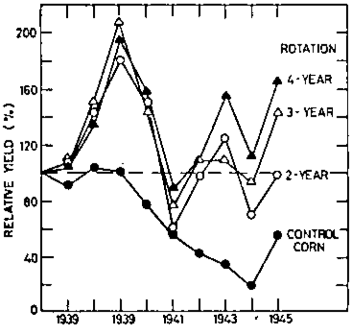

Fig. 20 Long-term effects of rotations on the relative yields of maize *(Page and Willard [1946])*. By courtesy of the Soil Science Society of America.

experiments it was concluded that growing maize continuously for a long period of years is possible provided adequate rates of fertilizers are applied annually, such as 132 kg N, 94 kg P and 94 kg K/ha *(Englehorn et al. [1964]).*

In Iowa, a rotation experiment in which continuous maize had been grown since 1915 was redesigned in 1952, and new treatments including fair levels of N, with and without P and K, superimposed on the old treatments.

Yields of maize on plots that had grown this crop continuously for 37 years, were increased to high levels by application of N up to 176 kg/ha, P at the rate of 27 kg/ha and K at the rate of 55 kg/ha.

The addition of phosphorous and potassium did not increase yields on the old continuous maize with nitrogen during the first years of the experiment; response to the P and K in conjunction with N increased in later years, as soil reserves of these elements became depleted by the high yields obtained. The authors conclude that continuous maize can be grown successfully on soils of low fertility if an adequate fertilizer program is followed *(Englehorn et al. [1964]).*

Although research and experience have shown that it is possible to grow maize continuously on the same soil when adequately fertilized, erosion losses on certain soils may be excessive with clean-cultivated maize. Under these conditions there still seems to be need for a ley crop in rotation with the intertilled crop *(Englehorn et al. [1964]).*

2.4 Economic aspects

The need for specialised, expensive equipment is an important argument that cannot be overlooked, but must be considered within an overall economic appraisal of the cropping systems. This problem can also be overcome by employing contractors for certain operations such as mechanical harvesting.

The most desirable crop rotation is the one that gives the maximum profit, on a sustained basis with the least fluctuations, over a period of years.

Against the economic advantages claimed for monoculture, are the lesser fluctuations and smaller risks involved in growing a number of crops, since price and weather fluctuations do not affect all crops equally.

Farmers will have to balance greater stability in income, and thus lower risks, against the possibly higher income obtainable from a single crop.

The farmer who grows maize continuously cannot be sure that his yield levels are not declining gradually. Even in a crop like maize, which is relatively insensitive to continuous cropping, yields may decline after a certain period. Such a decline will be masked by annual yield fluctuations due to environmental factors. Worse still, yields may drop suddenly and steeply, as the result of a build-up of disease organisms to epidemic proportions.

Where irrigation farming is practiced, the possibility of using irrigation water efficiently for many months of the year, as is possible when several crops are grown, may be the overriding economic factor. With a single crop, it is the peak period of water requirement which will limit the area it is possible to cultivate with the amount of water available.

Summing up, it can be stated that the farmer is no longer as dependent on crop rotation for maintaining high levels of production, as he was in the past. However, a well planned crop rotation still has important functions in soil sanitation and fertility, weed control, regulation of labour and water use, stability and security of income, and in many cases can confer economic advantages over monoculture.

The conditions under which maize monoculture can be practiced at a sustained high level of yields have not yet been fully established. Up to the present, experience indicates that it is possible to grow maize continuously on a wide range of soils, provided they are not prone to erosion, at yield levels approximately 15 per cent lower than those of maize grown in rotation under similar conditions *(Tisdale and Nelson [1966])*. Growing maize continuously does not necessarily imply that the whole farm is devoted to a single crop. Ideally, it signifies that those fields best adapted to maize production are reserved for this crop, and other crops, such as for pasture, are sown on other fields, less suitable for maize *[ibid.]*.

2.5 Types of rotations practiced for maize

2.5.1 Cover crops

In many maize-growing areas of the United States, the growing of cover crops of legumes and cereals during the winter months preceding the sowing of maize, is a widely recommended practice. The winter-sown crops serve as green manure or for winter grazing. The advantages of the cover crops are that they add or conserve nutrients or make them available to the following maize crop, reduce erosion, improve soil structure, and provide forage. The disadvantages are the cost of the cover crop, the difficulty in establishing the maize crop, and a possible increase of insects and diseases *(Beaty and Giddens [1970])*.

The results obtained from green-manuring in experiments in Georgia, are shown in Table 11.

Table 11. Effect of green manures on maize yields *(Beaty & Giddens [1970])*

Green manure	*Amount of dry matter produced (kg/ha)**	*Average yield of maize (kg/ha)***
none	—	4 638
rye	3 423	4 825
crimson clover	2 542	4 912
rye and crimson clover	3 269	4 669

* Average of three seasons.
** Average of five methods of seed-bed preparation and three seasons.

In these trials, the effect of green manures on maize was negligible; it must, however, be pointed out that the amounts of dry matter produced by the cover crops and turned under were very small and that the yields of maize were also not high in these trials.

The effects of a number of cover crops on maize yields were investigated in field trials in Bulgaria *(Sarkizov [1967])*. The results obtained are shown in Table 12.

In humid climates maize is frequently grown in rotations which include leys for one or more years. These can be effective in increasing maize yields, their contribution

Table 12. Effect of cover crop on maize yields *(Sarkizov [1967])*

Cover crop	*Green matter produced* kg/ha	*Yields of maize* (3-year averages) kg/ha
none	—	6890
winter peas	25 200	7050
spring peas	19 500	6500
wheat/barley mixture	21 500	6920

depending on the legume species, the proportion of legume in the mixture, management practices, the yields obtained, soil fertility levels, seasonal conditions, etc. Similar maize yields have been obtained from different cropping systems; however, the quantity of fertilizers, in particular nitrogen, required to obtain these yields differed according to the kind of rotation *(Stickler et al. [1959])*.

Shrader et al. [1966] tested the premise that maize yields, over wide ranges of cropping systems, differ only because of differences in available nitrogen. This premise was tested by using the criterion of whether maize yields in long-term rotation experiments could be estimated by a common nitrogen response curve. On analysing data from two long-term experiments in Iowa, they were able to confirm their hypothesis that the maize yields from the different rotation systems could be fitted to one common function relating yield to nitrogen. With this mode, rotation effects could be expressed in terms of fertilizer nitrogen equivalents and substitution rates could be estimated.

In experiments on a red-brown clay soil in Southern Rhodesia, the turning under of a green manure crop was found to increase maize yields, but could do so to a high level only with concurrent phosphate fertilization (Table 13, *Thompson [1962]*).

Table 13. Effect of phosphorus applications and of green manure on yields of maize grown on a red-brown clay soil *(Thompson [1962])*

	No green manure	*Green manure*
No P	16.50	26.10
P (44 kg P_2O_5/ha)	39.76	44.06

It will be seen that the beneficial effect of green manure with phosphorus on yields is only slightly greater than that of phosphorus applied alone. Green manure was found to increase the K, Mg, Cu, and P contents of the maize leaves and to depress Mn, Zn and Ca (the effects on Mg, Ca and Zn levels were not statistically significant). The green manure also raised the Ca, Mg, Mn and Zn contents of the grain significantly *[ibid.]*.

In Georgia, it was found that nitrogen applied directly to maize was more effective than when applied to a preceding crop of green manure (rye). Although the green manure crop was fertilized with high rates of N (up to 168 kg ha) increased soil organic matter and soil N content, improved bacterial activity and soil structure, these favourable effects were not reflected by higher yields of maize than those obtained by applying N directly to the maize crop *(Giddens et al. [1965])*.

In the Philippines, hybrid maize was grown as a test crop during three wet seasons on plots that had been green manured with yellow mungo *(Phaseolus aureus)* or sown to maize. The test maize was top-dressed with various rates of N, P and K. Green manuring increased the yields of test maize by an average of 7.6 per cent (significant in the 2nd and 3rd years); this response was scarcely affected by level of applied fertilizers *(Aala and Gonzales [1964])*.

Experiments carried out by *Sutherland et al. [1961]* tended to confirm that the main benefit that the maize crop derives in rotations with legume leys in humid regions is the additional nitrogen resulting from N-fixation. The estimates of the amounts of nitrogen supplied by the legumes ranged from 135 to 220 kg/ha in one season and from 60 to 91 kg/ha in another season. These figures illustrate the wide range of variability involved.

With the availability of less expensive commercial nitrogen, the comparative value of nitrogen fixed by legumes and that supplied by fertilizers has become an important economic consideration.

In France, it was established that the uptake of nitrogen after lucerne by three successive crops (maize, wheat, oats) receiving no additional nitrogen, amounts to 150 kg/ha *(Jacquard et al. [1969])*.

In investigations in Iowa, the effect of the nitrogen contained in 19 legume green manures on maize yields was compared with that of inorganic nitrogen. Grain yields were significantly increased by both nitrogen sources. However, when maize production was used to evaluate the relation effectiveness of legume and fertilizer nitrogen, the value of legume nitrogen was equivalent to that of 37 kg N/ha for the first-year maize crop, and of 70 kg/ha for the combined two-year production of maize **(Figure 21)** *(Stickler et al. [1959])*.

2.5.2 Shifting cultivation

In tropical Africa, the dominant cropping system is 'shifting cultivation', in which land is cleared of trees and brush by slashing and burning, cultivating for a few years and after soil fertility is exhausted, returning to natural vegetation for a fairly long period – usually more than twice as long as the cropping period *(Miracle [1966])*.

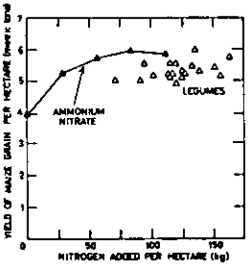

Fig. 21 Average yields of maize in two years on a silty clay loam soil following oats alone or following a single season of legumes *(Strickler et al. [1959])*. The ammonium nitrate was added only to the maize following oats. By courtesy of the American Society of Agronomy.

In the savannah regions, the rest period consists of allowing the land to revert to grass. In the tropics, the need to devise arable cropping systems that can replace shifting cultivation, has concentrated on the use of crop residues, cover crops, green manures, etc., as means for maintaining soil fertility.

The yields of crops grown under these conditions are considerably influenced by the nature of the preceding crops. *Bennison and Evans [1968]* relate this effect of crop sequence mainly to the amount of soil nitrates remaining at all depths in the soil. The quantity of nitrates left by a crop generally depends on its own utilization of nitrates and is therefore influenced by its vegetative bulk, its rooting habit and the length of its growing period. The lowest levels of nitrates were found after a maize crop; the levels were higher for beans and highest for fallow. The more plentiful the supply of residual nitrates, the more rapid was the development of the crop and as a result, flowering was more abundant and yields were higher.

Whilst fallow stores water as well as nitrates, it was shown in three investigations that the amount of water left after an early harvested crop was little less than after fallowing, so that the main differences between preceding crops in this case was in the nitrate levels found after harvest and not in the moisture status of the soil *[ibid.]*.

In subhumid regions, maize yields following a ley may be actually lower than when maize follows maize. Leys use moisture more intensively than does maize, and for this reason land following a ley may have less stored subsoil moisture than land following maize. This may be the factor limiting maize yields in regions in which the rainfall during the growing period is less than optimal *(Shrader and Pierre [1966])*.

2.5.3 Maize – small grain rotations

In the countries of northern and north-western Europe, maize is valuable as a so-called 'break crop' in intensive cereal production *(Hall [1968])*. It provides a degree of control over the build-up of cereal pests and diseases and an opportunity for the control of weeds. Maize fits easily into cereal – growing systems, it has a low labour requirement, and can largely make use of the usual farm equipment. Times of sowing and harvesting do not clash with those of other cereals. Maize is resistant to take-all, eye-spot and the foliar diseases of wheat and barley. Compared with other cereals, an almost complete absence of pest and disease problems has been noted, even after continuous growing of maize for six years. As the crop is sown during the last week in April, weeds can be mechanically controlled before sowing and during growth.

Highly efficient chemical control is also possible. The resistance to high doses of atrazine is of special value. Couch grass *(Agropyron repens)* is one of the major problems of cereal growers in England and other countries with similar climates. The control of couch-grass is not only important because of the severe competition of the weed, but also because it serves as a host for take-all fungus. The residual effect of atrazine used for couch-grass control is so persistent, that a two-year break in the growing of susceptible crops is essential. Maize is therefore a suitable alternative crop *(Gunn [1968])*.

In an experiment in Kent (U. K.), it was shown that the recuperative effect of a one-year break of maize on the yields of wheat that had been grown consecutively for four years was to increase yields from 5080 to 5715 kg/ha *[ibid.]*.

Other countries in Europe in which wheat and barley are economically important have also come to the conclusion that maize is a convenient crop to grow in rotation with the small grain cereals.

The following are crop rotations recommended in Germany:

1. Horse-beans – winter wheat – spring barley – maize – oats – winter wheat – spring barley;
2. Maize – spring hweat – winter barley – rape – winter wheat – oats – horse-beans winter wheat – spring barley;
3. Maize – maize – oats – winter wheat – spring barley; and
4. Maize – maize – spring wheat – winter barley (with green manure) – oats *(Zscheischler and Gross [1966])*.

In a decade of field trials with hybrid maize at several locations in Hungary, a biennial rotation of maize and wheat gave better results than a yearly rotation of these crops. With adequate fertilizer application, maize could be grown in monoculture for 6 years without loss of yield *(Kaposzta [1968])*.

In trials in Bulgaria, maize hybrids were grown as a catch crop after barley. When sown between 1 and 10 July, in 1960 and '61, they produced 11 800 to 33 500 kg green material/ha/yr and 1600 to 4400 kg grain, depending on cultivar and year. In 1962, a dry year, maize plants reached only the 5 to 6-leaf stage. It was estimated that in N. Bulgaria two good crops can be expected every five years *(Georgiev [1966])*.

One of the most important rotations practiced in North India is an alternation of maize with wheat. The maize receives relatively heavy doses of fertilizer, whilst the wheat is not fertilized and utilizes the residual effects of the fertilizers applied to the maize crop. In a field study on the residual effects of the N and P fertilizers applied to the maize, yield responses of 4.6, 2.3 and 2.9 kg of wheat per kg of N applied the previous year at the levels of 67,135 and 200 kg/ha of N, respectively, were recorded. By contrast, no significant responses of wheat to residual effects of the previously applied phosphorus fertilizers were noted *(Mathur et al. [1965])*.

2.5.4 Mixed cropping

Mixed cropping is a characteristic of primitive agriculture, dating from antiquity. It is method which attempts to make the most of the potentialities of the environment. By planting together a number of crops with varying planting and harvesting times and growth habits, plant nutrients in different soil layers are better exploited and light energy more effectively intercepted. Plants of the same species, compete more intensively with each other than plants of different species, mainly because of differences in the root systems and periods of peak water requirements of the latter, so that a limited water supply is used more efficiently in a mixed-cropping system than in pure stands. The risks due to diseases, pests and climatic factors are reduced and also better distributed, and weeds more effectively smothered. When primitive varieties are used, the total yield from a given area under mixed cropping may be greater than from pure stands *(Baldy [1963])*.

A notable example of mixed cropping practiced by a primitive people, with maize as the central ingredient, is the maize-bean-squash complex, which originated in Mexico during the period 1500–900 B. C. It was so successful that it spread out from Mexico and became the basis of practically all pre-historic Indian agriculture in all parts of America.

The complex of three crops exploited the soil and light energy most effectively: the beans climbed on the maize stalks, exposing their leaves to the light without excessive shading of the maize leaves: the squash grew prostrate on the ground and choked out weed growth. The mixed cropping also produced a highly balanced diet: the maize supplied most of the carbohydrates and certain amino acids in which beans are deficient; the beans supplied the bulk of the protein; also phosphorus and iron and the vitamins riboflavin and nicotinic acid. The squashes added calories and an increment of fat *(Stakman et al. [1967])*.

Intercropping is still practiced on a large scale in the Mediterranean region, in Africa and in India.

In tropical Africa, a number of crops are always sown together; the combinations of crops grown together vary widely, as do the sequences of crop combinations followed. Many of the ethnic groups each have a set of rules, handed down from generation to generation, specifying the kind of combination of crops suitable for each soil type, when planting should be done and what sequence should be sown *(Miracle [1966])*. *Evans [1960]* doubts whether it will be possible to replace intercropping by rotational systems of agriculture based on pure stands, as long as the hoe is the main agricultural implement. He found that intercropping maize or sorghum with groundnuts generally gave higher overall crop production per unit area than by growing these crops in pure stands. This was found to hold true in two areas of contrasting fertility as well as under conditions of contrasting rainfall: low, irregularly distributed rainfall and favourable rainfall.

Trials at two locations in W. Pakistan showed that a greater economic return was obtained by growing maize and soybean in mixed stands in alternate rows 60–120 cm apart instead of growing each in pure stands in rows 60 cm apart *(Sulyman et al. [1967])*.

Intercrops have been suggested in modern agriculture as a compromise between conventional rotations (including leys) and maize monoculture, and periodic interest is still being shown in alternating rows or strips of maize with other crops as a means of increasing total income per unit area.

In an experiment in Virginia, in which solid planting of maize was compared with alternate pairs of maize rows and soybean rows, it was found that the maize in the paired rows yielded approximately 30 per cent more (for area actually in maize) than when planted alone. No data on the effect on soybean yields as compared with solid planting were obtained *(Alexander and Genter [1962])*.

In an investigation in Illinois on the possible advantage of alternating strips of maize and soybeans, it was found that alternating four 100 cm rows, or six 60 cm rows of maize and soybeans gave an increase in the yields of maize of approximately 20 per cent, with a parallel decrease of 20 per cent in the yields of soybeans-as compared with the yields from a similar area of solid sowing of the two crops.

The greater part of the difference was due to border effects (positive in the case of maize, depressing in the case of soybeans) in the rows in which the two crops were adjacent *(Pendleton et al. [1963])*.

In field experiments in Ohio, carried out over a six-year period, intercrops were compared with a maize-wheat-lucerne rotation. Where intercrops were used, yields of fertilized maize were 18 per cent lower than the yields from the three-year rotation. Yields of maize without fertilizer were unsatisfactory, whatever the intercrop adopted. By constrast, maize yields were excellent whenever sufficient nitrogen was applied, and showed little tendency to decline, with or without intercropping. Intercrops therefore seem to be of little practical value in improving maize yields in intensive cropping systems, unless soil erosion is a major problem *(Triplett [1962])*.

With very few exceptions, in particular forage and pasture crops, modern agriculture is based on pure stands. Weed control, whether mechanical or chemical, as well as pest and disease control, are hindered in mixed stands. Rational fertilizer applications are usually not possible to a mixture of different crops. However, probably the main limitation to mixed cropping in modern farming is that efficient mechanical harvesting of a mixed crop is not possible.

2.5.5 Organic manures in maize rotations

Organic manures have been traditionally used in European countries and to a lesser degree in the United States and elsewhere. Their long-term effect on soil fertility, in particular on sandy soils, is undisputed; however, their use for large-scale grain production is becoming more and more limited, mainly because of the labour problems involved.

Maize is frequently the first crop in the rotation to be sown after organic manuring. Most of the active growth of the crop is during a period of high soil temperatures and favourable moisture regimes. These are favourable conditions for the decomposition of the organic manure, and the release of nutrients is rapid. The quantities of farmyard manure normally applied are from 30 to 40 tons/ha. Excessive amounts are undesirable, as they may cause a delay in maturity, which in certain regions might prevent the timely ripening of the crop or make harvesting difficult. The later the manure is applied, the more important it is that it should be well decomposed.

In certain regions in Europe, crushed or chopped cereal straw is incorporated in the soil before maize. In order to facilitate decomposition of the straw and prevent nitrogen deficiencies during the growing season, sufficient nitrogen, usually 6 to 12 kg per ton of straw, is added so that the total amount of nitrogen, including that of the straw, should be 1.5 to 1.7 per cent *(Barley [1970])*.

Besides supplying appreciable amounts of plant nutrients, organic manures also affect nutrient uptake indirectly by increasing the availability of nutrient elements either present in the soil, such as P and K, or added in the form of relatively insoluble fertilizers, such as rock phosphate. *Saalbach and Judel [1961]* have shown that maize grown on magnesium-deficient soils, grew normally, when organic matter was added to the soil. In the case of farmyard manure, this effect could have been imputed to the Mg-content of the manure. However, similar results were obtained by incorporating cellulose. The authors conclude that the positive effect of the organic matter on the availability of magnesium, was due to the increased microbial activity following the incorporation of organic material in the soil and its decomposition under favourable conditions **(Figure 22)**.

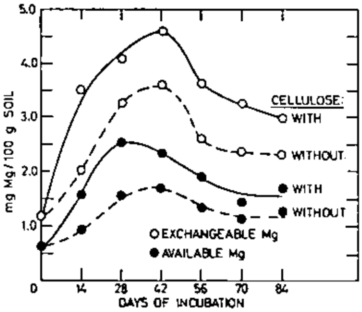

Fig. 22 Influence of adding cellulose to the soil on the availability of magnesium to maize *(Saalbach and Judel [1961])*. By courtesy of Zeitschrift für Pflanzenernährung, Düngung, Bodenkunde.

Experiments have shown that the immediate effects of farmyard manure on maize yields are not necessarily spectacular, especially in soils with high inherent fertility (Table 14).

Table 14. Effect of farmyard manure on yields of maize *(Gericke [1941])*

Soil type	*F. Y. M.*	*Grain yield (kg/ha)* *No mineral fertilizers*	*With NPK*
Sandy	none	2020	3340
	applied	3390	4260
Loam	none	—	4170
	applied	3520	4380

These results indicate that even on sandy soils, mineral fertilizers alone were able to produce yields practically equal to those obtained with farmyard manure and, more important still, that even at the relatively low yield levels of this experiment, farmyard manure alone was not able to supply sufficient nutrients required for grain yields of 4 tons/ha and more.

2.6 Place of maize in the rotation

Maize is considered an excellent preceding crop for all other crops grown in the rotation. If the maize is properly cultivated, it leaves a soil in good tilth, and free of weeds. The residues left after harvesting are the equivalent of approximately 20 tons stable manure per ha. Yields of crops after maize are usually higher than after other cereals. In trials on irrigated land at Bukhara, Uzbekistan, for example, yields of seed cotton after maize were 280-290 kg/ha higher than in monoculture *(Bodrov and Rakhimov [1968])*.

Maize can be grown after practically any other crop. It frequently follows sugar beets, field beans, lucerne, cotton, winter legumes for forage or hay, or temporary leys. Under irrigation, maize can be sown the same year after any crop that frees the soil before June. It can also precede almost any other crop without adverse effects.

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3. Tillage

3.1 Conventional methods

3.1.1 Evolution of tillage methods

The tillage methods practiced for maize production in the world are extremely varied, ranging from the most primitive to the most sophisticated used in crop production.
In many parts of the tropics, even to this day, a few kernels are dropped into a hole made with a sharp stick and then left without further attention until harvest *(Miracle [1966])*, a method identical to that used by Neolithic man, who cleared small plots of land by fire, and then used a 'digging stick' for preparing a seed bed (Plate 1).
In the Near East and in North African countries, a wooden plough is used to which

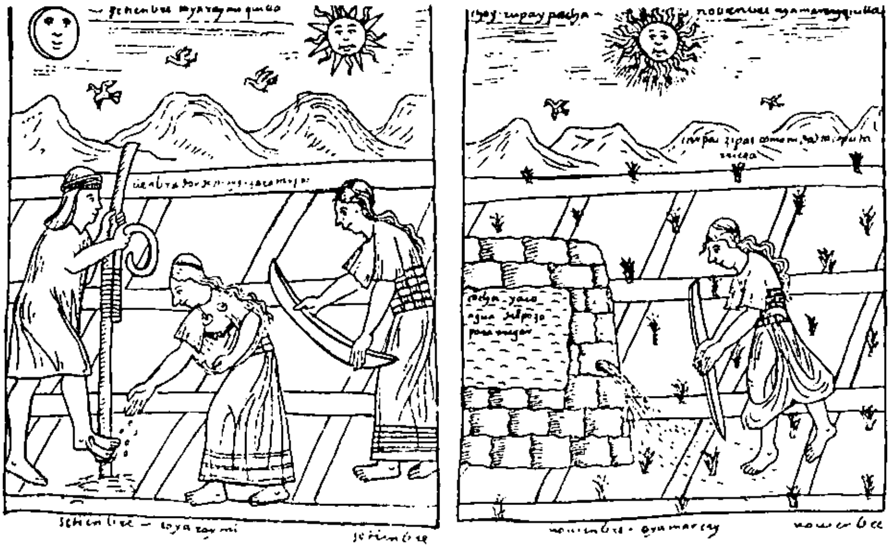

Plate 1
Reproduction of original sketches by Guamon Poma de Ayala, depicting the agriculture of the Incas: Left: The Sowing of Maize; Right: Irrigating maize.
From: Races of Maize in Peru: Their Origins, Evolution and Classification, Publication 915, Committee on Preservation of Indigenous Strains of Maize, National Academy of Sciences – National Research Council, Washington, D.C. 1961.

an upright tube is attached. While one cultivator holds the plough and leads the animals drawing it, an attendant drops the seed through a funnel placed on the tube. This method is identical to the scenes of sowing depicted on 4000-year-old tablets found in the Pyramids, the earliest example of the modern 'once-over' principle of sowing and tilling simultaneously!

In tropical Mexico, the soil may be scratched once with such a wooden plough, and than the seed is dropped in the furrow and stepped on *(Miracle [1966])*.

Many unproven theories explaining the functions of tillage have found wide acceptance in the past.

In the 18th Century, *Tull [1731]* proposed the theory that plants feed on soil particles, and the more the soil is cultivated, the more particles can be absorbed by the plant roots. The 19th Century added its spate of theories concerning the role of soil tillage. In 1891 *Walden* still stated categorically that the use of tillage implements was more effective in feeding plants than was the addition of fertilizers to the soil.

The composite picture that emerged by the beginning of the 20th century indicates a fairly good understanding of the objectives and effects of tillage: aeration of the soil, promoting increased availability of nutrients, better root penetration, weed control, breaking up compacted layers, etc.

The general consensus was therefore that the importance of tillage operations could hardly be overstated. This attitude, equating a maximum number of tillage operations with good husbandry, was further strengthened by the fact that the cost of upkeep of draft animals was practically the same, whether they were working in the field or stalled; farm labour was also cheap and plentiful.

The importance formerly attached to cultivation as an objective per se, and still held by many, is vividly reflected in the following quotation from the Standard Cyclopedia of Horticulture: 'It would have been a sorry thing for agriculture if there had been no weeds. They make us stir the soil, and stirring the soil is the foundation of good farming' *(Bailey [1935])*. In short, weeds justify their existence simply by obliging the farmer to cultivate the soil!

It was only following gradual replacement of draft animals by tractors, that these traditional concepts of tillage were submitted to close scrutiny. The cost of tillage operations became a substantial part of the overall production costs. Changes in the number and depth of soil cultivations could make possible considerable savings in production costs. Many experiments on the effects of tillage on crop production have been carried out since the beginning of the present century and the results obtained were most surprising to the early investigators. The overall picture that has emerged is that the need and justification for numerous tillage operations was grossly exaggerated in the past. As a result of the objective reappraisal of the effects of soil cultivation, a new understanding, new attitudes and new methods have evolved.

In no crop has this reappraisal led to such a drastic revision of tillage methods as is the case with maize.

3.1.2 Conventional soil preparation for maize

Conventional tillage for maize is generally a three-phase operation consisting of some form of primary tillage (ploughing, rotary tillage, sub-soiler); secondary tillage for seed-bed preparation (disking, harrowing, light cultivation); and post-emergence cultivation (shovel cultivations, rotary hoe, etc.) *(Van Doren, Jr. [1965])*.

3.1.2.1 Primary tillage

After harvesting the previous crop, the residues have to be chopped and ploughed under. For heavy soils, it is recommended to plough deep in early autumn, and leave the land in a rough state throughout the winter. Light soils receive a shallow ploughing in winter, followed by a somewhat deeper ploughing in spring.

Depth of ploughing

Increasing the depth of ploughing and other tillage operations has a very marked effect on cost: for every additional centimetre of increased depth the amount of soil to be moved or turned is increased by about 150 tons per hectare! The enormous additional effort required cannot be accomplished without a considerable expenditure of fuel.

Much research aimed at determining the most effective depth of tillage has therefore been carried out, mostly in temperate climates. It was generally found that increasing the depth of ploughing beyond the minimum needed for a specific purpose – weed control, seed-bed preparation, shattering a plough-sole, etc., did not improve yields. The minimum required depends on circumstances; ploughing to a lesser depth is then usually less effective than deeper ploughing.

In field trials in Dnjepropetrovsk Province, Ukraine, ploughing to a depth of 24–30 cm increased yields of maize by 270 kg grain per ha, and deeper ploughing (34–36 cm) increased yields by 380 kg compared with ploughing to 22 cm *(Shamkii [1969])*.

Pavlov et al. [1968] recommend a ploughing depth of 25–27 cm for maize grown on a dark grey forest soil in Bulgaria. Shallower ploughing gave lower yields, whilst deeper ploughing did not increase yields.

In India, hybrid maize, Amerillo-de-Cuba, was grown on a lateritic sandy clay loam after ploughing to depths of 6–8, 12–14, or 24–26 cm. The deepest ploughing significantly increased yields of grain and stover and reduced weed growth *(Moolani and Hukkeri*, 1965).

In Rhodesia, maize was grown on a granite-derived soil which was ploughed 10, 22.5, and 35 cm deep. The yields obtained were 2.9, 5.8 and 6.9 tons/ha, respectively. The shallow ploughed plots restricted root penetration, and many plants on these plots were not able to survive the early mid-season drought. As a result, the original stand of 36 300 plants/ha reduced to approximately 21 000 plants/ha, whereas the comparable stands in the more deeply ploughed land was in excess of 32 500 plants/ha *(Anon. [1967])*.

3.1.2.2 Seed-bed preparation

One of the earliest functions of soil tillage was to prepare a seed-bed and to cover the seeds. The primary tillage is not effective in this respect; it results in a too-loose soil, with high evaporation losses. Seeds cannot be placed at uniform depth, contact between seeds and soil particles is not sufficiently intimate to ensure movement of moisture to the seed, and the seed-bed dries out before seeds have germinated. Seed emergence is therefore irregular, and stand establishment incomplete. A number of additional tillage operations are usually needed to offset some of the negative effects of the ploughing: breaking down the clods that have been turned up and compacting the soil that has been excessively loosened, and levelling the soil surface. These operations are done in spring, as soon as the soil is sufficiently dry, and consist of harrowing, cultivating, rolling and/or disking according to circumstances.

The surface soil should not be broken down too finely, but left in a cloddy condition. Such a seed bed does not crust easily and water penetration is satisfactory.

Excessive packing of the soil surface must be avoided, as it increases crust strength and impedes emergence of the seedlings, thereby causing a spotty, unsatisfactory stand, which frequently results in the need for reseeding. It is therefore recommended to compact the soil at seed level, leaving the soil above the seed in a loose condition. This can be achieved, for example, by the use of a narrow press-wheel attached to the seed drill that presses the seeds into the soil, and then covers the seed with loose soil.

3.1.2.3 Post-emergence cultivation

Inter-row cultivation is supposed to be beneficial by destroying weeds, by improving soil aeration and by reducing losses of moisture from the soil. Numerous experiments carried out in the field to determine the effect of inter-row cultivation on yields and on moisture conservation have shown conclusively that the stirring of the soil was beneficial mainly in controlling weeds.

Besides weed control, cultivation may occasionally have additional beneficial effects. As a result of improved soil porosity infiltration is increased and soil loss reduced after cultivating a crusted soil surface, such as usually forms after irrigation or heavy rainfall on certain soil types *(Borst and Woodburn [1942])*. Infiltration rates have been increased six-fold by eliminating 0–8 cm of crusted surface soil *(Duley [1939])*. The best results are obtained when the rough configuration of the soil surface is preserved.

In a five-year study on a sloping, silt loam soil in Indiana, inter-row cultivation increased yields in four out of five years. The five-year average annual yield increase was 1232 kg/ha of grain from cultivated plots over the uncultivated plots. The yield increases were ascribed to improved infiltration of water into the soil because of destruction of surface crusts and the absence of competition from weeds *(Mannering et al. [1966])*.

Similar results were obtained in New Jersey where investigations on the effects of the number of cultivations on the yields of maize, showed that a single cultivation gave better yields than no cultivation, even where weeds were controlled effectively by chemicals. However, a single cultivation gave virtually as high yields as several. The investigators ascribed the beneficial effect of a single cultivation, relatively late in the cultivating season, to the breaking up of the puddled surface formed during the growth period, before the plant canopy protected the soil from rain *(Blake and Aldrich [1955])*.

Improved nitrification in the upper soil layer and somewhat lower temperatures in the loose soil may also result from cultivation, as compared with an uncultivated soil. On irrigated maize, deep inter-row cultivation (10 to 20 cm) resulted in higher grain yields than shallow cultivation, in which only the top 5 cm of soil were disturbed. The increased yields due to the deeper cultivation were attributed to improved nitrification of the ammonium fertilizer applied and to improved water infiltration resulting from the break-up of the compacted soil layer. Apparently roots that were pruned by the deeper cultivations were replaced by new roots, provided the last cultivation was done not later than at the time the maize was 75 cm high *(Nelson [1958])*.

An important benefit from maintaining a loose layer on the surface of the soil is obtained on soils that tend to shrink and crack deeply on drying. Such cracks, which penetrate deeply, may cause the loss of considerable amounts of moisture throughout much of the root zone. In Texas, it was found that the evaporation from the side-walls of shallow shrinkage cracks in a clay soil varied from 33 to 91 per cent of that from a comparable area of surface soil *(Adams and Hanks [1964])*. These cracks are filled and covered by the loose layer that is formed during cultivation of the soil surface.

In summary, the basic purpose of post-emergence cultivation is to destroy weeds, and the general rule is to keep the number of cultivations to the minimum required for weed control and to cultivate at the most appropriate time for this purpose. Occasionally, there may be additional objectives for post-emergence cultivation, in particular the destruction of surface crusts. Cultivation should be as shallow as is compatible with this purpose, in order to reduce damage to the crop's roots as much as possible.

3.2 Newer concepts in tillage methods

3.2.1 Stubble-mulch farming

The traditional methods of tillage developed in temperate, moist climates and based on the mould-board plough, when adopted indiscriminately in the drier regions, have frequently had disastrous effects, mainly in increasing erosion. The most well-known example is that of the 'dust-bowl' of the central United States, which was created as a result of ploughing the original prairie for the growing of cereals, using clean-tillage methods, until wind erosion assumed devastating proportions.

Under conditions of limited rainfall, maintaining a clean fallow during the autumn and winter preceding the sowing of maize is essential to build up sufficient moisture reserves in the soil for the maize crop. Frequent cultivations are needed to keep the fallow weed-free and to pulverise the soil surface; and the degraded and unprotected top-soil is then easily eroded by wind and rain.

The traditional concept of 'clean' cultivation, in which the farmer equated good farming practice with the complete burying of crop residues and weeds, had therefore to be abandoned. Instead, a new approach was developed, which aimed at keeping the soil protected at all times, whether by a growing crop, or by crop residues left on the surface during fallow periods. Hence, the name of the new system: stubble-mulch farming. In experiments in Nebraska it was found that rates of rain-induced erosion of a mulched surface were about one fifth of those resulting from 'clean tillage' with mouldboard ploughing *(Zingg and Whitfield [1957])*. Wind erosion was also substantially reduced: residues of various amounts, types and orientation removed from 5 to 99 per cent of the force of wind from the immediate soil surface *(Zingg [1954])*. The crop residues left on the surface of the soil not only offered protection against erosion, but improved water penetration and reduced losses from evaporation (**Figure 23,** *Wiese and Army [1958])*.

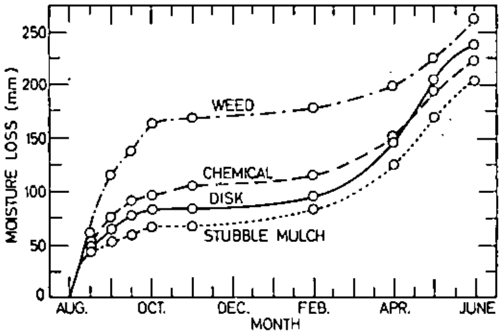

Fig. 23 Effect of different tillage methods on the cumulative moisture losses from the soil at various sampling dates *(Wiese and Army [1958])*. By courtesy of the American Society of Agronomy.

There are, however, a number of drawbacks to the system:

(a) Mulches may reduce soil temperatures; from 3° to 6°C at the 2.5 cm depth and from 2° to 4°C at the 10 cm depth *(McCalla and Duley [1946])*.
In regions in which soil temperatures during the early growing period are suboptimal, the additional reduction in soil temperature due to mulching may reduce growth and subsequently have an unfavourable effect on yields.
Mulch tillage frequently lowers yields of maize in the northern states of the U.S.A. whilst improving yields in the southern states.
Investigating this problem, *Van Wijk et al. [1959]* conclude that, since in the southern regions soil temperatures in the root zone of maize are not far from optimum during the early growing season, a reduction of 1–2°C as a result of mulching does not have a marked effect on growth. By contrast, in the northern states, soil temperatures during the same period are far below optimum, occasionally approaching the temperature at which growth stops. Under these conditions, a further decrease of 1–2°C due to mulching will markedly reduce the growth of maize.
Consistently lower yields from stubble-mulch tillage compared with conventional tillage are reported in Rhodesia. The growth of the maize was found to be noticeably less vigourous in the first half of the season, this was ascribed to the lower soil temperatures under the mulch. Differences in growth became less marked in the latter part of the season *(Rattray [1961])*.

(b) The high C/N ratio of the crop residues may depress nitrification, especially in the early growth period, and thereby adversely affect the growth of the crop and, ultimately, its yield.
Research data appear to indicate that the response to sub-tillage is closely linked with nitrogen availability, as indicated by the greater response to nitrogen of maize growing on sub-tilled plots as compared with conventional tillage. Soil analysis showed depressed nitrates under stubble-mulching *(Luebs and Laag [1964])*.
The lower rate of nitrification under sub-tillage may be due to lower temperatures, less effective aeration and – most important – nitrogen fixation by the crop residues,

which decompose more slowly on the soil surface than when incorporated in the soil. The obvious conclusion to be drawn from these observations is that a favourable effect from sub-tillage can be expected only if nitrogen applications are made in the quantities and at the times required to offset the negative effect of sub-tillage on available nitrate supply.

(c) Stubble-mulch tillage presents practical problems: The residues left on the surface interfere with seed bed preparation, weed control and sowing operations. The traditional tillage and sowing equipment are not suitable under these conditions, and a whole new class of equipment had to be developed before the new system became practical. Sub-surface cutting implements were developed which loosen the soil and cut the roots of weeds, leaving the residues on the soil as undisturbed as possible, and special implements were developed for weed-control, seed-bed preparation and sowing.

(d) The crop residues may also create plant disease problems: Growing maize under conditions of stubble-mulch tillage has been shown in Rhodesia to favour a noticeably earlier attack by leaf blight *(Helminthosporium turcinum)*. This is due to the mulch providing a reservoir of infested material from which the new crop is infected *(Rattray [1961])*.

Stubble-mulch farming has been found to be most effective and beneficial in regions and seasons of low rainfall, and critically needed where wind-erosion presents a considerable hazard. Under conditions of higher rainfall negative results have been reported; apparently, the stubble mulch is then conducive to an excess of soil moisture, with its resultant ill effects.

3.2.2 Ridge cultivation

The frequent traffic of machinery and equipment, especially in irrigated fields, causes the breakdown of the soil structure in the top soil layer, and considerable compaction of the lower layers. As a result, it is difficult to prepare a good seed-bed, germination is adversely affected and irregular stands are obtained.

One of the methods developed to overcome these drawbacks is 'ridge cultivation.' The principle of the method is to establish permanent 'tracks' in the field along which the tractors travel during the entire period of soil preparation and inter-row cultivation, and to create a deep-tillage zone between the tracks, which will serve as the seed-bed and growing medium for the roots.

It has been shown that the first time the tractor crosses a ploughed field, the soil is packed ten times as much as in subsequent passages *(Cook et al. [1958])*. Much compaction of the soil can therefore be avoided by driving in old tracks.

Ridge cultivation was originally developed for preparing seed-beds in fields that were to be irrigated by furrow irrigation; it was soon found that the method has merits quite independent of the irrigation method adopted. The furrows between the ridges provided efficient drainage during the rainy periods; in early spring the ridges dried more rapidly, and the soil warmed up sooner, than in land cultivated 'on the flat', in the conventional manner.

All the unfavourable effects of compaction following tillage operations remained confined to the furrows between the ridges; as a result, only one quarter, approximately, of the field was adversely affected, whilst roots found favourable conditions in the remaining three quarters, in which soil structure was well preserved and ensured favourable conditions of aeration and moisture.

There are four stages at which ridge cultivation for maize can be initiated: immediately after harvesting the previous crop; when preparing the land, before winter; during winter cultivation; and in spring, for seed-bed preparation.

If it is decided to start with ridge cultivation immediately after harvesting the preceding crop, the method used has been called *'precision tillage.'* In this case, the first operation consists of shopping up the residues of the previous crop. Then follows a tool consisting of two 75 cm shanks, followed by three bed-listers, mounted on a cultivator frame. In a single operation, the soil is sub-tilled to a depth of 50–65 cm by the shanks, whilst the listers place the ridges accurately above the deep-tillage zone, thereby covering the residues of the previous crop (Plate 2).

During the winter months, the ridges are reshaped and weeds are killed by a special implement called a disk-bed shaper, the wheels of the tractor always travelling in the furrows. If the field is too wet for cultivation, weeds are controlled by spraying.

3.2.3 Minimum tillage

Research in recent years has repeatedly shown that frequent tillage operations are rarely beneficial, and frequently detrimental, in addition to being costly. It is a paradox that the heavy equipment used for tillage, cultivation and harvesting damages the soil structure and increases soil compaction.

On excessively compacted soils, maize plants remain stunted and are yellowish in colour. Their development is retarded in comparision with plants grown under con-

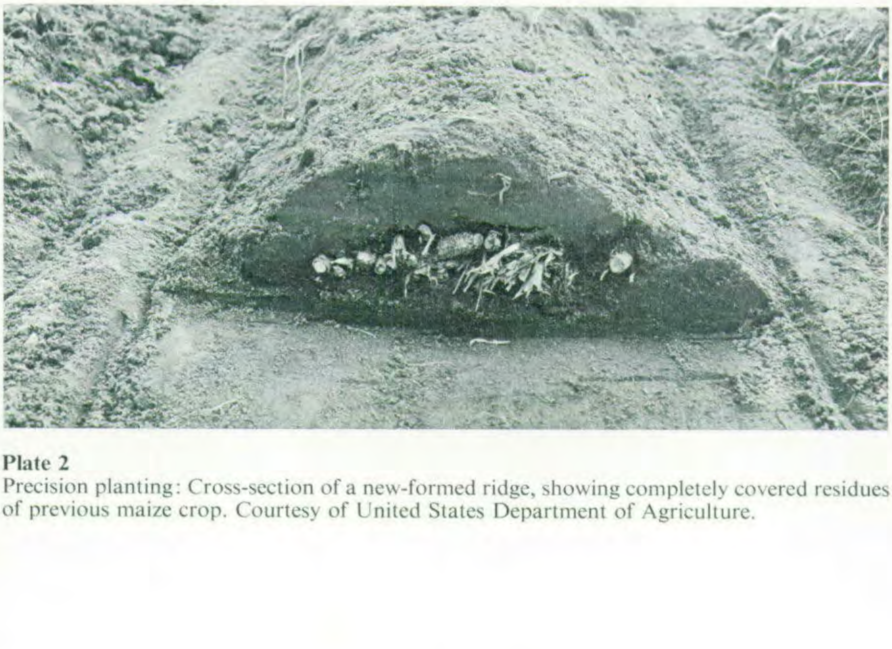

Plate 2
Precision planting: Cross-section of a new-formed ridge, showing completely covered residues of previous maize crop. Courtesy of United States Department of Agriculture.

ditions of favourable soil tilth. The root system remains poorly developed and the roots rapidly become necrotic. New rootlets grow in the direction of the soil surface *(Marty and Maertens [1966])*.

The problems are most acute under conditions of intensive cropping, involving frequent tillage operations and much movement of machinery, especially on soils with a relatively low organic matter content *(Free [1970])*.

A world-wide tendency to reduce tillage operations to a minimum has been in evidence in recent years. This involves two complementary approaches: (a) to omit any tillage operation whose cost exceeds its contribution to increased productivity or efficiency of production; and (b) to combine a number of operations in order to reduce traffic of equipment in the field to the essential minimum. Minimum tillage has been defined as 'the least soil manipulation needed for satisfactory planting, growth, and yield' *(Free [1970])*.

Minimum tillage for seed-bed preparation has been more extensively tested and adopted for maize than for any other crop; it has been made practical and economical by the development of special equipment for combined tillage and sowing operations, and by the enormous progress achieved in chemical weed control, both selective and general, which has rendered superfluous many previously indispensable tillage operations. Minimum tillage frequently gives as good as or even better yields than the conventional methods; the advantage in yield of maize obtained with minimum tillage was found to be even greater in years of low rainfall than in years of heavy rainfall *(Van Doren and Ryder [1962])*. These favourable results are ascribed to the following: *Improved soil physical conditions:* higher rate of infiltration, less soil resistance to penetration, less soil compaction, less erosion (**Figure 24,** *Rao Swamy et al. [1960])*.

In a five-year study on a sloping silt loam soil in Indiana, minimum tillage for maize substantially increased infiltration (by 24 per cent) and reduced soil loss due to erosion (by 34 per cent) as compared with conventional tillage methods. After five years of treatment, soil aggregation, organic matter content, and porosity were slightly higher on minimum tillage plots than on conventional tillage plots *(Mannering et al. [1966])*. *Indirect effects:* Less weeds, more root growth, better vegetative development, less lodging *(Rao Swamy et al. [1960])*.

These advantages are more apparent on coarse – and medium-textured soils than on the more heavy clay soils. In general, it takes two to three years before the favourable effects of minimum tillage are fully apparent. The improvement of soil compaction due to previous conventional tillage methods is a gradual process.

In general, germination is less even with minimum tillage; there is more danger of failures in crop establishment if the soil is worked when too dry than when too wet. In recent years, studies of soil structure in the root zone of maize have shown that the optimum conditions in the row are different from what is optimum in the region between the rows. Hence, the conclusion that fields in which row crops are grown should be managed as two distinct zones – the *seed-bed* zone, which needs to be firm, and the *root-bed* zone, which should remain loose as long as possible – has become accepted farming practice in the maize-growing regions of the United States *(Larson and Blake [1966])* (Plate 3 – see page 62).

3.2.3.1 Plough-planting

In this method, only a single trip over the field is required. The tractor pulls a plough and a planter, simultaneously. The seed row is centred on the furrow slice. The area between the rows remains rough, and weeds do not germinate easily.

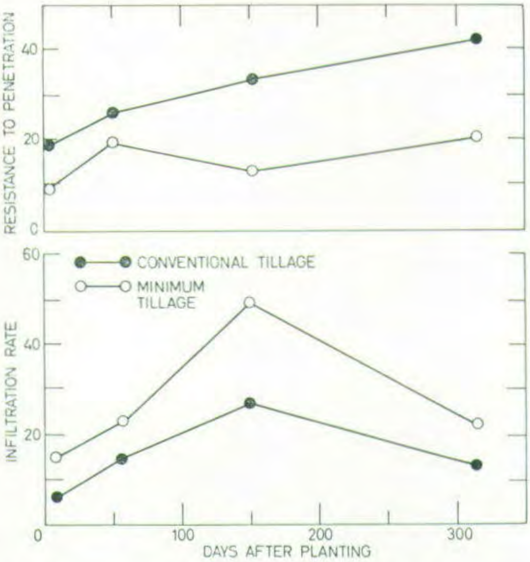

Fig. 24 Comparison of conventional tillage and minimum tillage. Seasonal changes in the maize row *(Rao et al. [1960])*. Top: in resistance to penetration. Bottom: in rate of infiltration. By courtesy of the American Society of Agronomy.

A plough-packer, attached to the frame of the plough, makes possible 'once-over' soil preparation. Costs of seed-bed preparation were found to be considerably reduced, whilst yields were not reduced, as compared with those obtained by conventional methods *(Cook and Peikert [1950])*. The main disadvantage of the method is that planting is slowed down, so that sowing may be delayed beyond the optimum period.

3.2.3.2 Till-planting (Plate 4 – see page 63)

A special 'till-planter' has been developed that prepares a seed-bed and sows two rows in one operation. The seed-bed is prepared by an implement equipped with a narrow and deep-penetrating sweep, a wider and shallower sweep, and sections of a rotary hoe. The strip between the row is not disturbed *(Aldrich [1956])*.

In Nebraska, till-planting gave somewhat higher yields than conventional practices. In this method, the row zone area, which is about 25 cm wide, is cleared of surface residues, which are concentrated in the inter-row zone *(Lane and Wittmuss [1961])*.

3.2.3.3 Wheel-track planting (Plate 5 – see page 63)

In this method, the field is ploughed as usual, but instead of using the conventional methods of seed-bed preparation, the seeds are planted in a seed-bed prepared by the wheels of the tractor. Experience has shown that tractor wheels make a satisfactory seed-bed even on cloddy soil, ensuring rapid and even germination.

The soil between the rows remains rough and loose, and is therefore better able to absorb moisture and to reduce run-off. Weed seeds lie dormant in the loose soil, until rain falls or the field is irrigated.

Wheel-track planting is the most widely adopted practice. If the ploughing is done at the right soil moisture content, excellent seed-beds and root-beds are obtained on most soils *(Rossman and Cook [1966])*.

Wheel-track planting was found to save about 40 per cent of tillage costs *(Peterson et al. [1958])*. By adding two extra rear wheels to the tractor it is possible to use a four-row planter. Experience has shown that the optimal soil moisture for ploughing is also optimal for seed germination *(Hansen et al. [1958])*. Any delay between planting and sowing always reduces soil moisture below the optimum for seed germination. In order to prevent the top soil from drying out and becoming hard before sowing, it is essential to plough and plant the field in one and the same day.

Plate 3
The two soil zones (water management zone and seedling environment zone) as prepared for maize, by minimum tillage. By courtesy of *W. E. Larson.*

Plate 4
Till-planter, sowing maize on land where the only prior preparation done was the chopping of the preceding year's maize stalks. Photo by *L.A. Wilkins*, by courtesy of the U.S. Department of Agriculture.

3.2.3.4 Effects of minimum tillage

In investigations in Ohio, the use of minimum tillage was found to result in higher grain yields, an average of 304 kg/ha more maize being produced than with conventional tillage. The difference tended to increase under conditions conducive to low

Plate 5
Wheel track planting. By courtesy of U.S. Department of Agriculture.

yields, such as low rainfall. Under conditions in which yields of 9500 kg ha were obtained, conventional tillage was slightly better than minimum tillage, the mean difference being 126 kg/ha. Weed control practices, soil surface texture, internal drainage and previous crop, had no effect on the yield difference between the tillage systems *(Van Doren and Ryder [1962])*.

In field studies in New York State, the plough-plant method was found to give higher yields than the conventional tillage method, under conditions of poorly-drained soil, as well as when the season was wetter and cooler than normal. In contrast with the Ohio trials the conventional tillage method gave better results than those obtained with plough-planting *(Fanning and Brady [1963])* under drier than normal conditions and on well-drained soils.

In trials on a chernozem soil in Yugoslavia, comparing minimum tillage for maize with conventional tillage, plots that were given minimum tillage yielded 2.67–9.97 per cent more grain than those given conventional tillage. The increased yields were considered not to be due to effects on soil moisture, which appeared to be more favourable on the conventionally tilled plots *(Drezgic et al. 1966])*.

Table 15. Effect of planting methods and pre-emergence spray on yield of maize in South Dakota *(Shubeck [1963])*

Planting method	Yields of grain (kg/ha)		
	No spray	Band spray**	Overall-spray**
conventional	3695	5340	5422
plough-plant	4927	5486	5289
wheel-track	4305	5467	5168
hard ground lister***	3854	4597	5162

* = Simazine in 32-cm-wide band over the row.
** = Simazine sprayed over entire area.
*** = listing maize in unploughed land.

In all the spray treatments tested, maize yields with plough-plant on wheel track were comparable to those obtained with conventional tillage. The large differences in the costs of tillage are shown in **Figure 25** *(Shubeck [1963])*.

Olson and Schoeberl [1970] also carried out a four-year investigation of the effects of four systems of tillage on the maize crop (conventional, wheel-track planting, till planting and listing) in South Dakota. They found that the three reduced-tillage methods produced yields that were at least as good as those from the conventional system. No significant differences among tillage systems in either total water use or the pattern of water use were detected.

3.2.4 No-tillage or zero-tillage

The ultimate limit of minimum tillage is the elimination of all tillage, except for the opening of a narrow slit for the placement of seed and fertilizer into the soil.

With modern herbicides, such as paraquat, it is possible to destroy the sod of pastures chemically, and to grow a crop of maize without ploughing or secondary cultivation, provided re-vegetation and weed growth are successfully controlled. The favourable soil structure of the pasture will be retained for an extended period; the dead sod improves infiltration, reduces moisture loss and minimises soil erosion *(Treanor and Andrews [1965])*.

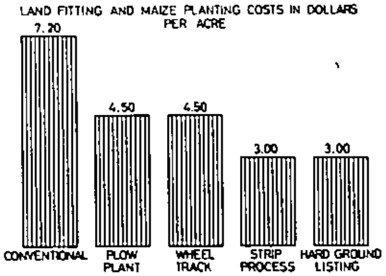

Fig. 25 Effect of minimum tillage systems on cost per acre for growing maize *(Shubeck [1963])*. By courtesy of the South Dakota Agricultural Experiment Station.

The herbicides used to kill the existing sod also control many of the annual weeds during the growing season. Soil disturbance is limited to that required for the proper placement of the seed and is usually provided by disks or similar equipment on the seed-drill.

Investigations on the possibilities of no-tillage for maize started in 1960, and the practice has developed rapidly since then *(Moody et al. 1961])*.

The concept of no-tillage has been emphasised mostly for maize production, mainly because of the economic importance of the crop, but also because it appears to be particularly well-adapted to the new practices: the wide rows used, the large seed with high germination capacity, and the high specific resistance to certain very effective weed-killers of maize, gives it advantages over other crops when the seed-bed is less than ideally prepared.

Field experiments were carried out in Virginia, in which maize was sown without tillage on sod that had been killed with chemicals approximately five weeks before sowing, and compared with conventional tillage. Soon after emergence, the maize in the no-tillage plots had a darker-green colour and was growing faster. The growth rate of the no-tillage plants was higher at all sampling dates **(Figure 26)**. A significant increase in yield of stover at harvest date was also recorded. There was no difference between treatments in the N, P and K content of leaves at silking time *(Moody et al. [1961])*.

No-tillage was also tried on a silt loam in New York State over a three-year period. The maize was sown following a heavy growth of lucerne with some grass. A spray of Atrazine plus Amino-Triazole was applied four to six weeks before sowing to kill the sod and to control weeds. The maize was fertilized at the rate of 110 kg N, 48 kg P and 91 kg K per ha, of which 80 per cent was broadcast before sowing and 20 per cent was applied in the band. The yields obtained with no-tillage averaged only 10 per cent less than those obtained under conventional tillage *(Free et al. [1963])*.

A six-year study on a silt loam soil in Virginia *(Jones et al. [1968])* also showed that

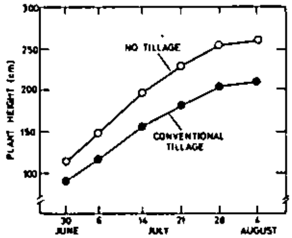

Fig. 26 Effects of tillage and no-tillage on the growth of maize *(Moody et al. [1961])*. By courtesy of the Soil Science Society of America.

no-tillage provided a rooting medium which was conducive to increased growth. Distinct growth differences were evident soon after germination and continued until tasselling. Final plant heights were greater in the no-tillage plots in each of the six years. The main factor which appeared to be responsible for the taller growth of the plants on no-tilled land was the better conservation of moisture under the mulch of such plots, which reduced surface run-off, improved surface infiltration and reduced evaporation.

Differences in available soil moisture (**Figure 27**) were in favour of no-tillage in each of the six years. In the top 15.2 cm, the differences were small, ranging from 8.1 to 1.5 mm in the various years. In the effective root zone (45.7 cm) the range was from 31.2 mm to 1.8 mm. There is little doubt that this improved growth.

In still other trials in Virginia, particularly favourable results were obtained with no tillage (Table 16). No-tillage, in comparison with conventional tillage, markedly decreased surface run-off and improved yields of dry matter and of grain.

The advantages of no-tillage over conventional tillage in terms of grain yield are imputed mainly to improvements in moisture supply, in particular when these occur during the period of maximum stress *(Jones et al. [1968])*. This is evidenced by significant yield increases of grain and stover, in years in which moisture supply was

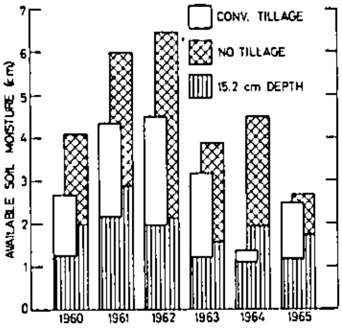

Fig. 27 Comparison of average available soil moisture (June, July and August) to the 45.7 cm depth for conventional and no-tillage maize 1960–1965 *(Jones et al. [1968])*. By courtesy of the American Society of Agronomy.

Table 16. Effect of tillage systems on run-off and on yields of maize *(Shanholtz and Lillard [1969])*

Tillage system	Yields (kg/ha)		
	Surface run-off	Total DM	Grain
Conventional	1.51–2.08	8273	5016
No-tillage (chemically killed sod)	0.10–0.50	11846	6458

critical. In the drought year of 1963, for example, no-tillage produced a yield increase of 1374 kg (or an increase of 38.6 per cent) as compared with conventional tillage. Even when rainfall was intermediate, as in 1964, the yields of no-tillage were 1045 kg/ha higher than those of conventional tillage, an increase of 17 per cent.

The average yields of grain and stover of maize grown in Blackburg, Va., during 1960–65 are shown in Table 17.

Table 17. Average yields from six-year trials comparing no-tillage and conventional tillage for maize *(Jones et al. [1968])*

Tillage system	Yields (kg/ha)	
	Stover	Grain
No-tillage	6467	7062
Conventional	5567	6327

These results were confirmed in a three-year study with maize on a light coloured silt-loam soil in Ohio *(Triplett et al. [1968])*. These soils form a surface crust after rainfall and therefore respond to cultivation even when there are no weeds present. Here, too, the beneficial effects of the mulch seemed to be associated with increased soil moisture. During intense storms, infiltration was highest for the no-tillage plots covered with crop residues, and lowest for the no-tillage plots from which the residues had been removed. During low-intensity rainfall, there were differences in infiltration rates between the different treatments. In all three years it was found that the larger the amount of crop residues present on the surface of the no-tilled plots, the higher were the yields of grain. In no case did conventional tillage give higher yields than those obtained from no-tillage, when the residues were not removed.

3.2.4.1 Long-term effects of no-tillage

Very few investigations have been carried out so far on the long-term effects of no-tillage on the soil and on maize yields.

It might be expected that leaving crop residues on the soil surface, year after year, might in time build up and create mechanical problems for seed placement or create an undesirable environment for plant growth. Untilled soil between the crop rows might become compact and possibly restrict root growth or rainfall infiltration.

In investigations by *Triplett et al. [1968]*, it was found that decomposition of stover left on the soil surface was quite rapid during the growing season. Althoug stover from a heavy maize crop covered 70 per cent of the soil at time of sowing, this amount had decreased to 40–50 per cent by the time the crop was harvested. After one or two seasons, the residues had lost their identity. The investigators concluded that a buildup of maize residues as a result of no-tillage is not to be expected in their region.

In field trials in Virginia *(Shear and Moschler [1969])*, maize was grown on a loam soil for a period of six years, and systems of no-tillage, tillage in alternate years and continuous conventional tillage, were compared. A cover crop was sown between every two consecutive maize crops in all the treatments. Fertilizers and seed of the cover crop were broadcast on the surface and the soil was lightly disked. For the no-tillage treatment, the cover crop was killed a month before sod-sowing the maize, by spraying with atrazine plus paraquat. In the conventional tillage, the cover crop was ploughed under, the soil was disked and harrowed prior to sowing and was not disturbed thereafter.

The crop was harvested for silage*, so that heavy crop residues did not become a problem.

The yields of maize grain and of stover were higher on the no-tilled plots in three of the six years, and equal in the other three years. Alternate tillage was not superior in any of the years to no-tillage. The fact that the yields of the no-tilled plots were higher than those of conventional tillage in the fifth and sixth years of continuous no-tillage indicates that the absence of tillage, even for fairly extended periods, has no detrimental effect on maize yields.

No significant differences in the bulk density of the soil at depths of 10 to 12 cm and 40 to 42 cm were found between tilled and untilled soils. Soil compaction was therefore no greater after six years of non-tillage than of conventional tillage.

In a similar investigation by *Triplett et al. [1968]*, using somewhat different techniques (no cover crops between consecutive maize crops, harvesting for grain, and maize residues left in the field), even more favourable results were obtained from no-tillage. This system gave higher yields than conventional tillage in each of the six years of the study.

The immediate and long-term effects of no-tillage were also investigated in an eight-year study on a silt loam in New York State *(Free [1970])*. The maize grown in these field experiments received every year 110 kg nitrogen, 48 kg phosphorus and 91 kg potassium per ha, 80 per cent of which was drilled on the surface of all plots before the final seed-bed preparation, and 20 per cent of which was applied in the soil with the maize planter. The crop residues were ploughed under for conventional tillage and were left as such on the surface of no-tillage plots.

Grain yields for first-year maize over an eight-year period under no-tillage averaged 6730 kg/ha, only slightly less than the 7110 kg/ha obtained under conventional tillage. Yields for maize after maize under no-tillage averaged 7048 kg/ha over a three-year period: in three out of six comparisons conventional tillage outyielded no-tillage by amounts ranging from 825 to 1200 kg/ha.

The results of chemical soil rests carried out on maize plots under conventional and zero tillage, are shown in Table 18.

All the test values for the upper half of the plough layer were significantly greater for

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* Ears and stover were weighed separately.

Table 18. Results of chemical soil tests of maize plots under conventional and zero tillage *(Free [1970])*

Depth (cm)	Tillage system	Organic matter per cent	Total N per cent	Available P kg/ha	Exchange-able K kg/ha
0 - 7.5	conventional	3.6	0.20	17	116
	no-tillage	4.3*	0.24*	41*	179*
7.5–15	conventional	3.8	0.21	5	72
	no-tillage	3.6	0.21	2	61

* Significantly different from conventional tillage at $P = 0.05$.

no-tillage than for conventional methods. The differences were less consistent at the 7.5–15 cm depth. These interactions reflect the cumulative effects of surface placement of fertilizers and the incorporation of crop and fertilizer residues into the ploughed layer by conventional tillage. For the entire sampling depth, the amounts of available phosphorus were 2.2 to 2.4 times greater under no-tillage than under conventional tillage and the amounts of exchangeable potassium were 1.2 to 1.5 times greater.

Total soil losses, under simulated rain totalling 94 mm, in three simulated storms, were 1.25 tons/ha for no-tillage and 9.75 tons/ha for conventional tillage, for first year maize, a ratio of about 1:8. Soil losses were higher for continuous maize, but the ratio was still 1:5.

Soil under conventional tillage was consistently looser and had a greater volume of larger pores than soil under no-tillage. Under both systems, aggregate stability decreased with increasing years of maize growing, but at a slower rate with no-tillage **(Figure 28)** *(Free [1970])*.

3.2.4.2 Evaluation

The important advantages of no-tillage as compared with conventional tillage were found to be a considerable saving of expenditure and a marked reduction in soil loss. The differences in grain yields were not consistent, but the differences in favour of the conventional tillage were rarely of great importance.

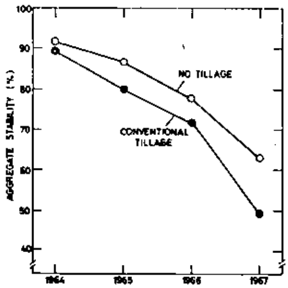

Fig. 28 Cumulative effects of tillage and no-tillage on aggregate stability *(Free [1970].)* By courtesy of Cornell University.

Certain problems related to the use of minimum tillage and non-tillage have not yet been resolved.

Efficient and consistent performance by herbicides is essential in no-tillage systems, as cultivation may not be feasible if a marked proportion of the weeds remains undestroyed by the herbicides. A number of conbinations of herbicides have been found satisfactory for maize. Most of these contain atrazine or simazine for the control of annual and perennial grasses, and 2,4 D or a similar herbicide for the destruction of broad-leaved weeds *(Triplett and Van Doren [1963])*.

Herbicide costs are still frequently in excess of tillage cost. Too little is known of the long-term effects of herbicide residues in the soil. The possibility that herbicide-resistant strains of weeds may develop has also to be considered.

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4. From sowing to harvest

4.1 Sowing

4.1.1 Time of sowing

4.1.1.1 Europe

Early sowing is critical in those regions in which the growing period is limited. Maize must be sown at the earliest possible date that enables exploitation of the full potential growing season. In Germany, it is estimated that every day's delay in sowing beyond the optimal sowing date entails a one per cent loss of yield. The most favourable times for sowing, depending on location, are between 20 April and early May. Sowing can be earlier on light soils than on heavy soils *(Zscheischler and Gross, [1966]).* The same dates are recommended in France *(Barloy, [1970]).* With earlier sowings emergence is much delayed, and with later sowings the crop cannot make full use of the growing season.

Very similar results were obtained in trials in Moldavia (Rumania): the favourable period for sowing maize was found to be during the last ten days of April, sowing before or after this period resulted in losses of up to 261 and 316 kg grain/ha, respectively *(Timirgazin [1968]).*

In a number of trials carried out during 11 years with 14 maize varieties, in southern and central England, it was shown that sowing date markedly affected speed of emergence. More than 40 days elapsed from March sowings until the mean date of emergence; about 25 days from mid-April sowings; 18 days from late April sowings, and 8-9 days from late-May or June sowings. Plants from sowings made in March or early April were not significantly earlier or more productive than plants from sowing made in late April. For grain production, however, any further delay in sowing usually led to lower yields, even with the earliest-maturing hybrids tested. In contrast, total plant dry matter yield was generally higher from mid-May sowings. Provided growth was not arrested by autum frosts before flowering was completed, plants from later sowings were taller and had more leaves than plants from earlier sowings. The conclusion was that late April is an appropriate time to sow maize in central and southern England *(Bunting [1968]).*

4.1.1.2 America

In field trials in central Missouri during 1960–4, maize of four maturity groups was sown on 20 April, 10 May, 1 June and 20 June, respectively. Yields were highest and root- and stalk-lodging were lowest for plants sown on the first two dates. Ear height increased and time to tasselling and silking decreased with delayed sowing. The late-

maturing hybrid had more root- and stalk-lodging than the early hybrid *(Zuber [1968])*
Three-year average yields for eight hybrids in central Missouri showed that May 10 sowing yielded 18 per cent less, and the June 20 sowing 34 per cent less than the April 20 sowing *(Grogan et al. [1959]).*

In Michigan, the results of 14 years of dates of sowing experiments showed that the optimum time for sowing was during the first ten days of May. A delay beyond May 9 caused a reduction in yields: of 15 per cent for May 22–31 sowing, and of 28 per cent for June 1–11 sowings. Sowing in the second half of April gave slightly inferior results to early May sowings, mainly because stands were slightly thinner.

Whilst the yields of all hybrids decreased with delayed sowing, those of early-maturing hybrids were less adversely affected than the yields of those with later maturity *(Rossman and Cook [1966]).*

Over a 20 year period in Ohio, the best yields were obtained by sowing between May 7 and 12. Delayed sowings of one, two and three weeks gave yield reductions of 127, 440 and 890 kg/ha, respectively *(Hume et al. [1956]).*

In Florida, April sowings yielded 27 per cent less than March sowings *(Norden [1961]).*

In brief: In the central Corn Belt, May 10 is considered the best date for sowing compatible with high yields. In the southern part of the Corn Belt, earlier sowing is favoured. In the 36–40°N latitude in Missouri, April 20 sowing is optimal, while in the southern part of the state April 1 sowing gives the highest yields. Still farther south, at 26–30° latitude N in Florida, high yields are obtained from March sowings *(Barber and Olson [1968]).*

4.1.1.3 Africa

In East Africa, experience and the results of field experiments have shown that planting maize early in the rainy period or even before the rains start, usually results in higher yields than planting later in the season *(Semb and Garberg [1969]).*

For example, in Kenya, maize sown on March 4 at Kakamega yielded 9632 kg/ha, while maize sown on April yielded only 1972 kg/ha. At Kitale, a two months' delay in sowing after the rains had started reduced yields from 4390 to 2598 kg/ha. In western Kenya the average decline due to a four weeks' delay in sowing was an average 67 kg/ha per day. Where the rainfall season is short, as in central Kenya, a delay in sowing causes even more drastic declines in yield; a two-weeks delay causing an average yield loss of 134.5 kg/ha per day *(Allan [1968]).*

The higher yields of early sown maize have been ascribed to an improved supply of nitrogen and/or more favourable moisture conditions during critical growth periods. At the onset of the rains, a flush of mineral nitrogen appears in the soil, so that with early planting maize is able to benefit from a better supply of nitrogen.

By early planting, maize plants develop a better root system and are thus able to utilize the moisture supply in the soil more effectively. Early-planted maize has given higher yields than late planted maize even when adequate amounts of nitrogen were applied in both cases *(ibid.)*. The higher yields in this case are ascribed to a better supply of moisture. Late planted maize has been shown to receive less rainfall during the critical period from tasseling stage to maturity than maize planted early in the season, so that the low yields of the late-planted maize are due primarily to water stress during the period of grain formation *(Turner [1966]).*

This view is not shared by *Anderson [1970]*. In view of rainfall variability in Tanzania, he recommends that sowing should not take place until at least 200 mm have fallen, or until the soil is moist to a depth of 60 cm, since moisture availability during grain formation is more important than any slight leaching of nitrates from the profile.

In western Nigeria, maize is sown twice in the year, once following the onset of the rains – in March or April –, and a second time in September or October *(Fayemi [1966]*.

In the Sudan, rain-grown maize is sown from the beginning of July through August. Conditions are very wet from the end of July until mid-September, causing a steady decline in the soil nitrate – nitrogen content. From the end of September onwards, the weather becomes increasingly dry and the plants grow under increasing moisture stress. These conditions explain why early-sown crops have a higher nitrogen content up to 25 days after sowing and a much higher rate of dry matter production throughout the growing season than late-sown crops. The latter experience adverse conditions throughout their growing period: water-logging when the plants are young followed by increasingly severe moisture-stress as they approach maturity; by contrast, the early-sown maize germinates under relatively favourable moisture conditions and matures its grain before moisture stress becomes excessive. As a result, the effect of fertilizers is more pronounced on early sown maize than on late sown maize *(Rai [1965])*.

4.1.1.4 Asia

In the Delhi region (India) maize is generally sown with the break of the monsoon at the beginning of July and is followed by a second crop of peas, wheat, gram, linseed, berseem or oats in the 'rabi'* season on irrigated fields. The time of maize harvest is therefore critical from the point of view of seed-bed preparation and sowing of the following crop. It has been established that pre-monsoon sowing of hybrid maize with irrigation gives better results than planting after the break of the monsoon. A more uniform plant stand is obtained, the plants are well developed before the onset of the rains, and are less adversely affected by excess moisture in the soil; the harvest is earlier and yields are higher *(Gautam et al. [1964])*.

Similar results were obtained in the Chindwara region in the Madhya Pradesh Province of India, where maize is also normally sown after the onset of the monsoon rains. However, where irrigation is available, earlier sowing is possible. Maize sown 20 and 10 days before the usual time, gave average yields of 7890 and 7550 kg grain/ha, respectively, compared with 6140 kg/ha when sown at the normal time.

4.1.1.5 Mediterranean-type climates

In regions with a Mediterranean-type climate the most favourable results are obtained with early sowing, as soon as soil temperatures at the 7–10 cm depth reach 15–16°C; this is usually in early April.

The early sowing enables maize to develop during a period of optimal temperatures; tasseling and pollination occur before the start of the extreme heat of summer. Under irrigation the date of sowing is less critical than for a rain-fed crop. Sowing can be

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* One of the two main growing seasons in India, 'rabi' refers to crops sown in October and November and harvested in March and April.

continued until mid June, provided hybrids with a growth period of 115 to 123 days are used.

4.1.2 Sowing equipment

Modern maize planters have been developed that place the seed at a uniform depth and fairly equidistant within the rows. Ensuring a full and even stand is more important for maize than for any other cereal, as it is far less capable of adjusting to a poor stand.

The best results are obtained by sowing in moist soils, 7–10 days after preirrigation. If for technical reasons it is necessary to sow in dry soil, and the field is to be irrigated only after sowing, the field should be given a pre-emergence spray with simazine, to prevent weed infestation.

In summary, the optimum time for sowing is that which will ensure as long a growing season as possible, and enable avoidance of periods of stress, in particular during pollination and early seed formation. In the temperate regions, this means sowing as soon as soil temperatures are sufficiently high to enable rapid and uniform germination; in the subtropical and tropical regions, the sowing date is determined mainly by sufficient available soil moisture.

4.2 Plant population density

Reducing plant density under dry conditions in order to achieve a balance between the amount of plant cover and the limited soil moisture has always been an accepted cultural technique. It is only in recent years that agronomists have become fully aware that the higher potential yields made possible by the favourable water regimes provided by irrigation, the high soil fertility levels resulting from heavy applications of fertilizers, and the genetic potentials of the new hybrids, could be achieved only after appropriate adjustments of the plant population. Research on adjusting population levels to all other factors of production has therefore become very extensive. In no crop has this subject been studied as intensively as in maize, and recommended plant densities with hybrids grown under irrigation at present-day levels of fertilization are at least 50 to 100 per cent higher than when open-pollinated varieties were sown *(Rossman and Cook [1966])*.

The results of research on the subject can be summed up briefly as follows: During the vegetative phase of development, the amount of photosynthetically active radiation intercepted by the crop canopy directly affects growth rate and dry matter accumulation by the crop. After tasseling, the shading caused by the tassels, the pollen covering the leaves and leaf senescence have a depressing effect on photosynthesis.

The yield of grain is positively correlated with crop growth rate up to an optimum population density. Thereafter, it becomes negatively correlated, probably because the excessive number of growing points makes too great a demand on the total production of metabolites by the plant community –, a minimum level of carbohydrate accumulation being a prerequisite for grain formation.

All available evidence indicates that the more favourable the conditions under which a crop is grown, the greater the plant density required to exploit fully the potential and to achieve maximum yield: and conversely, higher than average plant densities require more favourable growing conditions. This is particularly true for nutrient supply.

At higher levels of nutrient supply more plants per unit area are required to exploit fully the higher soil fertility potential and thereby to produce maximum yields. Conversely, as plant density increases up to a certain limit the crop will continue to respond to higher levels of added nutrients. This aspect will be discussed in detail in Chapter 15.

4.2.1 Rate of planting

Recommended plant populations for maize in non-irrigated semi-arid regions of the United States range from 1.5 to 3 plants/m² ha *(Colville et al. [1964])*. In South Dakota, dryland maize gave maximum grain yields at 4 plants/m² ha when moisture conditions were very favourable; under moderate drought, stands of 2 plants/m² were optimal; under very dry conditions, populations above 1 plant/m² produced little or no grain *(Termunde et al. [1963])*.

In the countries of Southern Europe, where drought conditions frequently prevail, recommended population densities are 2–3 plants/m² for rain-grown maize *(Lanza [1962])*.

In the southern, semi-arid steppe zone of the Ukraine, optimum planting density is 2.2–2.5 plants/m² with an inter-row spacing of 140 cm. However, very little maize is sown in this zone without irrigation. The principal maize belt is in the northern steppe zone and the southern and central areas of the forest steppe. Optimum planting density here is 3.5–4.0 plants/m² with inter-row spacings of 90 to 105 cm *(Momotenko [1968])*.

In Germany, the recommended rates are from 4 to 10 plants/m² depending on earliness, as shown in Table 20 *(Zscheischler and Gross [1966])*.

Table 20. Optimum number of plants at harvest

Maturity group	*FAO index*	*Plants/m²*
Early	150–190	7.5–10.0
Medium early	200–240	6.0– 8.0
Medium late	250–290	5.0– 6.5
Late	300	4.0– 5.5

In England it was found that for fodder or silage production, a plant density of 10–15 plants/m² gave the best results when medium-late hybrids were used. Higher plant populations might give slightly higher yields, but the differences were not throught to be of practical importance and were likely to be offset by increased lodging and the consequent increase in harvesting difficulties *(Bunting and Willey [1959])*.

In general, plant densities are higher – up to double – in Europe than in the United States. It is suggested that the higher organic matter levels in the soil in Europe are an important factor accounting for the efficacity of higher plant populations *(Dungan et al. [1958])*.

Under irrigation, the optimum plant population depends on the hybrid sown, the level of fertility and the moisture regime. Population and plant spacing appear to become more critical when yields reach or exceed 10000 kg/ha. In Nebraska, the highest yield (11 570 kg/ha) was obtained under irrigation with 5 plants/m^2. Population increases over 6 plants/m^2 generally resulted in yield decreases. Drilled maize was found to give consistently higher yields than hill-dropped or checked maize *(Colville and McGill [1962])*.

In Israel, under irrigation, the highest yields have been obtained with populations of 5-6 plants/m^2 except for dwarf single crosses, which yielded best with 7 plants/m^2 *(Shlomi [1968])* (Plate 6 – see page 79). In Algeria, 4–5 plants/ha have generally given the best yields *(Gueit and Laby [1956])*.

4.2.2 Seed rates

There is usually a 10 to 25 per cent loss in stand between sowing and harvest due to germination losses, soil insects, birds, rodents, etc. To obtain a desired plant density, it is therefore necessary to increase the number of seeds per m^2, taking into consideration these losses.

4.3 Planting patterns

4.3.1 Row width

Traditionally, in mechanised agriculture, maize has been spaced in rows approximately 100 cm apart, originally because this was considered the minimum width allowing passage of a horse or mule cultivating between the maize rows, and subsequently because of the design of planting, cultivating and harvesting machinery adapted to this width.

The minimum width of row that permits efficient operation of the tractors and farm machinery currently in use for maize production is about 75–80 cm. This is also the minimum width required for furrow irrigation. Narrower rows cannot be harvested with the pickers, picker shellers and combine corn heads used at present. Hybrids would also have to be 'tailored' for narrow row production.

The possibility of controlling weeds with herbicides, and the development of attachments to the grain combine for harvesting maize, have made it possible to chose the row spacing which gives the highest yields under specific circumstances.

It has been estimated that 60-cm rows might intercept 15 to 20 per cent more energy for photosynthesis than 100-cm rows *(Denmead et al. [1962])*.

4.3.2 Row width and moisture utilization

Tanner and Lemon [1962] have shown that when soil moisture is available, and a substantial crop cover shades the ground, most of the net radiation is used for evapotranspiration. Therefore, differences in net radiation resulting from different plant populations and row spacings should also result in differences in water use and water use efficiency.

Denmead and Shaw [1959] found that maize in Iowa approached the condition of a crop 'fully covering the surface' for only two – three weeks, from shortly before silking to about 16 days after silking.

Tanner et al. [1960] found that even fully grown maize in 100-cm-rows, with a plant density of 3.25 or 5.0 plants/m^2, does not intercept radiation fully, so that the potential evapotranspiration associated with a fully covered surface is not realized.

In trials carried out by *Yao and Shaw [1964]* it was found that when inter-row spacings

Plate 6

A perfect stand of a maize top-cross grown for silage. (The adjacent rows were cut, in order to enable a close-up view of the plant distribution in the standing row.) The planting density was 5 pl/m^2; the fertilizers applied 1200 kg/ha sulphate of ammonia (in two applications) 1000 kg/ha superphosphate and 600 kg/ha muriate of potash. 400 mm of irrigation water were applied. The yield obtained was 18 000 kg/ha dry matter *(*Photo *A. Shlomi)*.

were maintained constant, doubling the plant density increased water use, but the increase in water use was much smaller than the stand increase. The narrowest row spacing (52 cm) used significantly less water than wider spacings, with the differences in water use between treatments becoming more apparent as the season progressed. The highest efficiency of water use was achieved at the narrowest spacings with the double plant density.

4.3.3 Irregular spacings in the row

4.3.3.1 Check-row planting

In order to improve the efficiency of cultivation for the control of weeds, crops may be sown in such a way that rows of equal width run in two directions. This is achieved by check-row planting, which enables cross-cultivation. This method, which considerably slows down sowing operations, has lost much of its utility with the advent of improved weed control practices, both mechanical and chemical.

There are relatively few experiments comparing uniformly distributed plants in the row with hill or pocket groupings. Uniform spacing generally gives a greater yield than hill groupings under favourable soil moisture conditions *(Colville and McGill [1962])*. However, when moisture is limiting, the advantage may be small or nil *(Dungan et al. [1958])*. *Donald [1963]* suggests that the advantage of the uniform spacing under favourable conditions is due to reduced competition for light; when soil moisture is lacking, light is no longer the limiting factor and the advantage of uniform spacing is lost.

4.3.4 Broadcasting

Ethiopia is the only African country in which farmers sow their maize broadcast *(Miracle [1966])*. Experiments at Jima in Ethiopia have shown that yields are reduced by more than 50 per cent when the seed is broadcast rather than row-planted (2627 kg/ha vs. 5681 kg ha) *(Burley [1957])*.

4.3.5 Row direction

Very few investigations on the effect of row direction on yields have been made. The few results have been surprisingly similar with different crops grown under widely different conditions.

In India, it has been found that maize planted in a north-south direction yielded significantly more grain and forage than that planted in an east-west direction *(Dungan et al. [1955])*.

Whilst a full explanation for these results is not available, it is possible that sunlight and the amount of reflected light are influenced by row direction: N-S rows enjoying better lighting than the northern exposure of the E-W rows.

4.4 Chemical weed control

Pre-emergence sprays with atrazine and simazine are highly effective for controlling weeds that germinate in the top 2 cm of soil. Maize is highly tolerant of these two triazine herbicides. Simazine is only slightly soluble in water and is absorbed exclusively through the roots of the plant. Atrazine is far more soluble, and can be absorbed both through the root system and through the foliage.

Atrazine has the advantage over simazine that it acts more rapidly and requires less water to reach the roots of the weeds. Sufficient rainfall must occur or an irrigation of about 20 mm must be given to enable the herbicides to penetrate into the soil, as they have to be absorbed through the roots of the weed seedlings.

Because atrazine can be absorbed through the foliage, early post emergence applications are being increasingly used and give good control. The herbicide is applied when the maize plants are 10 cm high, and the weeds still in the rosette stage *(Zscheischler and Gross [1966])*.

The drawback in the use of the triazines is that herbicidal residues may damage the crop following maize. Wheat, barley, flax, soybeans and sugar beets are among the sensitive crops that may be harmed.

Mixtures of atrazine with prometryne, ametryne, or linuron have been tested; they appear to be as effective as atrazine alone for weed control, and the danger of carryover to the next crop is considerably reduced.

The most widely used herbicide for post-emergence spraying is 2,4-D, but it is effective only against broad-leaved weeds, and not all of them. It is sprayed when the maize is 15 to 20 cm tall; earlier or later applications may harm the crop. After the plants have four or five leaves, only directed sprays that do not wet the foliage should be used.

When later applications are required, a combination of 2,4-D, nitrogen fertilizers in solution and a wetting agent is used, in a spray directed at the base of the maize plants and between the rows, at a time when the maize stalk is 50 to 60 cm tall.

As an emergency measure, directed sprays of mixtures of 2,4-D and dalapon are occasionally used in the growing crop, to control heavy mixed-weed infestations of grasses and broad-leaved weeds. The maize plants must be at least 20 to 50 cm tall if injury by dalapon is to be avoided. More recently, directed paraquat sprays are used. Every precaution must be taken to avoid spraying the foliage of the maize plants. Mixtures of paraquat with 2,4-D have also given good results *(Barloy [1970])*.

4.5 Irrigation

4.5.1 Water requirements

Maize has a high water requirement, but is extremely efficient in water use for the production of dry matter.

Alessi and Power [1965] have shown that both forage and grain yields are highly correlated with total available moisture (irrigation + rainfall) **(Figure 29).**

Comparative average yields of irrigated and non-irrigated maize in a semi-arid region are shown in **Figure 30** *(Colville [1967])*.

The total amount of water required for irrigation depends on environmental conditions and on the efficiency of irrigation. For near-maximum yields the total water requirement is approximately 500 to 600 mm, depending on temperature, insolation, relative humidity, etc., and assuming that irrigation efficiency is within the limits of 65 to 75 per cent.

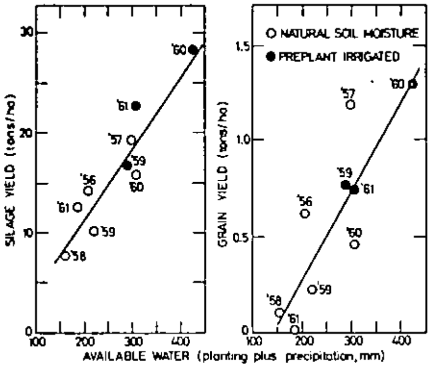

Fig. 29 Relation of maize yields to total available water in the growing season *(Alessi and Power [1965])*. Values represent means of a number of fertility rates and populations. By courtesy of the American Society of Agronomy.

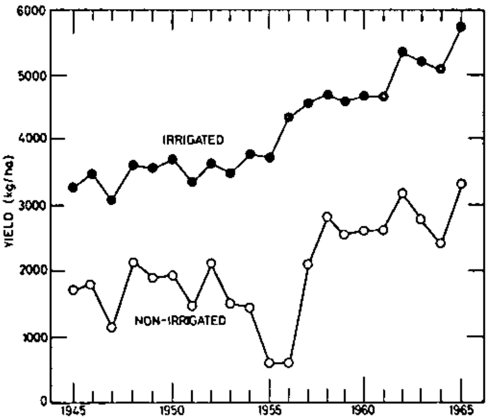

Fig. 30 Comparative average yields of irrigated and non-irrigated maize in a semi-arid region (Nebraska) during the period 1945 to 1965 *(Colville [1967])*. By courtesy of the American Society of Agronomy.

From the point of view of water supply, there are four periods in the growth of maize: rapid growth of the root system; vegetative growth; flowering and seed-set; and maturation of the grain.

Until the plants are 30 to 40 cm tall, temperatures are mild and transpiration by the small plants is limited; water requirements are therefore low, approximately 2–3 mm daily. As the plants develop, evapotranspiration increases gradually. During the vegetative stage the retarding effect on growth rate of a temporary moisture stress was found to be partially compensated for by a rapid growth rate after soil moisture stress was removed. This is attributed to an accumulation of simple sugars during the stress period *(Kemper et al. [1961])*. Evapotranspiration reaches a peak of 7 to 10 mm daily during tasseling, earing and pollination. This is a period when the maximum water needs of the plant coincide with high temperatures and low air humidity. Moisture stress during this period may cause the tassel and the upper leaves to dry up; the tassels may fail to shed viable pollen and fertilization will then at best be only partial.

The silking period, which normally is not much longer than ten days, can extend over a period of four weeks and more. When the plants are close to wilting, or actually wilted, the extension of the silks out of the husks is slowed down and complete silking is delayed.

Normally, pollen starts to shed at about the time the first silks appear, and continues until most of the silks have been exerted. However, the high temperatures which usually accompany drought conditions hasten and shorten the period of pollen shedding, so that late silks are not pollinated. The combination of lengthened period of silking – due to drought, and shortened period of pollination – due to high temperatures, may cause a high percentage of barren stalks and barren parts of the ear *(Pesek et al. [1955])*.

During the five weeks that follow tasseling, water use is about 50 per cent of the total seasonal water requirements. The overriding importance of an adequate supply of water during this period has been confirmed by many research workers. It has been shown that when soil moisture is depleted to the wilting point, even for one or two days during the tasseling or pollination period, grain yields are reduced by over 20 per cent; if the moisture deficiency is allowed to persist for six to eight days, yields are reduced by 50 per cent *(Robins and Domingo [1953])*.

The time at which moisture stress occurs during this generally critical period also affects yields, as illustrated by the data in Table 21.

Table 21. Effects of stress periods* on yield of maize *(Denmead and Shaw [1960])*

State of development	*Yield reduction (%)*
Before tasseling	25
During flowering	50
After pollination	21

* Approximately seven days of moderate stress.

The effect of stress periods at different stages of growth of maize is shown graphically in **Figure 31** *(Barloy [1970]* based on *Robelin [1967])*.

4.5.2 Irrigation practice

Irrigation research in Israel has shown that for near-maximum yields of maize, irrigation should be timed to replenish soil moisture before moisture depletion in the root zone exceeds 40 to 50 per cent of the available water *(Bielorai et al. [1956])*. In a six-year study of water requirements of maize grown on a clay soil in Iowa, the highest yields were obtained when soil moisture was maintained at above 60 per cent of the available moisture content *(Beer et al. [1967])*.

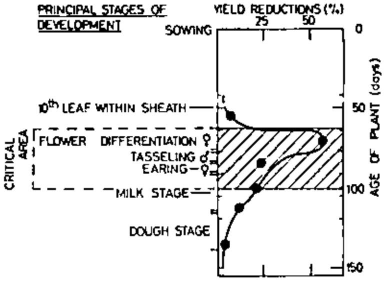

Fig. 31 Effect of moisture stress periods at different stages of growth on yields of maize *(Barloy [1970], based on Robelin [1967])*. Each point on the graph represents the reduction in yield caused by a moisture stress period of 14 days, at the respective stage of development. By courtesy of «Engrais de France».

In a trial in the Valle del Canca (Colombia), maintaining a minimum of 50 per cent available moisture in the upper 40 cm of the soil by sprinkler irrigation was shown to increase grain yields by an average of 1–2.26 tons/ha. Irrigation was most effective during the 15–20 days before earing *(Gómez and McClung [1968])*.

If water available for irrigation is limited, maximum benefit will be obtained from a pre-sowing irrigation and from preventing moisture stress during the period from tasseling to silking. Maize uses water to a depth of 150–200 cm. Though maximum depletion occurs in the top layers, the moisture in the deeper layers is important in preventing excessive stress towards the end of the interval between irrigations. At each irrigation, sufficient water should be applied to replace the moisture deficit in the entire root zone. The following outline can serve as a general illustration of an irrigation schedule for near-maximum yields to be adjusted according to the hybrid used, soil type, climate, fertility level, irrigation efficiency, etc., assuming that no rainfall occurs during the growing period *(Arnon [1971])*:

A pre-sowing irrigation should be given to bring the whole root zone profile to field capacity, to a depth of approximately 150 cm. If the seeds are sown into moist soil, they will germinate and emerge rapidly. The roots will develop in depth and no irrigation will be required for 30 to 50 days or more, depending on the rate of evapotranspiration. A premature irrigation will promote a shallow root system, increased vegetative growth and will waste water.

The first post-emergence irrigation, generally of 60–70 mm, should suffice to fill the root zone to field capacity. After a 14 day interval, an irrigation of 60–80 mm is given; the next irrigation of 100–110 mm follows after 10 to 14 days. The fourth irrigation of about 80–100 mm should be timed for when the plants are about 65–70 days old and have reached their full development. This irrigation is aimed at supplying sufficient moisture for an adequate supply during flowering, so that overhead irrigation can be avoided during pollen shedding and fertilization. The fifth and last irrigation is generally given when the plants are approximately 80 days old and the grain is in the milky stage.

This outline is based on the water requirements of a hybrid with a growing period of 115 to 120 days, growing in a region with a completely dry summer. Naturally, in regions with summer rainfall the irrigation schedule must be far more flexible, and adjusted to expected rainfall or as it occurs.

4.5.3 Supplementary irrigation

Even in regions with relatively high average amounts of rainfall, supplementary irrigation during the critical period of maximum water requirement, which usually coincides with insufficient rainfall and high temperatures, can give appreciable increases in yield.

In the south-west of France, the average increase in yields over a six-year period (1961–66) was 3150 kg/ha. In the Paris region, yields were increased by an average 30 per cent over a ten year period *(Barloy [1970])*.

In the central area of the Elbe lowland (Czechoslovakia), irrigation was found to increase grain yields of an adapted hybrid by 73.4 per cent. Irrigation decreased the incidence of smut *(Ustilago zea)* and the proportion of insufficiently pollinated ears *(Slepicka [1969])*.

In Bulgaria, hybrid maize irrigated so as to maintain the moisture level at or above 80 per cent of field capacity, yielded on an average (during three years) 10 080 kg grain/ha, compared with 4350 kg/ha obtained without irrigation *(Dimitrov [1969])*.

Brouwer [1958], in experiments with supplemental irrigation in Germany, showed that the greatest effect was obtained by irrigating during the period from flowering to the beginning of ear formation. In Germany, this signifies from mid-July to mid-August. His results are shown in Table 22.

Table 22. The effect of time of irrigation on yields of maize *(Brouwer [1958])*

Time of irrigation	*Amount of water* (mm)	*Yield of grain* (kg/ha)	*Increment due to irrigation* (%)	*W.U.E.*
Control	—	2235	—	
1 and 10 June	2 × 25 mm	2355	5.4	2.4
10 and 20 July	2 × 25 mm	3208	43.5	19.4
20 July and 1 August	2 × 25 mm	3715	66.2	29.6

It must be pointed out that yield levels in this case were generally low, indicating that other factors, besides moisture regime, were limiting. However, these results show how a relatively small amount of water applied at a critical time can give marked increases in yield – with an additional 20 to 30 kg of grain per mm of water applied.

In a study by *Storchschnabel [1964]* on supplemental irrigation of maize in Austria, the effects of the timing of the irrigation on the relative development of the root system, vegetative growth and grain production was investigated. His results confirmed earlier findings – namely that by irrigating the young plants, vegetative growth was promoted but a shallow root system tended to develop. Irrigations given at a later stage, resulted in less top-growth but a deeper and more extensive root system, enabling the plants to maintain an adequate uptake of water during the period of maximum requirement, viz. the period from tasseling to silking.

4.5.4 Methods of irrigation

The most widespread method of irrigation used for maize is furrow irrigation (Plate 7 – see page 87). The use of overhead irrigation is spreading because of its general convenience, high efficiency and adaptability to non-level fields. The increasing interest in close planting of maize also confers an advantage on overhead irrigation.

Overhead irrigation has, however, two limitations, specific to maize: (a) the tall crop makes the transfer of the mobile lines of pipes difficult and labour consuming; and (b) overhead irrigation during the period of flowering may interfere with fertilization, causing reduced seed-set and lower yields. There are a number of ways to overcome these limitations: (1) Combining two irrigation methods: using overhead irrigation during the first period of growth until plants are 80–100 cm tall and irrigation in furrows for the rest of the irrigation period. (2) Leaving paths within the stand, perpendicular to the direction of the rows, in order to facilitate the transfer of the irrigation lines. (3) Interplanting maize with low-growing crops on which the sprinkler lines are set. (4) Using compact types of hybrid maize.

4.6 Disease and insect control

4.6.1 Diseases (Plate 8 – see page 89)

4.6.1.1 Seed and seedling diseases

Seed germinating in a cold, wet soil may be attacked by fungus parasites such as *Pythium* spp., *Diplodia zeae, Gibberella zeae* and others. The use of sound seed, treated with an appropriate compound such as thiram, captan, etc., and delaying sowing until the soil has warmed up sufficiently, will speed germination and provide good control.

4.6.1.2 *Root rots*

Root rots are caused by *Gibberella, Diplodia* and other fungus parasites; they may cause a high plant mortality and the plants that remain alive will be weakened, chlorotic and frequently barren.

Pythium root rot occurs frequently in compacted, poorly drained soils. The attacked roots disintegrate and the affected plants tend to lodge.

4.6.1.3 Leaf diseases

Of the many leaf diseases that attack maize, only a few of the most important will be mentioned:

Rusts:

Maize is susceptible to three principal rust diseases, of which common rust is the most widespread.

– *Common rust (Puccinia sorghi)*

The disease is characterised by the appearance of brown powdery pustules on both sides of the leaves. As the plants mature, black pustules are formed. The spores are carried by the wind; when temperature and moisture conditions are favourable, they germinate on and penetrate into the leaves. Frequent heavy dews therefore favour the

Plate 7
Furrow irrigation, primitive and modern:

Top A: Primitive system, note the short irregular furrows, requiring considerable manual labour and the irregular water distribution.
By courtesy of Soil Conservation Service, Israel.

Bottom B: Modern system; note capillary rise of moisture. By courtesy of *O. A. Lorenz*, College of Agriculture, Davis, California.

spread of the disease. The spores produced at the end of the season, when the maize plants are approaching maturity, overwinter in crop residues; in spring they germinate and infect an alternate host – *Oxalis* spp., on which they pass through a sexual stage. In warm regions the alternate host may be by-passed.

Common rust usually does not cause marked damage to maize that is sown early in the season; a delay in sowing may cause a heavy attack resulting in a marked reduction in yield.

Genes for resistance to specific physiologic races of this rust have been identified and can be used in hybrid programmes *(Ullstrup [1966])*.

The most destructive and widespread disease of maize in tropical Africa is a rust *(Puccinia polysora)* recently introduced from America, which often causes considerable damage, particularly in the more humid regions of western Africa. Resistant varieties and earlier sowing can reduce losses considerably *(Miracle [1966])*.

Leaf blight (Helminthosporium turcicum) is a disease of maize which is prevalent wherever the crop is grown. Small, greenish-grey elliptical spots appear on both sides of the leaf. The spots become lighter-coloured, and in due course the lesions join so that parts of the leaves become dry. The disease starts on the lowest leaves and spreads upward.

The amount of damage caused depends on the stage of development at which it appears: the younger the plant, the greater the reduction in yield. Young plants may dry up and die; if the disease becomes severe shortly before silking, yields may be reduced by 60 to 70 per cent *(Ullstrup [1966])*; if the plant is attacked as it approaches maturity, yields will usually be only slightly affected, but the danger of transmission of the disease to the following crop is increased.

The most practical method of control is to avoid infection by the use of resistant hybrids. Where these are not yet available, partial control is possible by spraying with appropriate fungicides. A properly balanced nutrition, in particular the application of potassium fertilizers on soils deficient in this element, reduces the severity of the diseases *(Ullstrup [1966])*. *H. turcicum* is not seed-borne, but the fungus overwinters inside the dried infected leaves so that crop residues are a potent source of re-infection. Therefore, complete coverage of these residues is an essential sanitary precaution and – in extreme cases – burning of the residues may be indicated.

4.6.1.4 Diseases of the inflorescences and seeds

Common or boil smut (Ustilago maydis)

This is the most ubiquitous disease of maize, and is characterised by galls of various sizes that appear on the plant. Whilst the ears are the most vulnerable to infection, the galls may develop on all above-ground parts of the plant: the stalks, leaves, tassels and even the brace-roots. When the galls are mature, they break open and release their spores.

The spores of *U. maydis* overwinter in the soil; seed disinfection is therefore not very effective against the disease. Common control measures are the removal of the galls before the spores are disseminated, and rotation with other crops. Many commercial hybrids are moderately resistant to the disease.

– *Head smut (Sphacelotheca reiliana)*

Head smut is an important disease of maize grown in dry regions. The disease differs

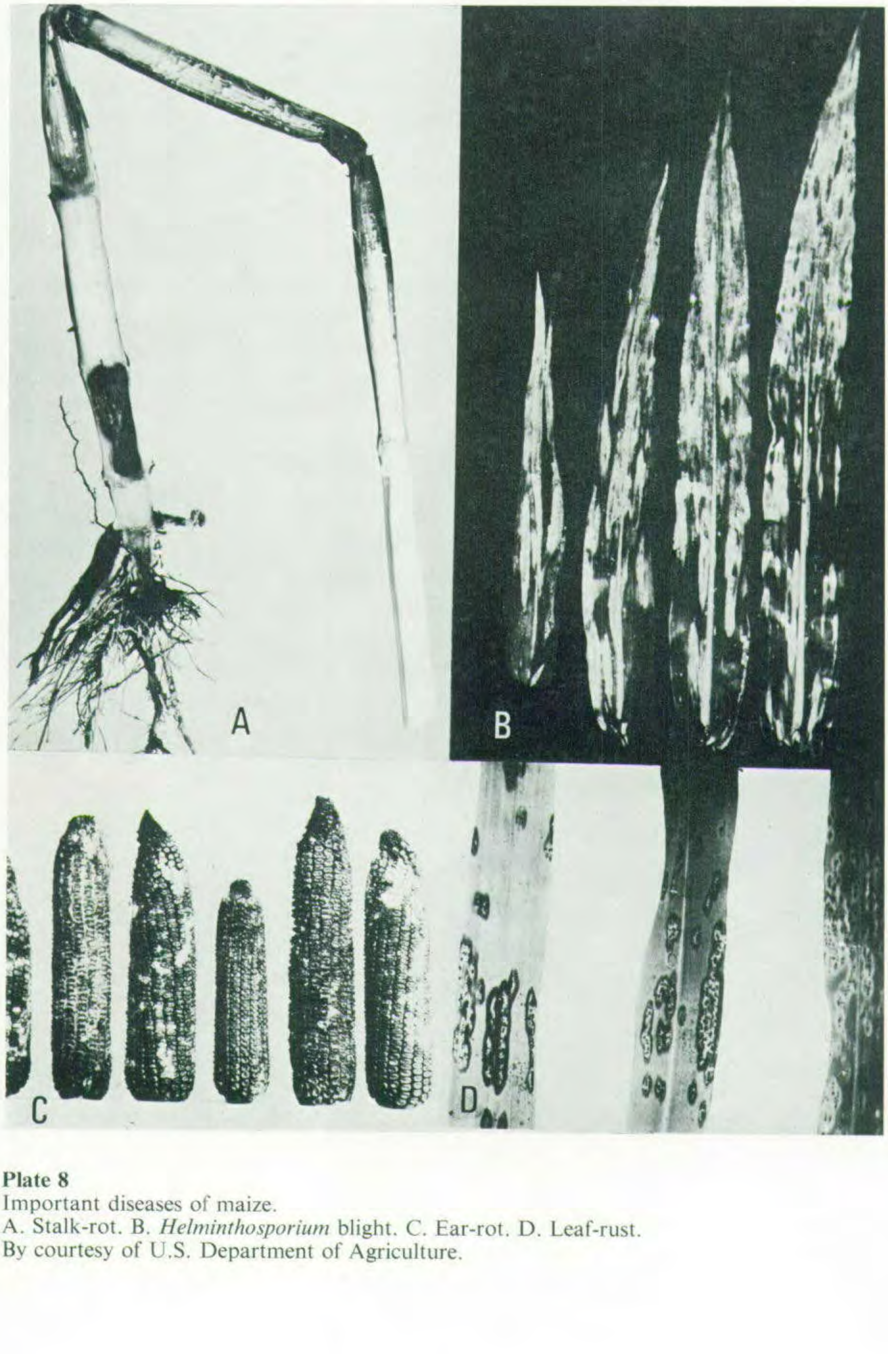

Plate 8
Important diseases of maize.
A. Stalk-rot. B. *Helminthosporium* blight. C. Ear-rot. D. Leaf-rust.
By courtesy of U.S. Department of Agriculture.

from boil smut in that after it has penetrated the tissues the parasite becomes systemic throughout the plant, but the latter does not show any symptoms until the inflorescences appear. The tassels and ears of infected plants are transformed partly or entirely into a black mass of spores.

No effective control measures against head smut have yet been developed; whilst there are marked difference in resistance between different genotypes, no resistant commercial hybrids are yet available *(Ullstrup [1966])*.

– *Diplodia ear rot (Diplodia maydis)*

is a very prevalent and frequently destructive disease. The spores are wind-borne and lodge between the husks of the ear. They germinate when moisture conditions are favourable and penetrate into the developing ear on which a characteristic greyish-white mould develops. The rot starts at the base of the ear, and progresses toward the tip. Early infection may result in the complete destruction of the ear.

The same fungus also causes a *stalk rot*. The tissues of the lower part of the stalk are softened, the stalk turns brown and the affected plants appear to wilt. After the pith in the stalks is destroyed, the stalks become partly hollow and break easily, especially when the crop approaches maturity.

Ears from fallen plants are likely to be of poor quality and difficult to harvest by machinery *(Otto and Everett [1956])*.

In lightly infected plants or in plants in which the disease appeared fairly late, the grain is usually shrunken and of inferior quality. In severely infected plants, the ears are very small, the kernels are small and loosely attached to the cob. It is estimated that the yield of infected plants is reduced by upwards of 40 to 50 per cent *(McKeen [1953])*.

The fungus survives from one season to the next on old stalks and on the seed. Seed treatment will prevent infection only from the latter source. Sowing resistant hybrids is the only practical measure against infection in the field.

– *Gibberella ear rot (Gibberella zeae)*

The fungus generally attacks ears with loose, open husks or such that have been damaged by maize earworm. The rot begins at the top of the ear and progresses towards the base. A brick-red fungus growth covers the ears, husks and kernels. *G. zeae* also causes a stalk rot of maize characterised by the reddish-pink colour of the diseased pith. The fungus overwinters in the soil and on old plant parts. Crop rotation and the covering of crop residues by clean ploughing are sanitary measures that help to control the disease.

– *Fusarium kernel rot (Fusarium moniliforme)*

Fusarium kernel rot is fairly common in the drier regions. The fungus frequently gains entrance to the ear through holes made by maize borers or other insects. It is characterised by the pale-pink colour of the infected kernels which are distributed at random over the ear.

– *Stunt*

Stunt is a relatively new virus disease, prevalent in dry regions, that causes a high rate of mortality in affected maize, and dwarfing of the surviving plants (Plate 9).

Plate 9
Maize-Stunt.
Diseased plant (left) compared with normal plant of same age (right).
By courtesy of U.S. Department of Agriculture.

The leaves of virus-infected maize become dark-green with faint yellowish stripes on the upper leaves; the upper internodes cease to lengthen, giving the plants a stunted appearance. Usually no inflorescences are formed. If infection occurs at a later stage, pistils and stamens degenerate and the shape of the ear becomes abnormal. The severity of the disease is highly variable, and depends on the degree of genetic resistance of the host, on the prevailing environmental conditions and on the abundance of the vector responsible for transmitting the disease.

The disease is not seed-borne. Control is possible by spraying the foliage with an insecticide, such as malathion or DDT, that is effective against the vector of the disease. The disease itself may be due to a new strain of a known virus, a complex of two or more viruses, or an entirely new virus *(Ullstrup [1966])*.

There appear to be marked differences between inbred lines and also between hybrids in their susceptibility to stunt.

– *Nematodes*

A marked reduction in yields of maize attacked by nematodes (*Trichodorus* spp., *Tylenchorhynchus acutus*, *Pratylenchus zeae* and other species) has been recorded in north Louisiana. The damage was most severe for continuous maize, which allows a buildup of nematode populations, in the soil. Fumigation with nematocides increased yields considerably. The nutrient content of the plant tissues was not significantly affected by the nematode damage, but total nutrient uptake was increased by controlling the nematodes *(Wilcox et al. [1959])*.

4.6.2 Insects (Plate 10)

4.6.2.1 Soil insect pests

Rootworms, wireworms, white grubs, ants and other soil-inhabiting insects may cause considerable damage to the germinating seed and emerging seedling. Others damage the root system at different stages of growth of the plant, increasing lodging and the losses of harvestable grain.

The principal chemicals used to control soil insects are aldrin and heptachlor, applied as sprays or more recently in granulated form. The materials may either be broadcast over the entire surface of the field or applied in the seed-band by means of planter-mounted equipment. The former method is used once in three years of continuous maize growing. The granulated insecticides are frequently broadcast in mixture with fertilizers *(Lofgren [1959])*.

– Maize rootworms

Rootworms such as *Diabratica* spp. periodically cause serious damage to maize, especially when the crop is grown continuously. Crop rotations help to reduce the incidence of these pests. Chemical control as described above is effective. Varieties that are capable of regenerating their roots rapidly appear to be relatively tolerant to rootworms *(Dicke [1955])*.

– Chinch bugs (Blissus leucopterus)

Chinch bugs in moderate numbers do not cause damage of economic importance to maize plants when mass infestations occur crop loss can be severe. Sunny, dry con-

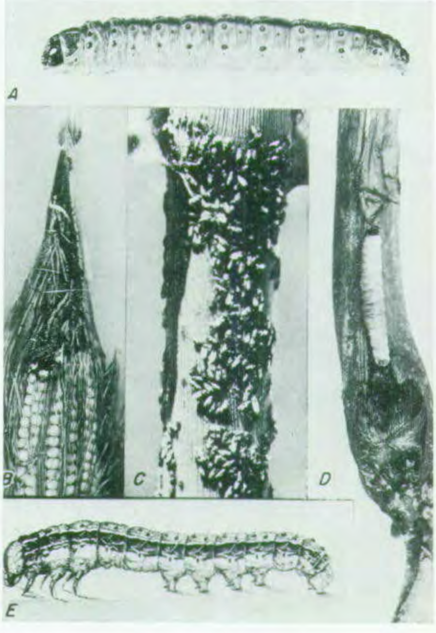

Plate 10
Important insects of maize:
A. European maize-borer.
B. Maize ear-worm.
C. Chinch-bugs.
D. Maize root-worm *(Diabrotica* Sp.)
E. Army worm.
By courtesy of U.S. Department of Agriculture.

ditions favour chinch bug proliferation. A practical control method is to spray protective barriers around the maize fields with dieldrin, whenever chinch bugs begin migrating from other crops to the maize.

– *The seed-maggot (Hylemyia cilicrura)*
This species is distributed throughout the world. In warm climates it is active throughout the year *(Dicke [1955])*. The adult is similar to the housefly and the maggots are white, almost conical, and have black mandibles. They penetrate into the germinating seeds and also attack young seedlings.
Soil treatment provides effective control and the use of seed with good viability is a useful preventive measure.

– *Cutworms (Agrotis* spp. and others)
The larvae of cutworms are characterised by their plump, curled-up appearance and vary in size from 3 mm when newly hatched to 45 mm when fully grown (*Dicke,* 1955). The moths lay clusters of white eggs in moist sites near a potential food supply. The small larvae feed on the leaves, but when they become larger they attack the young seedlings, cutting the stems just below the ground. Moving along the row, the damage they cause may be so considerable that reseeding becomes essential.
The cutworms remain hidden in the soil or under stones during the day and feed at night.
Effective control can be achieved by using poisoned baits of fluosilicate salts or applying toxaphene, banded along the rows, as soon as damage becomes apparent.

– *Army worms (Prodenia* spp.)
There are a number of different species designated as army worms. *Prodenia* spp. is widespread and damages a large number of crops.
The worms feed in the whorl and on the leaves of the plant during the daytime. The damage they cause to maize is usually not of economic significance because.
Army worms usually have a large number of natural enemies; however, outbreaks causing serious damage are quite frequent.
Poison bran baits and spraying with toxaphene give reasonably good control.

– *The European maize borer (Ostrinia nubilalis)*
The female moth lays masses of 15–50 eggs at night, on the underside of the leaves. The worms have a pink, transparent body and a brown head. On each segment of the body are four dark patches; in the centre of each patch is a single stiff hair. The larvae overwinter in old corn stalks and cobs and pupate in spring; the moths emerge in late spring. The young worm penetrates deep into the whorl of the leaves. Approximately two-thirds of its life is spent within the stalk or ear. The location of the hole through which the borer has penetrated is easily noted by the detritus it leaves on the surface. It is estimated that first-generation borers decrease yields by 5 per cent for each borer that matures per plant *(Petty and Apple [1966])*.
Control, if it is to be effective, must be carried out as long as the larvae are small, active and feeding on the leaves. Repeated applications of granular DDT to the whorl have been found to be effective. Cultural control consists in ploughing under all crop residues to a depth of at least 15 cm. Some hybrid varieties are more tolerant or

resistant than others. Many natural enemies contribute to checking the population of the corn borer.

– *Maize ear-worm (Heliothis armigera)*
The light yellow to olive-coloured moth of the maize ear-worm lays small, pearly white eggs in early summer; the first generation of larvae feed on young maize. The fully grown larva is about 35 mm long and varies in colour from brown to green. The last generation larvae reach the pupal stage before the onset of cold weather and overwinter below the surface of the soil in the fields.
The larvae feed in the whorl of the young plants, and later in the developing tassels and in the ears. After the silks dry out, the developing kernels are attacked.
Severe infestations may cause yield losses of up to 50 per cent *(Leonard and Martin [1963])*. Chemical control with DDT or sevin applied at the ear zone can be effective but is generally not economically justified.

– *Sesamia (Sesamia cretica)*
The larvae of sesamia are characterised by their pink colour, brown head and the dark band along their body. They may reach a length of 30 to 35 mm. In young plants, the larvae bore into the whorl and cause a cessation of growth of the maize stem; in more developed plants, the larvae do not prevent growth. At a still later stage, the larvae also attack the ear; damage to 5–10 per cent of the ears is quite common, but in the case of a heavy infestation up to 90 per cent of the maize plants may be attacked. Control is not very effective; the same cultural measures as those described for controlling the corn borer can be used.

– *Grasshoppers*
Many species of grasshoppers feed on maize. Normally, they eat only the leaves, but when numerous they may destroy part of the stalk and ears as well.
As the eggs are laid in pods 5 to 10 cm below the soil surface, ploughing usually reduces the number of grasshoppers that reach the adult stage. The grasshoppers have many natural enemies, including insects, rodents and birds. Disease epidemics are also effective in reducing the population.
When infestation assumes a level of economic importance, a number of insecticides can be used for control, such as toxaphene, malathion, diazinon, etc.

4.7 Harvesting

In primitive agriculture, the outstanding feature of the maize harvest is that it is gradual: harvesting begins as soon as ears are ripe enough to be eaten on the cob, and continues until well beyond maturity *(Miracle [1966])*. With the open-pollinated varieties used, maturity is very non-uniform so that harvest extends over a protracted period.

4.7.1 Mechanical harvesting

Mechanical harvesting of maize is possible in a number of ways: the most common method was to pick and husk the ears with a mechanical picker and then store them in a crib where the cobs dry naturally.

In regions with humid climates and relatively short growing seasons, as in many European countries which grow the crop, maize has to be harvested when the grain still has a high moisture content – 30 to 40 per cent. At this stage migration of nutrients to the grain is completed and the grain is physiologically ripe. The moisture content of the grain makes it suitable for mechanical harvesting with a minimum of loss but it is essential to dry the grain artificially after harvest, unless it is ensiled. A delay in harvesting may increase lodging and grain losses, and also retard soil preparation for the following crop.

With artificial grain-drying units, it is possible to carry out early harvesting, which reduces field losses. The picker-sheller may also be used at 26 per cent moisture and the shelled grain ensiled, at a high moisture content.

Equipment is also available that picks and shells the maize in the field; picker-shellers, either tractor-drawn, tractor-mounted or self-propelled, and corn handling attachments for the standard grain combines. The field-shelled maize has to be dried artificially. Field losses of grain depend largely on the moisture content of the maize at harvest: losses at high moisture content are low, with a minimum occurring at 24–30 per cent *(Barnes and Link [1959])*.

4.8 Maize for green forage and silage

4.8.1 Production methods

Most forage plants are harvested exclusively for their leaves and stalks. Not only are the seed yields of most widely-used forage crops insignificant, but the nutritive value of the vegetative parts of the plant declines steeply after flowering.

When maize was first established as a forage crop in the United States, it was grown in very much the same manner as other forage crops. Vary late, open-pollinated varities were grown in dense stands, and the crop was cut at the time of tasseling, six to eight weeks after sowing.

Research on growth and dry matter accumulation by the maize plant has, however, demonstrated that maize, in particular the hybrid varieties, is entirely different from most other forage crops. The maximum production of carbohydrates occurs after flowering and these are stored mainly in the ears. When the grain is in the milk-ripe stage, the ears are very attractive to livestock, stalks and leaves are still green and succulent and have a high sugar content, and therefore all parts of the plant are readily eaten by the stock.

It was also shown that early varieties are as productive in dry matter yield as late varieties, with an equal lenght of production period. However, earlier varieties can produce an ear with practically ripe grain before the onset of killing frost, whereas later varieties only reach the flowering at this time. Consequently, very late varieties have been superseded and production methods for forage maize are generally very similar at present to those practiced for grain production *(Bunting and Willey [1959])*.

Present day methods are based on growing maize for forage or silage in almost the same way as for grain; somewhat more nitrogen is applied, plant population density is slightly increased **(Figure 32)**, and somewhat less water may be required. Harvesting is simply carried out earlier, when the grain is passing from the 'milky' to the early dough stage, about 90 to 95 days after sowing. Special hybrids may be preferred to those grown exclusively for grain. For every ton of forage harvested, approximately $^2/_3$ ton consists of stalks and leaves, and $^1/_3$ ton consists of cobs with grain.

Harshbarger et al. [1954] report that the *proportion* of ears in the dry matter of forage was significantly increased by fertilizers in only one year out of five years of trials. They conclude that the larger forage yield from fertilized maize is generally due to equal increases in leaves, stalks and ears.

Renewed interest has been shown in recent years in growing dense-drilled corn, at a sowing rate of 65 to 130 kg seed ha in 15–20 cm rows, with plant populations of 25 to 100 plants/m². Under the name 'high population corn for forage', this method has recently attracted much attention, but it is really an old method under a new name, and with the same attendant disadvantages as before *(Reid [1959])*.

4.8.2 High lysine maize

The discovery at Purdue University that two recessives gene called 'opaque 2' and floury-2 respectively, are related to high lysine content, makes possible the breeding of maize with significantly higher levels of lysine than formerly. Work on incorporating this desirable characteristic into commercial hybrids is proceeding at a number of research centres. This subject is discussed in more detail in chapter 9.

4.8.3 Excessive nitrate accumulation in forage maize

Herbicides, particularly 2,4-D, occasionally interfere with the normal transformation of nitrate to protein, resulting in an excessively high nitrate content in maize for silage that may be toxic for cattle. Under these circumstances, cultivation is preferred to chemicals for weed control. Further factors causing excessively high nitrate content of maize forage are periods of stress due to drought, high temperatures, or imbalance between the supply of nitrogen and that of phosphorus and/or potassium *(Kurtz and Smith [1966])*.

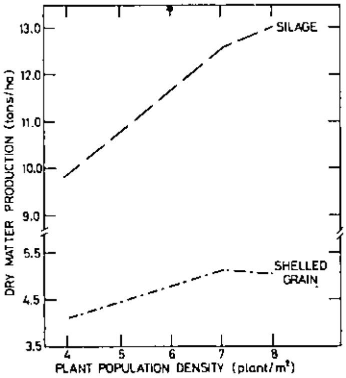

Fig. 32 Effect of plant populations on silage, dry matter, and on the amount of shelled grain *(Rutger and Crowder [1967])*. It will be observed that in this case, 7 pl/m² was the optimum for grain production and 8 pl/m² for silage production. By courtesy of the Crop Science Society of America.

4.8.4 *Dual-purpose maize*

A dual-purpose system, whereby a field of maize produces both forage and grain, is in use in India and other parts of the world. Heavy seeding rates are utilized, and as the maize grows, individual plants are removed for green livestock feed, and the remaining plants are allowed to mature a crop of seeds. On the assumption that such a system is more efficient in utilizing solar energy than the conventional planting methods, an investigation was carried out in Illinois to test this hypothesis. Planting patterns were evolved which would enable the mechanical harvesting of the forage. It was found that maize planted in 100 cm rows and harvested either for grain or for silage yielded more than any of the dual-purpose systems tested *(Jain et al. [1963])*.

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5. Nutritional requirements of maize

5.1 Macronutrients and secondary nutrients

As plant nutrients have the same general effects on different crops, it is not proposed to go into detail on the subject in this book, and the reader is referred to much excellent and recent textbooks as *Barber and Olson [1968], Cooke [1967], Linser [1969]* and *Tisdale and Nelson [1966]*.

Here we will concern ourselves exclusively with specific effects of the macro and micronutrients on maize.

5.1.1 Nitrogen

Nitrogen is taken up in large amounts by maize, and therefore the dominant form in which its supplied will have a marked influence on the cation: anion balance in the plants. When ammonium-N is absorbed, the uptake of other cations, such as potassium, calcium and magnesium, will be decreased. Conversely, the uptake of anions, and in particular of phosphorus, will be favoured. The opposite occurs with N-nitrate uptake *(Mengel [1968])*.

The relative proportions of nitrogen taken up by the maize plant in the form of ammonium-N and nitrates-N, depend on the age of the plant. Young maize plants absorb ammonium-N more rapidly than nitrate-N, while older plants absorb the major part of their nitrogen in the form of nitrate-N, which may normally account for up to 90 per cent of the total nitrogen uptake *(Coïc [1964])*.

Excessive amounts of nitrogen stimulate protein synthesis to such a degree that the bulk of the carbohydrates is used in the formation of amino acids and proteins, whilst the formation of strengthening tissues is insufficient. This results in spongy and weak tissues, predisposing maize plants to lodging and reducing their resistance to adverse weather conditions and diseases *(Jacob and von Uexküll [1963])*.

Since maize can potentially use all the nitrogen available in the soil, the maximum yield, when nitrogen is not limiting, is governed by other production factors **(Figure 33).**

5.1.2 Phosphorus

The quantities of phosphorus present in the tissues of most plants are much smaller than those of the other two major nutrients-nitrogen and potassium: about one tenth of the nitrogen and one fifth of the potassium.

An adequate supply of easily available phosphorus is of great importance during

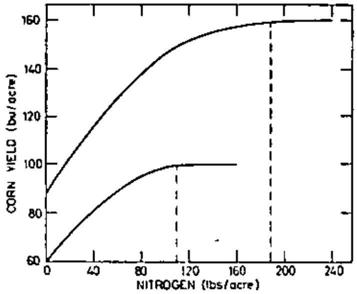

Fig. 33 The relationship between applied nitrogen and maize yield at two yield levels *(Barber and Olson [1968])*. The figure illustrates that the maximum yield levels in the two curves are governed by other production factors, other than nitrogen. By courtesy of the Soil Science Society of America.

the early stages of growth when the limited root system is not yet capable of drawing sufficiently on the phosphorus reserves in the soil, and cannot effectively compete with soil microorganisms for the available phosphorus. A deficiency at this stage adversely affects the laying down of the primordia for the reproductive parts. High doses of phosphorus available to young corn plants were also found to enhance the rate of nitrogen metabolism *(Pleshkov [1958])*. Adequate phosphorus, supplied at a later stage, therefore cannot remedy the adverse effects of a deficiency at the critical earlier stage.

Plants are able to accumulate high concentration of inorganic phosphate within their tissues, despite the low concentrations of this ion in the soil solution. The phosphate concentration in the cell sap of maize is frequently several thousand times higher than that in the displaced soil solutions *(Pierre and Pohlman [1933])*.

5.1.3 Potassium

Potassium is the only univalent cation that is generally indispensable for all living organisms, and its concentration in the plant tissues exceeds that of any other cation *(Evans and Sorger [1968])*. The optimum potassium content of the plant depends on its physiological age. In young plants it may be as high as 4–6 per cent of the dry weight of the plant *(Mengel [1968])*; for of its life-time, 2 per cent is generally considered an adequate level for near maximum growth *(Nelson and Stanford [1958])*.

Though potassium is not a constituent of important plant components such as protoplasm, fats or cellulose, an essential role has, at one time or another, been ascribed to this element in every important physiological process of the plant *(Mulder [1950])*; it thereby directly determines rate of growth and yields. Photosynthesis may be decreased and respiration increased, under conditions of potassium deficiency. Of particular interest is the ability of potassium to increase photosynthesis under conditions of low light intensity and also to make more efficient use of light at higher intensities *(Kick [1969]*, an important factor in the high plant population densities characteristic of modern maize production. Potassium also contributes to a strengthening of the sclerenchyma fibres, and consequently increases resistance to lodging *(Jacob and von Uexküll [1963])*.

The most important contribution of potassium fertilizers to the intensive production of maize is to offset to a certain degree the negative effects of the heavy applications of nitrogen needed for high yields.

5.1.4 Sodium

Maize apparently belongs to those crops that respond very slightly if at all to Na under any conditions.

It was found to absorb less than 1 meq Na per 100 gram dry matter when grown in two soil types supplied with different levels of Na. No yield responses to sodium were recorded. Na additions had no effect on cation uptake, excepting at the lowest level of K, when it increased K uptake slightly *(Larson and Pierre [1953])*.

When maize was grown in aerated nutrient solution cultures containing varying levels of potassium and sodium and adequate balanced amounts of the other nutrients, it was found that sodium entered through the roots in appreciable quantities but failed to pass into the tops of the plants. The probable reason for this appears to be the inability of the sodium to pass freely through the nodes, where it accumulates. In maize, it does not therefore appear feasible to make any marked substitution of sodium for potassium, or to markedly increase growth, by additions of sodium salt *(Truog et al. [1953])*.

Somewhat different results were obtained by *Cope et al. [1953]*. When the maize was harvested at the tasseling stage, it was found that the addition of sodium to the soil gave a significant increase in the yield of dry matter; increases from potassium were highly significant. The yield increase from the potassium was greater than that from the sodium. The application of sodium to the soil did not result in an appreciable amount of sodium being absorbed by the maize, but the potassium content was increased as a result of Na fertilization. It is therefore assumed that the yield increase following sodium application should be ascribed to the improved potassium uptake.

5.1.5 Calcium

Calcium deficiency symptoms may be observed in maize growing in sandy soils that have pH values of less than 4.5 and contain less than 2 meq of exchangeable calcium per 100 g of soil. They are, however, rare on silt loam soils *(Melsted,* [1953]). It is of interest to note that the calcium deficiencies do not become evident until all the other nutrient deficiencies had been corrected through large applications of soluble fertilizers. Plants showing typical calcium deficiency symptoms contained less than 0.2 per cent of calcium in the plant as a whole (ibid.).

5.1.6 Sulphur

Maize has a relatively low requirement of sulphur, as compared with many other crops, such as vegetables, clovers, lucerne and cotton. When maize is grown at intermediate nitrogen levels, field applications of sulphur do not usually result in increased growth of maize *(Jordan and Ensminger, [1958]*.

Maize plants grown on a sulphur-deficient soil, which received nitrogen fertilizer without added sulphur, showed yellowing within 30 days after emergence. When 1 ppm S was added with each 30 ppm N, the deficiency symptoms were slower to appear *(Stewart and Porter [1969])*.

5.2 Net needs for nutrients

The *net need* for a nutrient is the total amount of the nutrient accumulated by the crop. This in turn depends on the composition of the mature plant and the total yield of dry matter produced. The actual *fertilizer requirement* is the net need, less the amounts of the nutrient that can be taken up from the soil by the crop. Further adjustments must also be made on account of losses of nutrients by leaching, fixation of nutrients into unavailable forms, erosion, etc.

Information on the following points is therefore needed for estimating the fertilizer requirement of a maize crop: the composition of different parts of the maize plant at maturity; the relative proportions of the different parts of the crop in relation to total dry matter production; the total yield of dry matter; and the nutrient supply from the soil.

5.2.1 Composition of the maize plant at maturity

The composition of the maize plant at maturity varies considerably, as it is markedly affected by the nutrient and moisture status of the soil, the genetic constitution of the plant, and actual yields achieved. Therefore, the results obtained by different investigators are not always identical, but do give an idea of the variations to be expected under different conditions. Unfortunately, much of the early work on maize nutrient content was done when yields were normally far lower than those achieved at present by progressive growers, and are therefore generally no longer relevant.

Sayre [1955], working in Ohio investigated the percentage composition of the tissues of the maize plant just before maturity, after growth had ceased but before disintegration of the tissues had occurred. The results are presented in Table 23. The roots are not included in the table; on the basis of other studies the weight of roost of the average maize plant is about 30 g.

Soubiès and Gadet [1953] obtained the following results, based on hundreds of samples of maize grown in France:

Nitrogen: The percentage of nitrogen in the grain was found to vary considerably, from 1.10 to 2.21 per cent for the same variety, depending on growing conditions and yield levels. The lowest concentration of N was generally obtained in cold, rainy seasons, when the crop was grown on poor soil without nitrogen fertilizer. The highest concentration was usually found in grain grown under irrigation during a warm summer and receiving heavy fertilizer applications of nitrogen.

In the cob, husks and shanks, nitrogen concentration is low, approximately 0.35 per cent. Even a heavy yield does not remove more than 3–4 kg of N/ha in these plant parts. The nitrogen content of leaves and stems is approximately 0.6 per cent in hybrids

Table 23. Estimated percentage composition of tissues of the maize plant just before maturity (on a dryweight basis) *(Sayre [1955]*

		Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
Leaves a		2.0	0.25	1.6	0.3	0.25
Sheaths		0.4	0.10	1.2	0.3	0.20
Stem b		0.7	0.11	1.2	0.1	0.09
Tassel		0.7 c	0.10	1.0	0.1	0.08
Ear						
	Grain	1.5	0.29	0.35	0.01	0.08
	Cob	0.2	0.12	0.40	0.09	0.06
	Husks	0.4	0.11	1.10	0.09	0.07
	Shank	0.5	0.12	1.10	0.09	0.07

a 78 per cent of the leaf tissue was blade (blade margin = 12 per cent) and 22 per cent was midrib.

b 78 per cent of the stem tissue consisted of internodes and 25 per cent of nodes.

c 2.4 per cent before pollen shed.

grown on fertile soil, and 0.7 to 0.8 per cent in a local open-pollinated variety grown on the same soil.

Because of the low nitrogen content of the vegetative parts and the high proportion of grain in the total yield, at least three-quarters of the total uptake of N by the plant is in the ears.

For each 100 kg of grain harvested, the total amount of nitrogen taken up by the crop is frequently 2 kg, but in well-fertilized fields of maize it may easily reach 2.5 to 3.0 kg.

Phosphorus: Phosphorus content of the grain was found to be remarkably stable, varying only from 0.6 to 0.8 per cent for maize grown under widely different conditions. The cob, husks and shanks contained only 0.15 per cent, and the leaves from 0.16 to 0.40 per cent. Total uptake is practically proportional to grain yield: 0.85–1.0 per 100 kg of grain harvested.

Potassium: Potassium content of the grain was found to vary from 0.36 to 0.52 per cent, but was most generally around 0.40 per cent. The cob, husks and shanks are relatively rich in K, varying from 0.5 to 1.0 per cent, the most frequent percentage being approximately 0.8. The ears account for 25 to 45 per cent of the total uptake.

From hundreds of maize samples, grown in France under different conditions of fertilization, *Soubiès and Gadet [1953]* draw the following conclusions:

1. The requirements of *phosphorus* are roughly proportional to the amounts harvested.
2. Only the *potassium* exported in the grain is proportional to yield, because the composition of the vegetative parts is usually most variable.
3. The requirements of nitrogen depend not only on yield, but also on the protein content of the grain.

5.2.2 Dry matter distribution at maturity in the different parts of the plant

Examples of the relative proportions of dry matter at maturity in the different parts of the plant are given in Table 24.

Table 24. Dry matter distribution at maturity in the different parts of the plant (in per cent)

		Sayre [1955]	*Depardon-Meauvisseau [1952]*
Leaves		12	22
Sheaths		6	
Stem		22	16
Tassel		1	
Ear		(59)	(62)
	Cob	8	
	Husks	5	17
	Shank	1	
	Grain	45	45

5.2.3 Total accumulation of nutrients by the maize crop

The yield level is a major factor in determining the amounts of nutrients required by the crop. As the farmer is usually unable to predict exactly the yield he will obtain, the normal practice is to determine a realistic yield level which can be expected under given conditions and on this basis to determine the amounts of plant nutrients which should be supplied to the crop.

However, not all nutrients increase in proportion to yield, and this is frequently overlooked when calculating nutrient requirements of high-yield crops, by extrapolating known data from lower yields. There are several reasons for this:

(a) Under conditions of yield response to certain nutrients the concentration of these nutrients in the plant may also increase, requiring an adjustment in the calculations.

(b) Each nutrient has a critical level in the maize plant, below which the plant cannot achieve its yield potential (cf. .). When supply and uptake of a nutrient are in excess of the critical level, this constitutes luxury consumption and has no additional effect on yield. Yield increases may also on occasion cause a reduction in nutrient content, as a result of dilution (cf. p. 211).

(c) Certain losses of nutrients may occur before maturity.

A number of example are therefore given below; showing the net nutrient requirements of maize obtained under different conditions and yield levels.

The figures in Table 25 do not take into account losses of nutrients that occur during the growing period. A crop of maize, that produced a total of 15 tons/ha of dry matter, of which 45 per cent was in the grain, showed a slight loss of nitrogen that occurred before maturity, as a result of leaching and/or disintegration of tissues. The loss of potassium was about 20 kg K_2O/ha, and that of CaO about 1.5 kg/ha. No losses of phosphorus or magnesium were recorded *(Sayre [1955])*.

5.2.4 .Micronutrients

Most of the micronutrients are components of a key substance in plant metabolism, or essential to the functioning of an enzyme system. Therefore, though the quantities of the essential minor elements required for normal plant growth are extremely small, as compared with the major nutrients, a deficiency of a micronutrient may have extremely disturbing effects on vital plant processes.

Table 25. Total accumulation of nutrients by maize at different yield levels

Yield level (kg/ha)	Location	Accumulation of nutrients (kg/ha)					References
		N	P_2O_5	K_2O	CaO	MgO	
1700–2600	Kenya	38–68	13–22	34–63	—	—	*Drysdale [1965]*
4400–5500	Kenya	130–140	44–53	130–162	—	—	*Drysdale [1965]*
5000	France	125	50	75–100	—	—	*Soubiès and Gadet [1953]*
5000–6000	Germany	100–180	40–70	100–150	40–50	—	*Zscheischler and Gross [1965]*
5600	Rhodesia	100	44	77	—	—	*v. Burkersroda [1965]*
6000	France	135	55	90–120	33	30	*Loué [1963]*
6250	USA	154	55	110	—	—	*Krantz and Chandler [1954]*
6270	USA	167–241	50–90	101–196	—	—	*Smith [1952]*
6750	USA	158	75	130	18	23	*Sayre [1955]*
7400	USA	232	79	271	—	—	*Benne et al. [1964]*
8000	France	175	75	150	42	35	*Loué [1963]*
9200	France	200	80	131	—	—	*Soubiès and Gadet [1953]*
9500	USA	187	85	230	35	40	*Barber and Olson [1968]*
9600	USA	225	60	288	43	35	*Jenne et al. [1958]*

When deficiencies occur, a very small amount of chemical containing the micronutrients may suffice to restore normal plant growth; however, an excess application of certain minor elements may be even more dangerous to the plant than the deficiency it was supposed to cure. For several of the micronutrients, such as iron, manganese, copper and zinc, their concentration in the plant in relation to other heavy metals is of greater importance than the absolute amounts present *(Tisdale and Nelson [1966])*.

– Boron

The minimum requirement of boron for adequate growth of maize is 0.1 ppm in a hot water extract of soil *(Berger [1949])*.

Boron toxicity assumes great practical significance when irrigating with water of high boron content. Maize is considered as semi-tolerant to boron, but optimum growth of the crop will require that its concentration in the soil solution extract should not exceed 1 ppm *(U.S. Salinity Laboratory Staff [1954])*.

Small concentrations of boron are distributed in all parts of the maize plant. In a yield of 8.7 tons dry matter per ha, the total amount of Bo was found to be only 0.126 kg/ha. Harvesting the grain with a picker-sheller removes only 0.034 kg of this total; harvesting for silage removes 0.113 kg and leaves 0.013 kg in the soil *(Benne et al. [1964])*.

Deficiencies of boron are generally rare in arid soils, and available boron is well distributed through most arid soil profiles *(Berger and Pratt [1963])*. When deficiencies do occur, they can be remedied by the application of fertilizer borate*, applied to the soil at rates of 0.7 to 1.0 kg boron/ha *(Olson and Lucas [1966])*. However, boron becomes rapidly fixed when applied to an alkaline soil; therefore, borate has to be applied annually in small dressings, to crops grown on boron-deficient soils *(Cook and Davis [1957])*.

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* Borate: Anhydrous sodium tetraborate ($Na_2B_4O_7$), containing 20 per cent boron.

– *Iron*

Maize has very low requirements of iron, in comparison with other crops. A soil level of iron that will cause severe deficiency symptoms in sorghum, may be quite adequate for maize *(Olson and Lucas [1966])*.

In solution-culture trials with maize, adding 6–9 mg Fe/l. to the nutrient solution was found to increase the contents of a and b chlorophyll per 100 cm^2 of leaf from 5–7 mg in plants which received no Fe, to 28–32 mg. Higher doses of Fe and Mn resulted in smaller increases of chlorophyll contents *(Godnev et al. [1969])*.

Iron accumulates especially in the sclerenchyma cells around the vascular bundles. Accumulations of iron are found in the nodes of maize, with amounts decreasing from the oldest to the youngest nodes *(Kliman [1937])*. The highest concentration of Fe are consistently found in the roots of the plant, and the lowest concentrations in the component parts of the ear and in the part of the stalk above the ear *(Benne et al. [1964])*.

A mature crop of maize, with a yield of 18.7 tons/ha dry matter, accumulated 6.24 kg/ha Fe. Harvesting the grain crop, consisting of 7.4 tons/ha dry matter, with a picker-sheller, removes 0.143 kg/ha Fe from the field; and harvesting the crop for silage removes 2.74 kg/ha, leaving more than half the amount accumulated in the field *(Benne et al. [1964])*.

– *Copper*

Maize has been found capable of developing into mature plants on an organic soil, with a copper content of 11 ppm, though wheat under the same conditions resulted in a complete failure. The copper-deficient maize plants, when they were about 60–70 cm high, failed to unroll their leaves at the terminal portions. The plants recovered about two weeks after these symptoms appeared and produced mature plants.

Seed taken from those plants that had shown copper deficiency symptoms, produced chlorotic seedlings, with a poorly developed root system, and failed to elongate at the internodes. Chlorotic leaves did not regain a normal colour even after copper was applied, but all leaves newly developed after the copper applications had a normal colour *(Brown and Harmer [1950])*. Apparently the seed used in the first place had sufficient reserves of copper to enable the maize to partially overcome the copper deficiency; this was not the case with second generation maize grown on a Cu-deficient soil.

Small amounts of copper are normally distributed throughout the plant. A mature crop of maize, producing 18.7 tons/ha dry matter, contains only 0.199 kg/ha Cu. Harvesting the grain crop, consisting of 7.4 tons of dry matter, with a picker-sheller, removes 0.172 kg/ha of this total from the field; harvesting as silage removes 0.037 kg/ha, leaving 0.027 kg/ha in the field *(Benne et al. [1964])*.

– *Manganese*

The manganese requirements of maize are relatively low, in comparison with other crops. Normal plant tissues of deficient plants generally contain less than 25 ppm *(Olson and Lucas [1966])*.

The highest concentration of manganese in maize plants approaching maturity is found in the leaves, both above and below the ear. A mature crop of maize that has produced 18.7 tons/ha dry matter, accumulates 0.483 kg/ha of manganese. Harvesting the grain crop, amounting to 7.4 tons/ha of dry matter, with a picker-sheller, removes 0.037 kg/ha of manganese from the field; harvesting the crop for silage removes 0.385 kg/ha, leaving only 0.098 kg *(Benne et al. [1964])*.

Manganese levels of over 400 ppm in maize tissues are toxic *(Olson and Lucas [1966])*. Manganese toxicity may affect crops under a number of different conditions. The solubility of manganese increases with a lowering of the pH, and the amounts of divalent Mn increase with reducing conditions. Available Mn in the soil may also be increased to toxic levels by application of KCl fertilizer, especially in unlimed soils. This may explain the reductions in yield that are sometimes observed from band applications of KCl at planting time *(Jackson et al. [1966])*.

– *Zinc*

Chlorosis of maize is frequently observed on desert soils in central Washington State (U.S.A.) after they are reclaimed for irrigation, and the apparent damage to the photosynthetic area observed under these conditions causes marked reductions in yield. Foliar sprays of $ZnSO_4$ solutions to the maize plants have consistently prevented this chlorosis or have restored normal growth of plants that were already chlorotic. No response to sprays of Cu, Mn, B, Fe or Mo was observed, indicating that chlorosis was in these cases specifically due to zinc deficiencies. *Viets et al. [1953]* found that 15 ppm of Zn in the sixth leaf of maize, at the time that pollen is shedding, appears to be an adequate level for yields in the range of 6700 to 8400 kg/ha. *Brown and Krantz [1966]*, however, obtained their highest yields of maize with zinc levels of only 6.5 ppm. In investigations by *Fuehring and Soofi [1964]*, it was found that in maize with concentrations in the sixth corn leaf ranging from 20 to 145 ppm, applications of Zn decreased grain yield but considerably enhanced the yield of stover. This appears to indicate that the response of maize to Zn is directly opposite between vegetative and storage parts of the plant. Grain yield was relatively high at 20 ppm while yield of stover was highest at the 145 ppm content.

On soils that are borderline in their ability to supply zinc, fertilization with this element may give important increases in yield. On a calcarous clay loam in Michigan, yields of maize were increased from 8250 kg/ha to 9550 kg/ha by an application of 4.4 kg/ha of Zn as $ZnSO_4$ *(Roscoe et al. [1964])*.

A crop of maize producing 18.7 tons/ha of dry matter, of which 7.4 tons/ha are in the grain, accumulates only 0.44 kg/ha Zn. Harvesting with a picker-sheller removes 0.187 kg/ha, whereas harvesting for silage will remove 0.396 kg/ha *(Benne et al. [1964])*.

– *Molybdenum*

Only minute quantities of molybdenum are required. As little as 0.1 ppm of this element may be sufficient to maintain normal growth of maize so that, as a rule, the seed may contain enough molybdenum for several generations *(Peterson and Purvis [1961])*.

Maize plants that had been grown for 8 weeks on a molybdenum-deficient soil, contained in their tops only 0.07 ppm of molybdenum on a dry-weight basis, and yet showed no symptoms of molybdenum deficiencies. No increase in growth or change in the appearance of the foliage was observed after adding molybdenum to the soil at

1 ppm, though the concentration of molybdenum in the tops was increased to 1.03 ppm *(Johnson et al. [1952])*.

However, when seed that has inadequate reserves of molybdenum is sown on a soil deficient in this element, this may result in molybdenum-deficiency symptoms in maize.

Weir and Hudson [1966] found acute symptoms of molybdenum deficiency in maize plants grown from seed containing less than 0.02 ppm. Although the molybdenum content of maize is normally low, there is a minimal level needed for healthy seedling growth on low-molybdenum soils. Once the plants have survived the seedling stage, they become efficient extractors of molybdenum *[ibid.]*.

By growing maize in Mo-free mediums, deficiency symptoms were developed in the second generation. The germination of the Mo-deficient seed was at a slower and lower rate than for seed adequately supplied with the microelement. Some of the Mo-deficient seeds that did germinate, produced distorted seedlings which died at an early age. The leaves of plants from deficient seed have the following typical deficiency symptoms: the younger leaves first wilt, then die along the margins, and in some cases become twisted. The older leaves die at the tops, then along the margins, develop necrosis between the veins, and then die *(Peterson and Purvis [1961])*.

A mature crop of maize, that has produced 18.7 tons/ha of dry matter, accumalates only 0.0111 kg/ha of molybdenum. Harvesting the grain (which accounts for 7.4 tons/ha of dry matter) with a picker-sheller, removes 0.0055 kg Mo, whereas utilizing the crop for silage would remove 0.0088 kg/ha *(Benne et al. [1964])*.

An efficient method of applying Mo is to soak the seeds in a solution of sodium molybdate. A seed dressing containing sodium molybdate has been developed and it is claimed to give excellent results *(Climax [1959])*.

Weir et al. [1966] have shown that freedom from molybdenum deficiency in hybrid seed can be assured, by applying, where necessary, sufficient molybdenum to the parent seed crop (**Figure 34** – see page 110).

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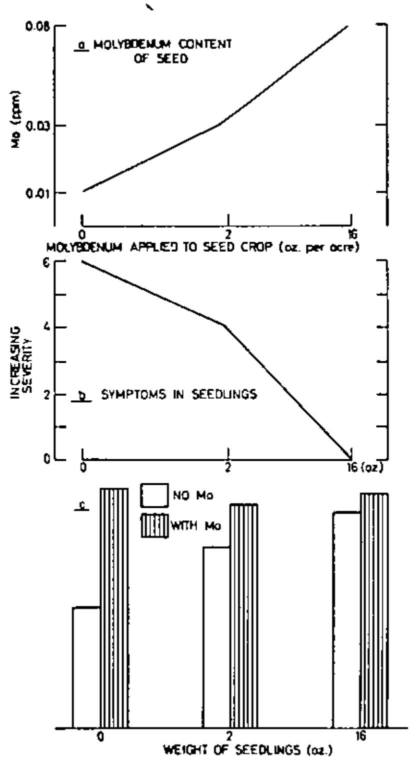

Fig. 34 Effect of soil applications of molybdenum to a parent crop of maize on the seed *(Weir et al. [1966])*. Soil applications of molybdenum to a parent crop caused (a) the molybdenum level of the seed to rise to a «safe» level; (b) symptoms in seedlings grown from this seed to be reduced to nil, and (c) molybdenum response in seedlings to become insignificant. By courtesy of the New South Wales Department of Agriculture.

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6. Nutrient supplying power of the soil

The quantities of fertilizers required for a crop are predicted in part on the basis of the amounts that may become available to the crop during its growth, from nutrient reserves in the soil. The nature of the parent material of the soil, and the processes of weathering, determine the potential reservoir of plant nutrients.

The chernozem soils, which have been formed under grass vegetation in humid, temperate climates, are typically high in organic matter and nitrogen, and are among the naturally most fertile soils in the world. These are the soils that form the heart of the Corn Belt in the United States *(Simonson [1957])*.

The latosolic soils that dominate in the equatorial belt of Africa, South America and southeastern Asia, are strongly weathered and leached to considerable depths. They are generally poor in plant nutrients, but have a high capacity to fix phosphorus in unavailable forms.

The limited leaching to which arid soils have been submitted, has resulted in the accumulation of mineral substances, including the important plant nutrients. These soils are therefore generally rich in calcium, potassium, magnesium, sodium, phosphorus and sulphur, and deficiencies of microelements are rare. However, the absence of leaching has also resulted in many cases in the accumulation of salts detrimental to plant growth, such as chlorides, carbonates, sodium and magnesium. Where the soluble salt content of the soil exceeds 0.5 per cent, soil productivity is adversely affected, and above 1–2 per cent, the soil is actually barren.

6.1 The soil as a source of nutrients

When potential yields are high, crop prices favourable, and fertilizers relatively inexpensive, the contribution of nutrients from the soil is generally only a fraction of the total requirements, and can therefore be more or less neglected in calculating the rates of fertilizer applications.

Conversely in less favourable conditions, when yields and crop prices are low and fertilizer prices relatively high, the nutrient supply from the soil assumes considerable importance, and must be estimated as accurately as possible.

6.2 Nitrogen

6.2.1 Forms and amounts in the soil

Parent rock does not contain any nitrogen; the primary source of soil nitrogen is the inexhaustible supply obtained directly or indirectly from the atmosphere. The amount of nitrogen in the ploughed layer of cultivated soils usually ranges from 0.02 to 0.4 per cent by weight *(Black [1968])*.

Some highly productive soils in the maize-belt ('Corn Belt') of the USA may contain over 6000 kg/ha of nitrogen in the ploughed layer. Maize roots, of course, range much deeper than the ploughed area, and the total nitrogen in the organic matter-rich horizon is estimated at 15 000 kg/ha and more. By contrast, less fertile soils may have only a few hundred kilograms of nitrogen in the soil profile *(Donald et al. [1963])*.

Most of the nitrogen in the soil is in organic form; it is generally assumed that organic matter contains about 5 per cent nitrogen. For the nitrogen present in the organic matter to become available, the organic compounds must first become mineralized. In the course of the growing season of a crop, about 1 to 2 per cent of the nitrogen may be released from soil organic compounds in temperate regions if moisture is not limiting. This could supply up to 80–100 kg N/ha in fertile soils.

The amount of organic matter present in tropical soils depends largely on the rate of annual additions. Investigations in Ghana indicate that long-fallowed forest soils have about 6 per cent organic matter in the top 15 cm and corresponding savannah soils, when burnt every year, only about 2 per cent. The amounts in the cropped soils depend on the intensity of cropping and frequently fall to 30–50 per cent of these values *(Nye [1963])*.

The level of organic matter in these soils can serve as a rough guide to nitrogen availability to crops. Crops on long-fallowed forest soils show little response to nitrogen in the first few years of cropping, while on savannah soils the response is almost always positive *[ibid.]*. The proportion of total nitrogen released to maize during one cropping season in Southern Rhodesia was found to vary from 2 per cent in clays to 4 per cent in sands, with appreciable variation depending on the past history of the field. A correlation coefficient of 0.83 has been established between mineralisable nitrogen and maize yields *(Saunder [1954])*.

6.2.2 Mineralisation of nitrogen compounds

From the foregoing it is clear that the total amount of nitrogen in the organic matter of the soil is not an indication of the amounts of this nutrient immediately available to a crop, but constitutes a reserve from which nitrogen may become available to plants – and not necessarily at a rate commensurate with the requirements of an actively growing crop, such as maize.

When organic materials, such as stable manure or crop residues, are added to the soil, the nitrogen they contain is immobilised, as far as crop plants are concerned, until the transformation of the organic matter into humus is completed and the microorganisms themselves die and decompose. Organic matter with a C:N ratio of 20–30 will itself supply all the nitrogen required for its decomposition; with a wider ratio (> 30), soil nitrogen will be immobilised, whilst with a ratio narrower than 20, nitrogen will be released at a fairly early stage of decomposition *(Tisdale and Nelson [1966])*.

This explains why the addition of undecomposed manure with a large proportion of straw, or the ploughing under of large quantities of stover or stubble, may cause a temporary deficiency of nitrogen, unless appreciable amounts of nitrogen fertilizers are added. Well-decomposed manures, on the other hand, in which the nitrogen:

carbon ration has been narrowed outside the soil, do not have this effect. Similarly, the ploughing under of an immature stand of leguminous plants will rapidly release nitrogen, which is immediately available to the following crop.

The decomposition of low-nitrogen organic matter requires a larger amount of nitrogen in soils with high temperature than in colder soils. A ton of straw that is ploughed into the soil in winter, may 'fix' 8–9 kg of nitrogen, whilst the same quantity in summer may require 10–14 kg *(Pinck et al. [1946])*. If other nutrients, besides nitrogen, are in short supply in the organic material to be decomposed, these may also be 'fixed' by the microorganisms. The ratio of carbon to nitrogen in the top-soil tends to be constant at approximately 10:1; in the sub-soil the ratio is usually narrower, approaching 5:1. This may be due to fixed ammonium in the sub-soil *(Cooke [1967])*.

The level of organic matter in the soil and the rate of its decomposition are markedly dependent on temperature and soil moisture regime.

The percentage of nitrogen in the soil tends to remain constant at a level which depends on the nature of the parent material, on the leaching characteristics of the soil (mainly determined by its texture) and on the management system adopted *[ibid.]*.

6.2.3 Additional sources of nitrogen

6.2.3.1 Symbiotic fixation by microorganisms

Prior to the production of low-cost nitrogenous fertilizers, the principal source of nitrogen for maize, besides farmyard manure, was derived from the inclusion of legumes in the crop rotation. Bacteria, belonging to the genus *Rhizobia*, are capable of fixing nitrogen in symbiosis with a legume host-plant. The rod-shaped bacteria are mobile in the soil; their mobility is, however, dependent on a sufficient supply of available phosphorus. The roots of leguminous plants excrete a substance which attracts the bacteria and promotes their rapid multiplication; the bacteria, in turn, produce a growth substance which enables them to penetrate into the roots through the root hairs. They proliferate rapidly and cause the formation of a swelling on the root: the typical nodule.

The bacteria obtain some of their nutritional requirements from the host plant: this provides them with the source of energy needed for fixing nitrogen. The nitrogenous substances formed by the bacteria are partly absorbed by the plant, and partly excreted into the soil, where they may benefit non-leguminous plants growing in association with the legume. However, most of the nitrogen derived from fixation by the bacteria is liberated only *after* the breakdown of the roots and their nodules, and not by excretion from the active root system.

The relation between bacteria and host plant, as decribed above, is typically symbiotic. However, there are circumstances under which the system is no longer one of mutual benefit.

Any deficiency in the supply of carbohydrates by the plant to the nodule bacteria, as a result of low light intensity, for example, will cause the latter to cease fixing nitrogen. The transport of sugars to the nodules breaks down if boron is deficient. The bacteria also require an adequate supply of calcium and phosphorus.

Fixation of nitrogen by clover was found in southern Australia to be proportional to the amount of superphosphate applied: approximately 80 kg of nitrogen for every

10 kg of phosphorus used *(Donald [1960])*. Whilst its exact role is not known, a minute supply of molybdenum is essential.

The bacteria will not be active in molecular nitrogen fixation if ample nitrate or ammonium is available in the soil. Nodule formation will also cease under these conditions.

Whenever conditions occur which limit or arrest molecular nitrogen fixation by the nodule bacteria, the relationship with the host plant ceases to be symbiotic, and becomes typically parasitic; the bacteria continue to obtain their nutrient supply from the plant, without the latter benefiting in any way from the presence of the nodule bacteria. However, under normal conditions, symbiosis is the rule, and parasitism the exception.

The plant supplies 15–20 per cent of the carbohydrates resulting from photosynthesis to the bacteria; in return it obtains 90–100 per cent of the nitrogen fixed by the bacteria *(Callaghan and Millington [1956])*. The total amounts of nitrogen fixed by Rhizobia may be quite considerable, and range from 50 kg/ha/year for subterranean clover in New South Wales *(Donald and Williams [1954])*, to 250 kg/ha/year for lucerne in Arizona *(Smith [1944])*. The principal factors influencing the quantities of nitrogen fixed are: the plant species, the effectiveness of the strains of bacteria involved, climate, nutrient levels in the soil and weed competition.

The amounts of nitrogen fixed by the plant are no indication of residual nitrogen that may remain available to the following crop. This depends primarily on the conditions under which the crop was grown, on the stage at which it was harvested, and the conditions prevailing during the period between harvesting the legume and the following crop. Legumes harvested for seed will leave very little or no residual nitrogen behind in the soil.

6.2.3.2 Non-symbiotic nitrogen fixation in the soil

Amongst the groups of microorganisms that are capable of fixing nitrogen from the air independently, are *Azotobacter, Clostridium* and several species of algae. Of these, *Azotobacter* is the most important. The fixed nitrogen becomes available to plants after the death of the microorganisms.

In the U.S.A., it has been estimated that the amount of nitrogen fixed by these organisms in temperate climates may reach approximately 7 kg of nitrogen/ha/year, and more so in warmer regions. Algae, especially the blue-greens, are considered to be capable of adding appreciable amounts of nitrogen to arid-region soils *(Fletcher and Martin [1948])*. In particular, after irrigation, an algal layer appears on the soil surface, that remains active in nitrogen fixation until the soil dries. After several such cycles, the amounts of nitrogen added may reach several kilograms per hectare.

6.2.3.3 Non-biological sources of nitrogen

Non-biological sources of nitrogen supply are the nitrogen brought down by rainfall, nitrogen fixation in the soil by sunlight, and absorption of ammonia from the air by cellulose and related materials as well as by organic and inorganic colloids in the soil *(Ingham [1950])*. Nitrogen gains from these sources are probably very small.

6.2.4 Contribution of soil nitrogen to maize production

Barber and Olsan [1968] point out that on many soils in the Corn Belt of the USA, the total nitrogen supply available to maize from organic matter decomposition, fixation by microorganisms, and broughtdown by rainfall, does not exceed 45 kg N/ha annually. Long-term experiments have shown that under continuous maize production, the nitrogen supply from the soil suffice to produce yields of about 2000 to 2500 kg/ha, without taking into account possible losses of nitrogen from the soil (see next paragraph). In order to achieve yield levels of 7000 to 12 000 kg/ha, the amount of nitrogen required ranges from 160 to 330 kg N/ha and more, and this can be obtained only by appropriate applications of nitrogen fertilizers.

6.2.5 Losses of nitrogen

6.2.5.1 Denitrification

Certain groups of microorganisms, active under anaerobic conditions and high temperatures, are capable of reducing ammonia and nitrates into volatile compounds that escape into the atmosphere.

Denitrification will cause appreciable losses of soil nitrogen in poorly drained soils *(Russell [1961])*.

6.2.5.2 Leaching

The nitrates that have been formed move freely in the soil: downward following rain or irrigation; upward, by capillary action, during the drying out of the soil. Large amounts of nitrogen may be leached beyond the reach of the roots or out of the soil, if rainfall is excessive or irrigation is not well controlled. Of all plant nutrients, nitrogen is the most easily lost to the plants. The amounts lost by leaching depend on time of application, soil texture, amount of rainfall or irrigation water applied and method of irrigation (see p. 86).The longer the period between nitrate formation (or fertilizer application) and uptake by the crop, the greater the proportion of nitrogen lost, whether by leaching or as oxides of nitrogen or as free nitrogen gas. Leaching losses are minimised in soils in which organic matter is being actively decomposed.

6.3 Phosphorus

6.3.1 Forms and amounts in the soil

Soil phosphorus is present in the soil in mineral and organic forms, usually in amounts far lower than nitrogen and potassium – usually varying from 0.1 per cent to 0.4 per cent and rarely more than 0.5 per cent *(Seatz and Stanberry [1963])*.

Most of the soil phosphorus is in the inorganic form, and its original source is the apatite group of minerals. The organic compounds containing phosphorus are derived from the decay of animal and plant bodies.

Most of the soil phosphorus is tied up chemically in a form that is not available to the crop in the course of the growing season; the amount of available phosphorus is not necessarily closely related to the total soil phosphorus, partly because the chemical nature of the phosphate compounds is not the same in all soils.

The quantity of phosphorus in the soil solution is always small, usually ranging from 0.1 ppm to 0.5 ppm in most soils *(Seatz and Stanberry [1963])*. Maize was found to make maximum growth at a concentration of 0.5 ppm in the soil solution, provided this level was maintained throughout the growing period *(Tidmore [1930])*.

Plants differ in their ability to obtain phosphorus from similar soils; maize is generally considered to be one of the 'poor feeders' for phosphorus *(Dickman and DeTurk [1940])*.

In California, it was found that phosphorus deficiencies were related to soil profile groups, as shown in Table 26.

Table 26. Relation of soil profile group to response of grain to phosphorus fertilizers *(Martin and Mikkelson [1960]*

Soil profile group	*Per cent of soils deficient in P*	*Characteristics*
Recent alluvial	19	Uniform texture, deep and permeable
Young alluvial	19	Uniform texture, deep and permeable
Older alluvial	30	Less well drained and permeable than above
Claypan	72	Strong accumulation at depth, poor drainage
Hardpan	83	Cemented hardpan layer, shallow, water logged
Upland	79	Developed *in situ* from weathering of parent rock

Most of the free-draining tropical soils (excluding alluvial soils) have been in place for a long time undisturbed by glaciation; this factor, in addition to the intensity of tropical weathering, is responsible for the predominance of kaolinite and of iron and aluminium oxides in their clay fraction, and is characteristic of these soils *(Nye [1963])*.

6.3.2 *Relative uptake of phosphorus from fertilizer and from the soil*

The young maize plant is almost completely dependent for its phosphorus supply on phosphorus fertilizer applied near the seed row at planting. As the plant develops it becomes more and more dependent on the soil phosphorus.

The degree to which the plant uses fertilizer phosphorus is not directly proportional to the amount applied. For example, at a rate of 22 kg P/ha, 3.6 kg was recovered in the above-ground parts of the plant; when four times as much phosphorus was applied, only twice as much was recovered *(Robertson et al. [1954])*.

The rapid decline in the amounts of fertilizer phosphorus taken up by the plant may be attributed to one or more factors:

1. Chemical or biological fixation of the applied phosphorus, which becomes progressively less available.
2. The fertilizer band becomes a less favourable medium for nutrient absorption, because of drying of the fertilizer zone through root action or evaporation.
3. The roots in the fertilizer band become cutinized.
4. The enlarged root system supplies all the phosphorus needs of the plant from soil phosphorus *[ibid.]*.

6.4 Potassium

The levels of both total and available potassium in the soil vary greatly. In general, soils low in total potassium will not supply adequate amounts of potassium for crop requirements. However, a high level of potassium in the soil may or may not supply sufficient available potassium to a high-yielding crop.

When levels of exchangeable potassium in the soil are very high or very low, it can be assumed that potassium supply will be adequate or insufficient, respectively. However, when the levels are in the intermediate range (100 to 200 ppm), the nature of the clay minerals in the soil will be the determining factor.

Micas and feldspars play a particularly important role in potassium supply because of their high potassium content, which may be as high as 7 to 8 per cent. The potassium of coarse micas or feldspars is slowly available to plants, whilst that in clay-sized particles is much more available, and may even be adequate for crop production *(Thomas and Hanway [1968])*.

Different types of clay have different initial concentrations of K ions, and are also different in their ability to retain K supplied by fertilizer applications to the soil. For example, illite clays are generally very rich in potassium, which can be progressively liberated, whilst kaolinite and chlorite are relatively much poorer in potassium. Further, different types of clay differ in their total absorbing surface and cation exchange capacity. For a given weight of clay, the absorbing surface and cation exchange capacity of montmorillonite, for example, are considerably greater than those of kaolinite. These characteristics have a considerable influence on the dynamics of potassium in the soil *(Ferrière et al. [1960])*.

Most soils of the temperate regions, as well as those characteristic of the Mediterranean and dry climates, act as excellent buffer systems which reduce to a minimum the fluctuations of potassium supply to the plants. By contrast, many soils of the humid tropics lack this buffering effect. Because of their low exchange capacity, high permeability and the considerable leaching to which they are submitted, very marked and sudden fluctuations occur in the potassium supply to the plants. These characteristics influence the dynamics of potassium in the soil, the potassium balance, and the methods of potassium fertilization.

The total exchange capacity of soils varies within quite wide limits but is on the order of 100 milliequivalent per kg of soil. The proportion of K^+ ions in relation to the total exchangeable cations is on the order of 5 per cent.

6.4.1 Forms and amounts in the soil

Potassium occurs in the soil in a number of forms, most of the K being unavailable to plants even after years of cropping:

(a) *Water-soluble:* the potassium which is present in the soil solution: this is a very small fraction of the total, and even in fertile soils this form cannot supply the major requirements of a crop.

(b) *Exchangeable:* the potassium held by the exchange fraction of the soil; this is the important reservoir of readily available potassium, though together with water-soluble potassium it represents only a small part – 1 to 2 per cent – of the total potassium of the soil *(Arnold [1960])*.

The exchangeable ions are hardly to be envisaged as occupying fixed points on the surfaces of the clay minerals but rather as forming a 'swarm', in continual movement. Use of radio-isotopes shows that rapid and continuous transfer of K^+ ions between the solid and liquid phases occurs, and that there is considerable transfer, though slower, between the exchangeable and non-exchangeable forms.

In mineral soils, the level of exchangeable K under moist field conditions is generally higher in the surface soil than in subsoils *(Hanway et al. [1962])*.

The amounts of exchangeable potassium in savannah soils in Africa are often very low; however, the levels of organic matter and exchange capacity are also low, so that the percentage saturation with potassium may be fairly high. This is probably the reason that crops on savannah soils rarely respond to potassium applications. For maize soils in Southern Rhodesia, *Saunder [1954]* stated that the potassium saturation should exceed 1 per cent. In Ghana, many soils have been found to have less than 0.1 meq of exchangeable potassium, although the percentage saturation ranged from 3 to 10 per cent *(Nye [1963])*.

(c) *Non-exchangeable* but slowly available, comprises the native soil potassium from partly weathered minerals. This forms the reserve from which the water-soluble potassium of the soil solution is gradually replaced, and therefore constitutes an essential element of the permanent fertility of the soil. The higher the temperature, the greater the release of non exchangeable K *(Burns and Barber [1961])*. Residual potassium from fertilizers is also in this form. The slowly available forms amount to 1–10 per cent of the total soil potassium *(Tisdale and Nelson [1966])*.

(d) *Inert:* present in the unweathered potassium-bearing parent minerals, and released at an extremely slow rate.

These groupings are somewhat arbitrary and the boundaries between them are not sharply delineated. The different forms tend to reach an equilibrium state: as potassium is removed from the soil by plants and by leaching, a transfer occurs from the slowly available forms; on the other hand, especially after applications of large amounts of potassic fertilizers, some of the potassium may revert to slowly available forms *(Hanway and Scott [1957])*.

It has been suggested that each soil has a characteristic equilibrium state *(Bray and DeTurk [1939])*. However, soil moisture content exerts a marked influence on the fixation and release of potassium, so that various states of equilibrium may occur in a given soil, depending upon its moisture content *(Luebs et al. [1956])*.

6.4.2 *Effects of drying soil on potassium availability*

Many soils, on drying, release fixed potassium to the exchangeable form. The reversibility of this process on rewetting differs widely according to soil type *(Luebs et al. [1956])*. A greater degree of reversion was found to occur in the least weathered soils *(Hanway and Scott [1957])*. These apparently have a larger capacity for releasing potassium from non-exchangeable forms *(Wood and DeTurk [1943])*. In highly weathered soils, adjustment to an equilibrium level proceeds very slowly *(Luebs et al. [1956])*.

Hanway and Scott [1957] report that subsoils release more K on drying than do the surface soils. Drying of both surface and subsoil, approximately doubled exchangeable potassium content *(Scott and Smith [1957])*.

The effects of alternate drying and wetting of the soil depend on the levels of potassium in the soil. An increase of exchangeable potassium usually occurs when the levels of soil potassium are low to medium. When the levels are high, the opposite may occur; the reasons for this phenomenon are not yet known *(Tisdale and Nelson [1966])*. *Attoe [1946]* found that whilst the drying of soils that had not been fertilized with potassium generally resulted in a quite considerable increase in the content of exchangeable potassium, the opposite occurred for soils that were fertilized with potassium prior to drying; in the latter case drying increased the rate of fixation of potassium. This fixation did not prevent the added potassium that had been fixed by drying, from being available for plant growth *(Dowdy and Hutcheson [1963])*. Drying soil had much less of an effect on P than on exchangeable K. Increases amounted to 10–11 per cent for fertilized plots and 18 per cent for unfertilized plots *(Grava et al. [1961])*.

6.4.3 Effects of thawing and freezing

Laboratory studies have shown that with alternate freezing and thawing in certain soils, a fraction of the fixed potassium is released into the exchangeable form. In soils having appreciable quantities of illite and high in exchangeable potassium, the opposite effect is observed, and part of the exchangeable potassium may actually be converted to the less readily available form *(Tisdale and Nelson [1966])*.

6.4.4 Contribution of soil potassium to maize nutrition

Plant species differ greatly in the amounts of potassium that they are capable of absorbing from the soil. In a comparison of four crops: maize, cotton, soybeans and groundnuts, potassium deficiency symptoms appeared first and more severely on maize. Whilst all crops responded in dry matter production to the application of potassium, the yield of dry matter of unfertilized maize was only 20 per cent of that of plants fertilized with potassium, whilst the corresponding figure for soybeans, for example, was 85 per cent.

All four crops absorbed more potassium than was applied in the fertilizer and the amount of exchangeable potassium in the fertilized soil was decreased to an extent almost as great as in the unfertilized soil *(Reid and York [1955])*.

6.5 Secondary nutrients

6.5.1 Calcium

The calcium content of soils varies more than does that of any other element. Calcium is a constituent of a number of primary rocks and minerals, which fall into five groups:

(a) Calcium present in the mineral particles, nearly all primary; (b) calcium carbonate, in general the most important source of calcium in soils; (c) calcium sulphate; (d) simple salts of calcium in the soil solution; and (e) exchangeable calcium.

Calcium carbonate ($CaCo_3$) occurs alone or often with magnesium in many arid regions (calcareous soils). Accumulations of calcium sulphate are found only occasionally in some arid soils (gypsum soils) and beds of gypsum occur at numerous locations. The most important form of calcium in soils as a whole is that associated with the exchangeable colloidal complex. Exchangeable calcium is considered readily available.

Calcium produces several specific effects, which result in the improvement of soil structure and in increased crop production. The leaching losses of calcium from soils depend on the quantities of calcium present, on the forms in which they are held, the amount of percolating water and the production of carbonic acid. In humid climates with high rainfall, leaching is high and the removal of calcium ions from the colloidal complex results in their substitution by hydrogen ions. In arid climates sodium ions frequently replace calcium ions on the colloids, resulting in soils with poor physical conditions.

In contrast to temperate climate soils, the liming of tropical soils, when the pH is not lower than 5, is rarely beneficial and frequently detrimental. Many tropical red clay soils have an excellent soil structure, probably due to the stable micro-aggregates found between iron oxide and kaolinite. Aggregation decreases as the pH rises, which may account for the unfavourable effect of liming on soil structure *(Nye [1963])*.

6.5.2 Magnesium

There is usually a very close relationship between calcium and magnesium in the soil. Magnesium carbonate is usually found in mixture with calcium carbonate, a dolomite ($CaCO_3MgCO_3$).

The exchangeable magnesium in the soil is derived from the wheathering of a number of minerals. Average amounts are 0.3 per cent in sands, 0.5 per cent in silts and 1.0 per cent in clays *(Millar et al. [1958])*. Magnesium deficiencies occur mainly on acid, sandy soils, in regions of moderate to heavy rainfall. Magnesium deficiencies in the soils of the clay regions are extremely rare *(Olson and Lucas [1966])*.

On soils of moderate or low exchange capacities, a level of 165 kg/ha of exchangeable soil magnesium appears to be generally adequate for maize. Where magnesium deficiencies do occur, adequate applications of magnesium sulphate or dolomite have been shown to give significant increases in yield of maize *(Key and Kurtz [1960])*.

6.5.3 Sulphur

Sulphur is present in the soil in both inorganic and organic materials. The total quantities found are extremely variable, and depend on the factors of soil formation and the amounts of clay and organic matter present. In well-drained soils, losses of sulphur due to crop removal, leaching and erosion may be substantial. However, sulphur may be added to the soil by rainfall, irrigation, and the application of various fertilizers, insecticides and fungicides. In the vicinity of industrial centres, sulphur deficiencies are rare *(Olson and Lucas [1966])*. Deficiencies of sulphur are usually associated with low soil organic matter, and are found on soils developed from sands and immature highly calcareous loess.

Crop responses to sulphur have been reported from equatorial Africa, Australia, Brazil, France, Japan, New Zealand, North America, Norway and Sweden *(Freney et al. [1962])*.

In an extensive series of field trials in North Rhodesia, there was strong evidence of sulphur deficiency. Adding flowers of sulphur at the rate of 27 kg/ha, in the presence of urea or ammonium nitrate, gave five-fold increases in maize yield over the control *(Vogt [1966])*.

6.5.4 *Micronutrients*

The greatly enhanced productivity of maize has considerably increased the demands of this crop for micronutrients. On soils on which no micronutrient deficiency problems have been encountered in the past, when yield levels were relatively low, deficiencies are frequently revealed at the higher levels of production that are now commonplace. These are usually more frequently encountered on coarse-textured soils than on more finely-textured soils, mainly because of their lower exchange and buffer capacity and lower capacity to hold organic matter *(Olson and Lucas [1966])*.

– *Boron*

The principal native soil mineral containing boron is tourmaline. Another mineral form is borax ($Na_2B_4O_7$). Boron is present as borate in very small amounts in the soil solution and as absorbed exchangeable borate. About 1–2 ppm are also found in the soil organic matter. Normally, soils contain from 10 to 20 ppm, of which about 10 per cent is water-soluble *(Vinogradov [1959])*.

Sandy soils in the humid regions, especially those with low organic matter content, are most likely to be deficient in boron, whilst this element may reach toxic levels in arid zone soils, in particular if they are irrigated with water with a relatively high boron content. Though maize is considered as semitolerant to boron, the maximum content of the soil saturation extract compatible with satisfactory growth is probably 1 ppm *(U.S Salinity Laboratory Staff [1954])*.

– *Iron*

Iron is extremely abundant in most soils, occurring in a large number of primary and secondary minerals. A small amount is found in the organic matter of the soil, and may have considerable nutritional significance.

Iron is absorbed from the soil in ionic form or as complex organic salts. Chlorosis, which is the typical symptom of iron deficiency in the plant, does not necessarily indicate a deficiency of this nutrient in the soil, but is proof of the inability of the plant to absorb soil iron. This happens most frequently on calcareous and alkaline soils. The lime-induced chlorosis is not due to the free calcium, but to the high pH which lowers the solubility of ferrous iron. Poorly aerated soils and high water tables are also conducive to making the soil iron unavailable to plants. In irrigated soils, Fe deficiencies may be alleviated by improved drainage and by increasing the intervals between irrigations *(Berger and Pratt [1963])*.

Iron deficiencies in maize are relatively rare, in contrast to other crops *(Olson and Lucas [1966])*. Nevertheless, the response of maize to iron is now observed in some areas *[ibid.]*. Iron deficiencies are generally found in soils with pH values above 7.0 under conditions of high moisture and poor aeration. This situation is frequently found in low-lying fields that have a high water table in the spring, and is generally associated with poor drainage. The presence of calcium carbonate reduces the availability of iron in the soil *(Chesnin [1963])*.

– *Copper*

The copper content of most soils is very low but soil fixation is minimal and a deficiency leading to crop problems is extremely rare in maize. Copper deficiencies are most likely to appear on acid, highly leached sandy soils, and on calcareous sands, especially if they contain considerable organic matter *(Olson and Lucas [1966])*.

Crops do not respond to copper fertilization if the soil contains more than 20 ppm Cu *(Lundblad et al. [1949])*.

– *Manganese*

Manganese occurs in the soil mainly as oxides and hydroxides. To be availabe, manganese must be in the reduced divalent state, availability being related to the degree of soil acidity *(Olson and Lucas [1966])*.

The exchangeable level should exceed 4 ppm *(Boken [1958])*.

Manganese deficiencies occur quite frequently on calcareous and alkaline soils, as well as on sandy soils. However, maize is able to grow normally at low levels of available manganese *(Olson and Lucas [1966])*.

– *Molybdenum*

Molybdenum is deficient in many soils in eastern Australia. Generally, molybdenum applications enhance the power of legumes to fix nitrogen, but do not enhance the growth of non-legumes *(Johnson et al. [1952])*. However, low reserves of molybdenum in seed grown in a low molybdenum soil may cause molybdenum deficiency symptoms in maize, when the maize is sown on a different soil.

Weir and Hudson [1966] found acute symptoms of molybdenum deficiencies on plants grown from seed containing less than 0.02 ppm. Although the molybdenum content of maize seeds is normally low, there is a minimal level needed for healthy seedling growth on low molybdenum soils. Once the plants have survived the seedling stage, they become efficient extractors of molybdenum.

– *Zinc*

Most of the zinc in the soil occurs in a non-exchangeable form, as part of the cristal lattice of clay minerals or in an organic complex. Water-soluble zinc is practically non-existent in the soil, whilst that in exchangeable form is usually less than 1 ppm *(Olson and Lucas [1966])*.

For normal maize growth, the required concentration in the soil solution is very small, probably no more than 0.1 ppm *(Thorne [1957])*.

Zinc availability declines with increasing pH *(Camp [1945])*.

Zinc deficiency is being encountered with increasing frequency in parts of the U.S.A. as a result of increased use of lime, large applications of high-analysis fertilizer and the high yields obtained by growing productive hybrids with improved cultural practices.

In research carried out on two soil types in Georgia – a sandy loam and a loamy sand – it was shown that though no visual deficiency symptoms were evident on any of the maize plants grown on the sandy loam, plant growth was increased by applications of Zn. On the loamy sand, all plants grown without Zn. showed symptoms of Zn-deficiency. These symptoms were increased by applications of lime or phosphorus and eliminated by applying Zn, whatever the form used. Under these conditions considerable increases in dry matter production resulted from the application of $ZnSO_4$: 166 per cent in unlimed soil and 210 per cent in limed soil *(Shukla and Morris [1967])*.

Maize grown on many of the dark-brown light clays and clay loams of southeastern Queensland often shows striking chlorotic symptoms 2–3 weeks after emergence. In some cases all leaves are affected, in others only the lower leaves show the deficiency symptoms. A foliar application of a 0.5 per cent zinc sulphate spray completely cured the deficiency symptoms and gave yield increases ranging from 24 to 76 per cent over untreated plants.

The optimum spraying time appeared to be about five weeks after emergence.

Zinc deficiency symptoms have also been observed in the Finistère region of France, on soils with a relatively high pH (6.75 to 7.3) and high levels of phosphorus (P_2O_5 sol in citric acid: 0.3 to 0.4 per cent). In these soils the Zn deficiencies appear to be associated with prior applications of high rates of lime and phosphoric fertilizers *(Coppenet and Duval [1965])*.

In an extensive investigation of zinc deficiencies in the Adour basin in France, *Dartigues and Lubet [1967]* established that there is a high probability of maize plants exhibiting zinc deficiencies when grown on soil with a pH higher than 6.4 and a zinc content of less than 40 ppm (total reseves) or 3.3 ppm of extractable zinc.

Zn deficiencies are associated mainly with loss of soil organic matter by erosion, or following land grading for irrigation or soil conservation works *(Chesnin [1963])*. For example, zinc deficiencies in maize have been reported when the crop was grown on land levelled for surface irrigation in certain areas of North Dakota *(Grunes et al. [1961])*. The exposed subsoils were found to be low in acid-soluble Zn and, as a result, low levels of Zn were found in the tissues of maize plants grown on these soils. Applications of $ZnSO_4$, either sprayed on the plants or applied to the soil, cured the Zn-deficiency.

6.6 The soil as a storehouse of nutrients

6.6.1 Ion adsorption

The soil colloids – clay and organic matter – are capable of both holding and gradually releasing cations, such as ammonium, potassium, calcium and magnesium; hence their importance for plant nutrition.

Under normal conditions, the soil colloids have a negative charge, and therefore attract cations of the opposite charge – commonly hydrogen, in addition to the other cations mentioned above.

6.6.2 Ion exchange

Exchanges occur between the cations held by the soil colloids and those present in the soil solution. This reversible process is called 'ion exchange.' The total of all the electronegative charges on the colloids represents the 'cation exchange capacity' of the soil.

The exchange capacity is normally expressed in terms of milliequivalents* per hundred grams of dry material (colloid or soil). The kaolinite colloids, due to their lattice structure and chemical nature, generally have a relatively low adsorptive capacity: 3–15 meq/100 g whilst the adsorptive capacity of the montmorillonite and illite clays is many times greater (80 to 150 meq/100 g). Organic colloids have a still higher adsorptive capacity, around 200–400 meq/100 g *(Webber and Elrick [1969])*. Thus, the adsorptive capacities of soils vary with the amount and kinds of clay they contain and with their organic matter content. The nature of the cations that predominate in the colloidal complex of the soil determines the pH (soil reaction): if hydrogen is present in considerable amounts in the complex, the soil will be acid; if calcium or magnesium predominates, the soils are in general neutral and provide a favourable milieu for most crops; if sodium and potassium predominate, the soils will be alkaline, a very frequent occurrence in arid and semi-arid soils.

In kaolinitic tropical soils the cation exchange properties of humus are of particular importance, since the humus contributes the larger part of the exchange capacity in the top soil – about 250 meq per 100 g of carbon *(Nye [1963])*.

The cations held by the soil may be readily removed from the soil colloids by simple exchange with other cations in solution, and are therefore called 'exchangeable cations.' For example, if a potash fertilizer such as $K_2SO_4$is added to a soil in which considerable calcium is associated with the colloids, the K ions will displace at least part of the Ca ions. The proportions of Ca ions displaced will depend on the amount of K_2SO_4 applied or, in other words, on the concentration of the K ions in the soil solution.

Most cation exchange reactions in the soil are reversible, though certain ions, such as potassium and ammonium, attached to specific exchange position, are held more strongly than others. Calcium, on the other hand, is not held very strongly by the soil colloids and is easily replaced by plant nutrients, such as potassium or ammonium, when these are added to the soil as fertilizers. They, in turn, are held sufficiently strongly to prevent their loss by leaching, but still remain easily available to plants. The amount of ions that can be held on the surface of the soil particles is limited, so that the total amount of bases in the soil liable to be adsorbed may be greatly in excess of the amounts actually adsorbed. The capacity of the soil to hold and exchange cations is therefore a measure of the ability of the soil to store plant nutrients and

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* The use of chemical equivalents (measured as milliequivalents – meq) which express the combining or replacing power of ions, is more desirable as a value discussing uptake of ions by plants or plant composition, than is the use of percentages, which tend to minimize variations in certain elements, such as magnesium, while accentuating them in other elements, such as potassium. Because of the respective equivalent weights of these two elements, over three times as much potassium as magnesium is required on a weight basis to obtain equal chemical equivalency.

make them available to the growing plants, according to their requirements; it is therefore an important factor in soil fertility.

6.6.3 Base saturation

A concept of great practical significance is the degree of 'base saturation', which is determined by the percentage of the total cation exchange capacity of the soil occupied by basic cations (calcium, magnesium, sodium, potassium).

For a soil of any given organic and mineral composition, the availability of the basic cations to plants, the pH level and fertility level increase with the degree of base saturation.

In general, the degree of base saturation of uncultivated soils is higher in arid than in humid regions, and higher in soils derived from limestone or basic igneous rocks than in those formed from sandstones or acid igneous rocks *(Tisdale and Nelson [1966])*.

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7. Dynamics of nutrient uptake and distribution in the plant

7.1 Nutrient absorption

The process of nutrient absorption involves four steps: a movement of ions from the solid phase of the soil into the soil solution, the movement of a nutrient from any point in the soil solution to the root surface, the passage of the nutrient into the root, and the translocation of the nutrients from the roots to the aerial parts of the plant.

$$\mathrm{M\ (soil)} \rightleftharpoons \mathrm{M\ (solution)} \rightleftharpoons \mathrm{M\ (vicinity\ of\ root)} \rightleftharpoons \mathrm{M\ (absorbed)} \rightleftharpoons \mathrm{M} \longleftarrow \mathrm{(plant\ top)}$$

Each of these steps takes place at a rate that is controlled by measurable factors of either soil or plant. One or more of these transfer steps may be rate-limiting for the whole process *(Fried and Shapiro [1961])*.

Hope [1960] lists the following external and internal factors influencing the amounts of nutrients taken up by plants and their interactions:

Soil factors	*Internal (plant) factors*
Availability (plant-soil relations)	Nature and extent of the root system
Nature and concentration of the ion	Free space available to the ion
Temperature	Number and concentration of ion-exchange centres
Oxygenation	Rate of transpiration
Water status	Age and rate of growth
Presence of other ions	Rate of respiration
pH	Internal ion status

7.2 Movement of ions from the soil into the soil solution

The soil contains a liquid phase which always has electrolytes in solution. This liquid phase is called 'the soil solution.' Having anions dissolved in it, it must also contain cations, and in particular potassium, whose concentration varies from about 2 mg per litre up to 50 mg per litre in cultivated soils. According to the magnitude of the cation exchange capacity, the exchangeable and dissolved K^+ ions will partition themselves differently. Thus in a sandy soil, not containing much clay, a relatively high proportion of the K^+ ions will be found in the liquid phase, and the reverse will apply to a clay soil.

Certain plant nutrients are frequently present in the soil in quantities that greatly exceed the requirements of a growing crop. For example, a soil containing 0.10 ppm

P_2O_5 will have a total of approximately 14 tons of P_2O_5 per hectare in the root zone, to a depth of one metre. The requirements of a single crop of maize do not exceed 50 kg P_2O_5 per hectare, and yet they will not necessarily be met from the phosphorus reserves of the soil. This is indicated by the frequently considerable response of a growing crop of maize to phosphorus fertilizers, indicating the low availability of the soil phosphorus to the plant.

The concentration of phosphate in the soil solution is usually low and is almost independent of the moisture content of the soil. The availability of phosphorus to the crop will therefore depend on the speed with which the phosphorus removed from the soil solution is replaced from the soil reserves.

Most of the cations held by the exchangeable complex of the soil are only very slowly soluble. At a given time, only minute amounts of these nutrients are in solution in the soil water, even in very fertile soils.

However, the cations in exchangeable form are usually far more numerous than those in the soil solution, so that they constitute a source from which the nutrients in the soil solution can be replenished.

An exchangeable equilibrium is established between ions held by the exchange complex of the soil and the soil solution; ions migrating between the two phases form what is called 'the labile ionic pool' *(Russell et al. [1961])*. As ions are taken up by the plant from the soil solution, this equilibrium is upset; new equilibria are then established by ions moving from the surfaces into solution.

The soil solution is therefore the intermediary whereby nutrient ions move from the soil into the plant, and the rate of uptake of a nutrient is a function of the concentration of the ion in the soil solution.

The availability of cations to plants is controlled by the following factors:

(1) The concentration of ions in the soil solution, which depends on the nature of the colloidal fraction and on the degree of their base saturation.

(2) The influence of one adsorbed ion on the release of another from the colloid surface. Polyvalent ions are held more strongly than univalent ions; hence, when the soil colloids hold large amounts of potassium and NH^{++}, plant deficiencies of calcium or magnesium may develop.

By contrast, practically all the nitrate and chloride present in the soil is in the soil solution, so that their concentrations vary inversely in relation to soil moisture content *(Russell [1961])*.

Whereas in humid regions the soil solution is very dilute and its osmotic pressure does not normally exceed one atm. even at wilting-point *(Russell [1961])*, the situation is entirely different in the irrigated soils of the arid and semi-arid lands, in which calcium and sodium salts, in particular, accumulate. Under these circumstances, the osmotic pressure of the soil solution may have an appreciable effect on crop growth, especially with increasing soil moisture tension.

7.3 Movement of ions from soil solution to root surface

7.3.1 Nutrient mobility

Bray [1954] defines nutrient mobility as 'the overall process whereby nutrient ions reach sorbing root surfaces, thereby making possible their sorption into the plant.' This concept encompasses two complementary process of equal importance: (a) the solution or exchange of nutrients and their movement to root surfaces, and (b) the growth or roots and extension of the sorbing root surfaces into areas where the nutrients occur. These two process together largely determine the soil nutrient supply to plants.

The availability* of a nutrient therefore depends not only on its chemical and physical nature, but also on the ability of the plant to 'forage' for the nutrient with its root system. For example, a maize plant growing in a container may take up practically all the exchangeable potassium present, because of the high concentration of roots in relation to the amount of soil, whilst under field conditions only 5 to 20 per cent of the exchangeable potassium might be removed from the same soil. Thus nutrient availability is dependent on soil – plant relationships.

7.3.2 Relative mobility of the principal nutrients

Nitrate nitrogen is highly soluble: it is not markedly adsorbed by the soil or by organic matter and is therefore the most mobile and hence available form of nutrient in the soil. It moves freely with the soil water and can be easily leached by rain or irrigation beyond the root zone, or it can move back to the soil surface as the soil dries. Because of the high mobility of nitrate nitrogen, plants can take it up very rapidly and deplete the soil nitrate to a very low level within their root-feeding zones. When the soil dries, the nitrate may be temporarily immobilised.

In soils of the humid regions, which have sufficient clay and organic matter, nutrient ions such as potassium, calcium and magnesium that are held on the surfaces of negatively charged colloidal clay and organic matter are relatively immobile. They are in equilibrium with the cations in the soil solution, by which they can be replaced. However, in the humid tropics, because of the low exchange capacity of most soils and their considerable permeability, the mobility of potassium is very high, and approaches that of nitrate nitrogen.

The unadsorbed ions such as nitrate and sulphate have a relatively high mobility in these soils, and the cations may move as companion ions of the unadsorbed ions.

Potassium in a clay soil is a relatively immobile nutrient. Although it is highly available at the root surface, its availability decreases rapidly with distance from the root, because of difficulty of movement of potassium through a charged soil system. As nearby exchange surfaces are depleted, these compete with the roots for any new supply of potassium.

7.3.3 Relation between nutrient mobility and net soil nutrient requirement

As the plant roots deplete the nutrient content of the soil at the root surface, the area of depletion about a plant root will depend on the mobility of the nutrient.

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* The available forms of a nutrient in the soil have been defined as those forms whose variations in amount are responsible for significant variations in yield and response *(Bray [1954])*.

Plant roots can remove practically the entire supply of the relatively mobile nutrients within their root zone. The 'net' soil nutrient requirement is therefore in this case close to the amount contained in the crop, if leaching and other losses from the soil are excluded.

By contrast, effective removal of relatively immobile nutrients occurs only in the soil that is actually in contact with the root surface, constituting only a small fraction of the total soil volume of the root zone. Plants can therefore remove only a fraction of the relatively immobile nutrients present. The amounts of these nutrients that must be present for maximum yields must therefore be several times greater than the amount actually taken up by the crop. Uptake decreases rapidly with distance from the root surface, and the total amount removed is usually limited to a fraction of the total nutrient supply present *(Bray [1954])*. It is for this reason that maize does not usually absorb more than 10 to 20 per cent of the phosphorus applied in fertilizers, and somewhat more of the potassium, which is more mobile than phosphorus. The remaining phosporus and potassium will be taken up in due course by the following crops.

In the concept developed by *Barber [1962]*, plant nutrient availability in a soil is determined principally by the rate at which the nutrient can move through the soil to the root surface. The concentration of available nutrients at the root surface will depend on the balance between the rate of movement to the root surface and the rate of absorption by the roots. At any one time it may be greater or less than the average concentration of the soil environment **(Figure 35)**.

As the plant root absorbs ions from the immediate vicinity of the root surface, a concentration gradient is established between the root surface and the surrounding soil, unless the ions removed are immediately replaced. Barber enumerates the following factors as affecting the concentration gradient that is established for a specific ion:

a) the initial concentration of the ion in the soil solution;
b) the rate of uptake of the ion per unit of root surface;
c) the rate of diffusion of the ions to the root surface;
d) the rate of movement of the ions to the root surface by mass-flow;
e) the rate of diffusion of the ion along the surfaces of soil particles;
f) the rate of replenishment of the ions associated with other ions in solution from ions held by the soil; and
g) the capacity of the soil to replenish the ions removed from the soil solution.

7.3.4 Mechanisms whereby nutrients reach the roots

There are three principal mechanisms by which nutrients in the soil may reach the roots: (a) the root may grow to the nutrients, (b) the nutrients may be carried by mass-flow in the water absorbed by the roots, and (c) the nutrients may diffuse from the soil to the root. Nutrient absorption by the root will lower the concentration in the soil at the root surface and thereby create the gradient along which the nutrients will diffuse *(Barber et al. [1963])*.

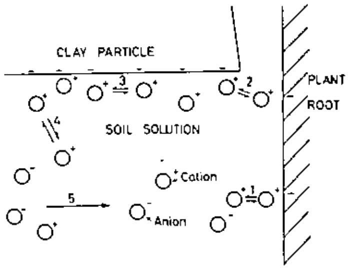

Fig. 35 A diagrammatic sketch of the processes involved in the movement of cations to the root surface: (1) solution diffusion; (2) diffusion from the particle to the root; (3) particle diffusion; (4) replenishment; and (5) mass-flow *(Barber [1962])*. By courtesy of the State University, New Brunswick, N.J.

7.3.5 *Role of root growth to the nutrients*

In Table 27 are shown the amount of major nutrients in the 0–150 cm layer of a fertile, silt-loam soil in Indiana, as well as the nutrient requirements of a 8000 kg/ha crop of maize.

Table 27. The relationship between the nutrient requirements of maize and the maximum amounts the roots would contact *(Barber et al. [1963])*

Nutrient	Amount available in a fertile soil (kg/ha)	Amount roots would reach (kg/ha)	Nutrient requirement of maize crop (Yield = 8000) (kg/ha)	Percentage of required nutrient that roots may contact
Nitrogen	330	10	165	6
Phosphorus	110	3	33	10
Potassium	330	10	110	9
Calcium	4400	132	44	300
Magnesium	825	25	33	80

The roots of maize occupy about 1 per cent of the total volume of soil in the top 18 cm. *Barber et al. [1963]* assume that the roots will reach 3 per cent of the available nutrients in the soil and that they are capable of absorbing the total amount of available nutrients. The amounts of macro nutrients that can be taken up as a result of root growth would range from 6 per cent for nitrogen to 9–10 per cent for phosphorus and potassium.

7.3.6 *The role of mass-flow in providing nutrients for maize*

The removal of water from the soil by the plant reduces soil moisture in the vicinity of the roots, and causes water to flow towards the roots. The term 'mass-flow' is used by *Barber [1962]* to indicate the movement of ions being carried along by this water. Wherever gradients occur, there is movement of ions from one phase to the other.

This movement is called replenishment by *Barber*. The two phases are not in equilibrium in the vicinity of the root,because of the dynamic nature of the system.

7.3.7 Movement of nutrients to the roots by mass flow

The amounts of nutrients that are moved to the plant root by mass flow depend on the amount of water taken up by the plant and the nutrient content of the water.

Table 28. Significance of mass-flow in providing nutrients for maize in the North Central United States soils *(Barber et al. [1963])*

Nutrient	Average content of maize (ppm)	Mode of saturation extract (ppm)	Mode x 500*	% supplied by mass flow
Calcium	3 000	30	15 000	500
Magnesium	2 000	25	12 000	625
Potassium	20 000	4	2 000	10
Phosphorus	2 500	0.05	25	1

* Mode: In the calculations in the table, the authors have assumed a value of 500 lbs of water used per lb of dry matter produced.

Mass-flow could supply an overabundance of the Ca and Mg required by maize and most of the mobile nutrients such as N, but would supply only a small part of the K and P requirements. On many soils, Ca and Mg would therefore tend to accumulate around the main roots, as mass-flow brings more of these elements than the plants can absorb.

7.3.8 Movement of nutrients to the root by diffusion

An adequate rate of nutrient uptake by the plant cannot be maintained unless the nutrients removed from the soil solution are replenished with sufficient rapidity. Whilst the soil does act as a buffer to maintain the level of nutrient ions in the solution, its capacity to do so in localised regions is limited.

In particular, the depleted soil particles near the root surface usually do not have sufficient nutrient ions available to maintain the solution concentration at the desired level at that point.

As the soil solution does not generally flow rapidly past the root, renewal of the ion supply will be dependent on ion diffusion towards the root *(Barber [1968])*.

Since neither mass-flow nor root growth can provide the maize plant with its full requirements of P and K, these must reach the root by diffusion, and this is the mechanism that supplies most of the P and K on many soils.

Diffusion occurs in the water films covering the soil particles, along a concentration gradient of the nutrient. The higher the water content and the thicker the films around the soil particles, the easier is the diffusion of nutrients to the roots. At a given soil water content, the rate of diffusion is increased by higher nutrient concentrations in the soil, by increased temperatures, and by reduced viscosity of the solution.

As it is difficult to calculate the contribution of diffusion in providing nutrients to the roots, it is assumed that the difference between the total amount taken up by the plant and that supplied by root interception and mass-flow was obtained as a result of diffusion.

Differences in availability between soils having the same level of available potassium will probably be due to differences in diffusion rates in these soils.

Soil tests for available nutrients must take into account the properties of the soil which affect the three processes involved in moving nutrients to the root surface.

7.3.9 Relative importance of mass-flow and diffusion

There is no general agreement on the relative importance of mass-flow and diffusion in supplying ions to the plant roots.

Shapiro et al. [1960] studied the effect of soil water movement versus phosphate diffusion on the growth and phosphorus content of maize. They observed that the diffusion process alone was unable to renew phosphorus at the root surface as fast as the observed rate of uptake. They therefore conclude, that, in contradiction to the opinion of *Barber et al. [1963]*, soil water movement probably accounts for a much greater transfer of P to the root surface than does diffusion.

Which of the processes will have the greatest effect on availability for a specific nutrient will depend on: (a) the concentration of the nutrients in the soil solution moving to the roots as a result of water absorption by the plant root, (b) the amount of water absorbed, which determines the flow rate of this water; and (c) the rate of uptake of nutrients by the plant root. When the amount of a nutrient moved to the root is greater than what the root can absorb, the nutrient accumulates at the root – soil interface. In this case mass-flow would be the dominant factor in determining availability.

Using maize seedlings grown in solution cultures, *Sabet and Abdel Salam [1966]* found that plant growth and phosphorus content were a function of both the rate of flow the nutrient solution and the concentration of phosphate. Similar trends were obtained with potassium.

In an investigation on the mechanism of movement in, and uptake of, potassium from the soil by maize roots, *Walker and Barber [1962]* found that when the roots start growing and most of the absorption is through new roots, ease of replacement from the soil affects uptake of potassium. After most of the potassium in the vicinity of the root is absorbed, mass-flow will no longer bring sufficient K to supply the plants requirements. Diffusion into the plant becomes the dominant factor determining availability of potassium and the rate at which it will move to the root.

Intensity of supply of K to the plant roots will depend primarily on its concentration in the soil solution. This in turn depends on the ability of the soil to replace K ions in the soil solution, as it is depleted. *Nemeth et al. [1969]* have shown that this ability is influenced to a considerable extent by the content of clay and silt, so that K supply cannot be estimated from the exchangeable K, without taking into account soil texture or K saturation of the inorganic ion exchangers.

Increased soil moisture levels improve the movement of potassium by diffusion.

The final process of absorption of the nutrients is through the water films surrounding the plant roots and colloid particles. It is assumed that the thicker the moisture films, the greater the uptake of ions *(Danielson and Russell [1957])*. There is therefore an overlap of ionic influences and the exchange properties of colloidal systems may become limiting for the uptake of ions by rapidly growing plants *(Marshall [1961])*.

7.3.10 Summary

The relative significance of root interception, mass flow and diffusion in supplying maize with its nutrients requirements from a typical fertile silt loam soil is summarised in Table 29.

Table 29. The relative significance of root interception, mass-flow, and diffusion in supplying corn with its nutrient requirements from a typical fertile silt loam soil *(Barber and Olson [1968])*

Nutrient	Amount needed for a yield of 9500 kg/ha	Approximate amount supplied by:		
		Root interception kg/ha	Mass-flow kg/ha	Diffusion kg/ha
Nitrogen	187	2	185	0
Phosphorus	38	1	2	30
Potassium	192	4	38	150
Calcium	38	66	165	0
Magnesium	44	16	110	0
Sulphur	22	1	21	0
Copper	0.1	0.01	0.4	0
Zinc	0.3	0.1	0.1	0.1
Boron	0.2	0.02	0.7	0
Iron	1.9	0.2	1.0	0.7
Manganese	0.3	0.1	0.4	0
Molybdenum	0.01	0.001	0.02	0

7.3.11 Passage of nutrients into the root

Three mechanisms are known whereby ions may enter the roots: (a) passive absorption by diffusion, (b) active absorption as a result of a metabolic process requiring energy, and (c) by exchange.

7.3.12 Passive absorption

The cell walls of the epidermis of the root contain cellulose fibres and pectic materials as main constituents. The cellulose acts like a sponge into which the solution can diffuse continuously; this volume and any voids that are filled are called *the water free space.*

Passive absorption consists in the diffusion of ions from the surrounding solution, into the so-called apparent free space*. This process occurs without expenditure of

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* *Apparent free space:* The volume of tissue into which the electrolyte apparently moves to equality of concentration with the outside by free diffusion; this includes intercellular spaces, wet cell walls, non-living cells and some parts of the cytoplasma *(Robertson [1958])*.

metabolic energy. It may precede or occur simultaneously with active absorption *(Barber [1968])*. The process is influenced mainly by ionic concentration and interrelationships between ions.

7.3.13 Active absorption

The pectic materials, contained in the cell walls of the root epidermis, are acid, having carboxyl groups which ionize to give H^+ and anions held in the wall structure.

These pectic materials hold cations by exchange, and because of their anionic character tend to exclude anions. The salt character of the pectic materials creates a Donnan system* for salt distribution and are therefore called the *Donnan space of the root*.

Inside the metabolically inactive wall of cellulose fibres and pectic material, the cells have an external membrane, the plasmalemma, which is probably the major barrier tissue which limits uptake rates of nutrients *(Hendricks [1966])*.

Active absorption consists in the passage of ions into the roots against concentration gradients.

7.3.14 The carrier-theory

There is generally wide agreement that the active absorption of ions by the roots involves the operation of carriers. The essential features of this concept are that the ions are attached to carrier molecules, that the resulting carrier-ion complex is able to move through a barrier of limited permeability to free ions intervening between an outer and an inner phase, and after the passage is completed, the ions are released from the carrier into the inner phase. The carriers themselves return to the outer phase.

This process is highly selective: certain ions compete for the same carrier, whilst others use different carriers. For example, calcium competes with strontium for the same carrier, but not with potassium, as they have different carriers.

Competition of certain ions for the same site is possibly one of the basic reasons for antagonisms between ions. For example, maize shows a marked selectivity for potassium when it is supplied together with sodium. The rate of absorption of potassium, from a solution in which both ions were supplied together at a constant potassium concentration of 1.6 meq/l, was twice as large as it was for sodium. Whilst Na-absorption was strongly inhibited by excess K, only part of the K-absorption was inhibited by excess Na *(Bange [1959])*.

Bange [1959] postulates that two carriers are involved in K-absorption: one that is able to transport K only, and for which Na shows hardly any or no affinity; and a second carrier capable of transporting both K and Na and for which these ions compete, if supplied together.

7.3.15 Factors affecting nutrient uptake

Active nutrient uptake by the roots takes place against a concentration gradient, and therefore requires an expenditure of energy by the root cells. The source of the

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* *Donnan system:* If a solution containing a salt with a non-diffusible ion is separated from a solution of an electrolyte containing diffusible ions by a semipermeable membrane, then at equilibrium, an electrostatic difference of potential will be established between the two solutions separated by the membrane. A difference in osmotic pressure will also be established at equilibrium *(Donnan [1911])*.

energy is provided by the breakdown of sugars. This energy-consuming metabolic process in the plant depends on respiration. Hence, all factors that regulate respiration, such as temperature, glucose content of the root, concentration of oxygen and of carbon dioxide in the soil, will also affect the active uptake of ions *(Schuffelen [1954])*. The removal of nutrients from the root to the aerial parts of the plant will reduce the nutrient concentration in the root and thereby promote an increased uptake by respiration energy, especially if translocation is the limiting factor *(Barber [1962])*.

7.3.16 Transpiration

In earlier work on the effect of transpiration on nutrient uptake an excellent correlation was observed between the amount of water transpired and nutrient uptake. However, in more recent studies, after a respiration inhibitor was added to the system, it was found that the relationship between transpiration and uptake was usually affected *(Fried and Shapiro [1961])*.

Ions and water can move into the plant independently, as a result of entirely different physical-chemical forces. Water moving to the roots carries ions in solution. A portion of these ions is taken up by the plant root by an independent mechanism, and the remainder is left behind at the root surface or on the soil particles and can therefore serve as a future source of supply *(ibid.)*.

There appears to be little doubt that, at least in plants with a high salt content, increased transpiration – and hence increased water absorption, is accompanied by increased absorption of nutrients. *Smith [1957]*, for example, found that increasing the transpiration of maize seedlings already high in salt increased the absorption of ^{32}P and its translocation to the shoots (**Figure 36**).

The question remains as to whether the increased absorption of the nutrients results entirely from the increased active transport or is at least partially due to passive movement in the transpiration stream. The fact that the concentration of salt in the xylem sap often becomes considerably higher than in the medium surrounding the roots supports the view that active transport of ions is an important part of the

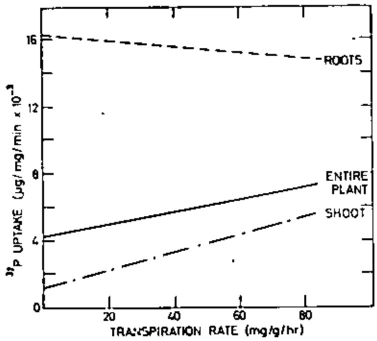

Fig. 36 Effect of increasing rate of transpiration on the accumulation of ^{32}P in the shoots and roots of maize seedlings *(Smith [1957])*. An increase in transpiration increased the translocation of ^{32}P from the roots to the shoots. By courtesy of Duke University.

process *(Kramer [1969])*. On the other hand, as most of the water passes through a protoplasmic filter, the latter has a marked regulatory effect on the movement of ions, as neither the concentration nor the composition of the xylem sap is identical to the external solution.

The rate of uptake of an ion in relation to the rate of water absorption and the mechanisms involved may vary with the growth stage of the plant. Young plants have a greater concentration of nutrients in their tissues and therefore, presumably, absorb more nutrients per unit of water than at later stages of growth. This would explain, at least partly, why a phosphorus deficiency may occur in young plants and disappear at a later stage of growth *(Barber [1962])*.

The data presented in Table 77 (chapter 14) on the ratio between nitrogen uptake and transpiration *(Shimshi [1966]* indicate that nitrogen is carried into the plant in direct proportion to the water flux. Theoretically, a reduction in transpiration rate could cause nitrogen deficiency, at relatively low nitrate concentrations in the soil solution, which would not occur at the same nitrate concentrations if transpiration were more intensive. This does not occur frequently, for the most usual cause of reduced transpiration is moisture stress, which also reduces growth, so that the nitrogen supply is no longer limiting. However, under conditions of high air humidity, transpiration may be reduced without a concomitant reduction in growth; under these circumstances, nutritional deficiencies could develop because of critically low concentrations of nitrate in the vicinity of the roots, as a result of the reduced mass flow *(ibid.)*.

7.3.17 Effect of potassium on transpiration

In experiments with maize it has been shown that a deficiency of potassium impairs the transpiration of the leaves *(Peaslee and Moss [1966])*. When the cut leaves were treated with a solution of KNO_3, leaf porosity slowly increased until it approached the level of normal leaves. *Fujino [1959]* suggests that ATP promotes the active accumulation of potassium in light into the guard cells of the stomata, this results in increased osmotic value, which induces swelling and consequently the opening of stomata. In the dark, ATP-ase activity causes the guard cells to lose potassium and the stomata to close.

7.3.18 Yield

Whilst it may appear at first sight logical to assume that total nutrient uptake is proportional to yield, this is not necessarily so.

Each nutrient has a critical level below which productivity is sharply reduced. Below this level, the reduction in growth may actually increase the concentration of the deficient nutrients in the plant tissues. When a nutrient is available in quantities far above the critical level, so-called luxury consumption may occur, in which the concentration of the nutrient increases in the plant without any increase in yield. When a limiting factor other than nutrition is eliminated, yields may increase considerably, without a parallel increase in nutrient uptake, whose concentration in the plant parts is thereby diluted.

The most frequent reason for discrepancies in the calculation of nutrient uptake based on yield is that the latter is usually assessed in terms of grain yield. However, the proportion of grain to total production of dry matter may vary considerably, from 30 per cent to more than 60 per cent *(Barber and Olson [1968])*, so that the same yields of grain may represent considerably different rates of nutrient uptake.

7.3.19 Exchange capacity of roots and nutrient uptake

The roots of plants can also be considered as colloidal systems, as are soils, and their cation exchange capacity (CEC), is one of their most important characteristics. This value represents the maximum of cations that can be fixed on the root surfaces, and is generally expressed in terms of meq per 100 g of dry matter *(Fréjat et al. [1967])*. As the surface of the roots has a negative electric charge, their ability to absorb cations is quite considerable. According to *Drake and Campbell [1956]* the cation exchange capacity of maize roots is 26.0 meq per 100 g dry matter.

The mineral nutrition of plant can therefore be considered as the result the interaction between two antagonistic colloidal systems, i. e., those of the root and the soil.

Jenny and Overstreet [1939] suggested that ions may move directly from the exchange site on a soil particle to the exchange site on the plant root without association with an ion in the soil solution as an intermediary step. They also suggested that ions would diffuse within the double layer on the soil particle surface. Ion uptake by the plant would create a concentration gradient so that ions might then diffuse along the soil particle toward the root.

7.3.20 Translocation of nutrients from the roots to the aerial parts of the plant

The vertical nutrient transport in vascular plants is determined by transpiration and by root pressure. *Locker and Brouwer [1964]* have shown that in young maize plants root pressure accounts for about two-thirds of the 'acropetal' water transport.

Root pressure is influenced by the metabolism of the plant and in particular by its nutrition *(Kramer [1951])*. Working with young excised primary roots of maize plants, *Mengel and Pflüger [1969]* showed that chlorides stimulated exudation rates* more than did sulphates, and that K^+ and N^+ ions caused higher flux rates than Ca^{++} and Mg^{++}. The highest exudation rates were obtained with KCl.

The transversal movement of water (from soil into the xylem) is the main obstacle to water uptake by the plant, and may limit water uptake even under conditions of high water potential in the soil. The results reported by *Mengel and Pflüger [1969]* may therefore provide an explanation for the favourable effect of potassium on the water balance of plants (see chapter 5).

Bange [1966] has made a detailed investigation on the upward transport of potassium in maize seedlings. He compared upward K-translocation in intact and decapitated seedlings. He found that shoot excision appeared to result in a serious reduction of upward K-transfer, whereas the K-content of the root was hardly affected. This effect is ascribed to a reduction in the rate of a metabolically controlled process, namely the transfer of potassium from the root cells to the sap.

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* Exudation rates are assumed to reflect accurately the root.pressure of intact plants.

7.4 Accumulation of dry matter and nutrients by the plant during different stages of growth

Knowledge of the patterns of growth and nutrient uptake by the maize plant throughout the growing season is useful in showing when the demand for nutrients occurs so as to be able to ensure an adequate and timely supply, thereby avoiding critical deficiencies. If such deficiencies are allowed to occur at any stage of growth, the resulting setback will affect the final yield, even if the nutrient supply is adequate at a later stage.

The patterns of growth and nutrient uptake in maize have been studied by a number of research workers, whose work has been reviewed by *Nelson [1956]*. However, the most recent and detailed investigation is that of Hanway in Iowa *(Hanway [1962 a and b])*, who has also considered the effect of different fertility levels on growth, development and nutrient uptake in maize plants. Hanway's results agree in general with those obtained by other investigators but he has provided more comprehensive information on this subject.

Table 30. Total dry matter production and N, P and K uptake (in kg/ha) as affected by nutrient supply *(Hanway [1962 a])*

Nutritional status of the soil	Total dry-matter production	Total N-uptake	Total P-uptake	Total K-uptake
Extremely N-deficient	6 460	35	10	32
K-deficient	14 250	158	29	64
P-deficient	14 700	161	23	82
No nutrient deficiencies	17 200	198	33	105

7.4.1 Accumulation of dry matter in relation to nutrient supply

Hanway [1962 a] found that the rate of dry matter production by maize was linear over a major part of the growing season at all fertility levels. However, the actual rates of dry matter accumulation by the plants were markedly affected by soil fertility differences. The highest growth rate for the maize was obtained when the plants had an adequate supply of nutrients, with a daily dry matter production of 245 kg/ha/day; for plants grown under conditions of P or K-deficiency these values were respectively 204 and 200. Under extremely N-deficient conditions, the growth rate was much lower, with a daily dry matter production of 82 kg/ha. These differences were reflected in the final weight of each plant part, but not in the relative proportion of each plant part. Dry matter production reached a peak at the beginning of August, when more than 308 kg/ha of dry matter was accumulated in a single day **(Figure 37)**.

7.4.2 Accumulation of nutrients

The accumulation of plant nutrients deviates from the linear character of the accumulation of dry matter by the plant **(Figure 38)**.

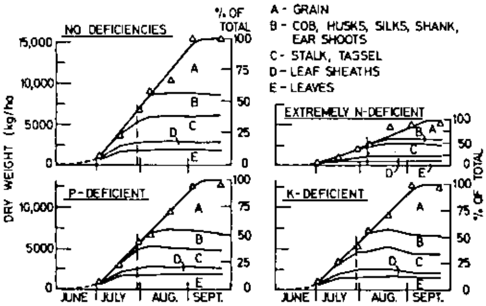

Fig. 37 Dry matter accumulation and its distribution in various parts of maize plants at different stages of growth as influenced by differences in soil fertility *(Hanway [1962a])*. Small triangles represent actual total dry weights obtained at each date. Vertical dashed lines indicate the dates of silking. By courtesy of the American Society of Agronomy.

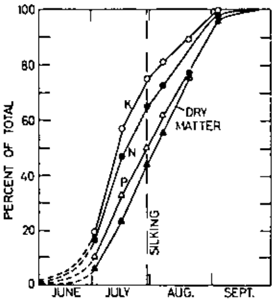

Fig. 38 Accumulation of dry matter, nitrogen, phosphorus and potassium in maize plants during the growing season *(Hanway [1962b])*. All rates expressed in per cent of total. By courtesy of the American Society of Agronomy.

7.4.2.1 Nitrogen

Nitrogen requirements vary considerably at different stages of development of the plant: minimal in the early stages, increasing as the rate of growth accelerates, and reaching a peak during the period between the onset of flowering and early grain formation.

Nitrogen accumulates more rapidly than phosphorus early in the season, and its uptake continues at a more rapid rate during early July. The rate declines somewhat after mid-July, but nitrogen continues to accumulate until maturity *[ibid.]*.

The amounts of nitrogen accumulated depend to a considerable extent on the general nutrient status of the soil **(Figure 39)**. The total uptake of N was as follows *[ibid.]*: Under conditions of extreme N-deficiency: 35 kg/ha; of K-deficiency 158 kg/ha; of P-deficiency 160 kg/ha; and of adequate N, P, K supply 198 kg/ha.

Sayre [1955] found that in the first 30 days, the maize crop had accumulated 3.8 kg/ha of nitrogen; 10 days later the plants had already accumulated 16.5 kg/ha. The highest daily rate of accumulation, of 4.4 kg/ha, was in the last few days of July – during the period between tasselling and silking.

In western Nigeria, nitrogen uptake was found to increase rapidly one week before the stage of linear increase in dry-matter production. Between the fourth and sixth weeks, nitrogen uptake averaged 2.75 kg/ha/day, but this decreased as the season progressed *(Bromfield [1969])* **(Figure 40).**

Whilst the nitrogen content of young maize plants is higher than that at any other time during the growth cycle, the actual nitrogen requirement is very low, amounting to a few kilogrammes per hectare. However, a deficiency at the time the plants are about 20 cm tall will cause a reduction in the number of rows of kernels per ear in the ear primordia, thereby lowering the final yield – an effect that cannot be overcome by an adequate supply at a later date *(Schreiber et al. [1962])*.

Hence, the importance during the seedling stage of having readily available nitrogen in the relatively small root zone; it should be applied as 'starter' fertilizer near the

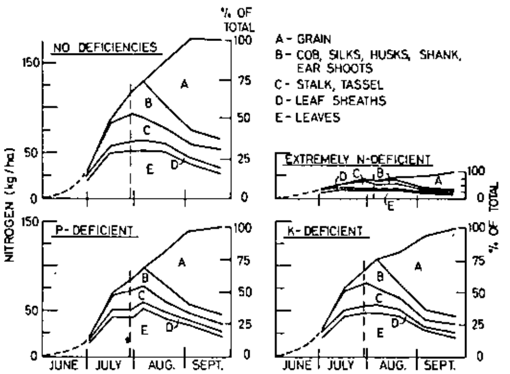

Fig. 39 Nitrogen contents of different parts of the maize plant at different times during the growing season, as influenced by differences in available nutrients *(Hanway [1962b])*. By courtesy of the American Society of Agronomy.

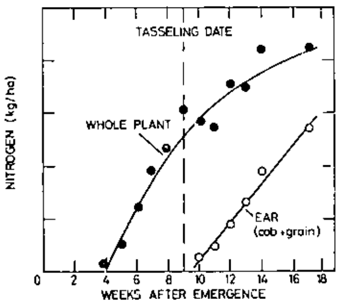

Fig. 40 Total uptake of nitrogen by a crop of maize in Nigeria *(Bromfield [1969])*. By courtesy of Cambridge University Press.

seed row. At this stage, the plant's ability to absorb nutrients is still limited because of its restricted root growth. Also, soil temperatures are usually relatively low at the time, so that nitrogen release from the soil organic matter is slow.

As the plants develop, the rapidly expanding root system is capable of taking up nutrients from an increasingly larger soil volume. It is at this stage that nitrogen – either broadcast before sowing or side-dressed to the growing crop – will be most effective, provided it is incorporated into the soil at sufficient depth, so that the fertilizer is placed in a zone that does not dry out between rainfalls or irrigations.

The pattern of N-uptake by the plants as presented above is undoubtedly modified under the influence of the seasonal changes in N availability from the soil, which in turn depend on time and method of application of N-fertilizer and rate of mineralisation of N from soil organic matter. The latter varies in different soils and climatic conditions.

7.4.2.2 Phosphorus

Maize accumulates phosphorus throughout the growing season, with maximum uptake occurring between the third and sixth weeks of growth *(Sayre [1955])*. Phosphorus uptake is slightly ahead of dry matter accumulation early in the season, and generally parallel to dry matter accumulation until the early dent stage. From early July to the beginning of September the accumulation of P is nearly linear *(Hanway [1962])*. Uptake practically ceases after the early dent stage.

As is the case for nitrogen, the amounts of phosphorus accumulated by the plant depend largely on the nutrient status of the soil **(Figure 41)**. N-deficiency has the most marked effect in this respect, reducing P-uptake to about one-half that of P-deficient soils.

Total uptake of P was as follows:

Under conditions of extreme N-deficiency: 10 kg/ha; of K-deficiency 29 kg/ha; of P-deficiency 23 kg/ha, and of adequate N, P and K supply 33 kg/ha.

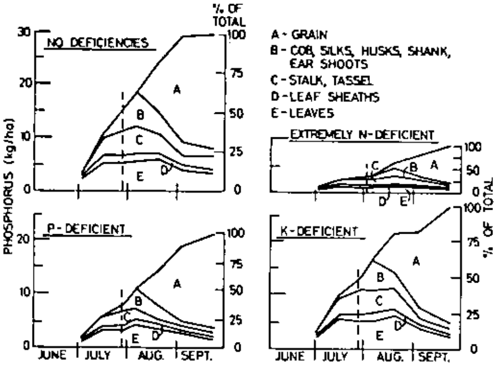

Fig. 41 Phosphorus contents of different parts of maize plants at different times during the growing season as influenced by differences in available nutrients *(Hanway [1962b])*. (Vertical dashed lines indicate the date of silking.) By courtesy of the American Society of Agronomy.

During the period from tasselling to silking, daily uptake of phosphorus may amount to 1.2 kg P_2O_5/ha/day *(Sayre [1955])*.

Somewhat different results were obtained by *Bromfield [1969]* working in western Nigeria. He found that the total phosphorus uptake was linear from 4 weeks until harvest, with an average daily uptake of 0.13 kg P/ha. Phosphorus in the ears increased from the tenth to the twelfth week, remained constant for the next two weeks and then increased steeply during the period between 14 weeks and harvest at 17 weeks. These results are unusual, as other workers have usually found a linear increase for phosphorus, similar to that noted for dry-matter, nitrogen and potassium **(Figure 42).**

7.4.2.3 Potassium

The rate of accumulation of potassium during the first 30 days of growth exceeds that of both nitrogen and phosphorus, thereby suggesting a greater requirement for potassium than for nitrogen or even phosphorus as a starter element.

In maize seedlings grown in nutrient solutions, absorption rates of N and P reached a maximum 28 days after germination, whilst the maximum rate of K absorption occurred immediately after germination *(Minar and Lastuvka [1969])*.

During a period of one month beginning about two weeks before tasselling, the daily rate of uptake has been calculated by *Sayre [1955]* to be 4 kg K_2O/ha, and according to *Chandler [1960]* may reach 7.3 kg/ha. During a period of one month from before silking until maturity, K-uptake follows a much different pattern from that of dry matter accumulation which appears to be essentially linear. Prior to silking the relative uptake of potassium was greater than the relative dry weight increase; at silking the plants had already accumulated 90 per cent of the total potassium absorbed; K-uptake practically ceased 10–15 days after silking, a period of fairly steep increase in dry matter accumulation. As a result, K-content of the plants is highest when they

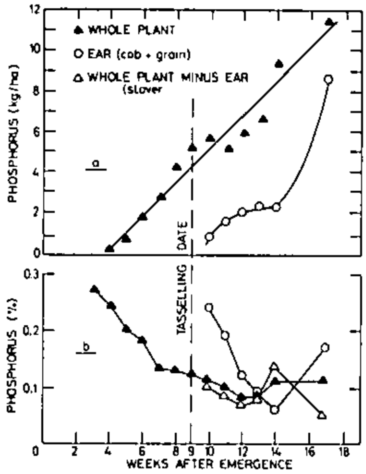

Fig. 42 Total uptake of phosphorus (a) and phosphorus content of maize (b) *(Bromfield [1969])*. By courtesy of Cambridge University Press.

are young, decreases rapidly until a short time after silking, and then decreases slowly until the end of the season. The actual per cent of K may vary from a maximum above 5 per cent, about a month before silking, to a low of 0.53 per cent at maturity. In most trials, the increase in per cent of K in the plants due to potassium fertilization decreased as the plants grew older *(Hanway [1962 b])* **(Figure 43).**

Similar results were obtained by *Bromfield [1969]* in western Nigeria:

Potassium uptake was rapid from 3 to 6 weeks after emergence, with an average daily uptake of 3.6 kg/ha. The amounts become lower and more variable from the eighth week onwards *[ibid.]* **(Figure 44).** (This variability has been ascribed by *Sayre [1955]* to mechanical loss of leaves, leaching by rain and loss of K from the roots.).

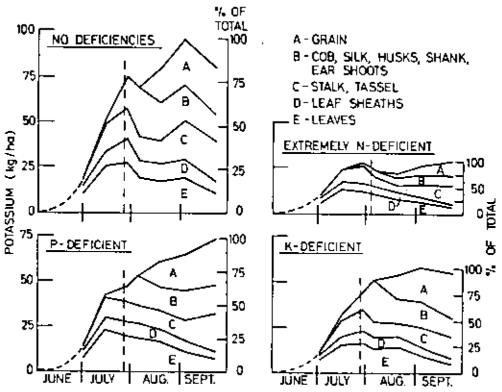

Fig. 43 Potassium contents of different parts of maize plants at different times during the growing season as influenced by differences in available nutrients *(Hanway [1962b])*. The loss of potassium in mid-season apparent in the two top graphs is assumed to be due to variability in K availability within these plots. (The vertical dashed lines indicate the date of silking.) By courtesy of the American Society of Agronomy.

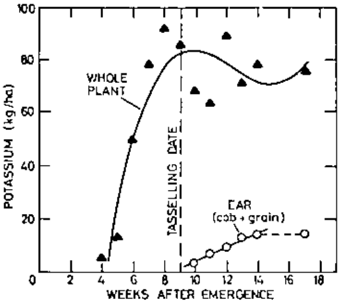

Fig. 44 Potassium uptake by maize in Nigeria *(Bromfield [1969])*. Uptake was most rapid 3 to 6 weeks after emergence, with an average daily uptake of 3.6 kg/ha. From eighth week onward the amounts were variable but lower. By courtesy of the Cambridge University Press.

The potassium content of the ear increased linearly and was greatest 3 weeks before harvest.

The amounts of potassium taken up by the plants were markedly influenced by nutrient levels in the soil.

The total amount of potassium taken up by the maize plants grown under conditions of extreme N-deficiency was very low – less than one-third of the amount taken up when nitrogen was not limiting. K and P deficiencies also reduce K-uptake markedly. Total uptake of K was as follows:

Under conditions of extreme N-deficiency: 32 kg/ha; of K-deficiency 64 kg/ha; of P-deficiency 83 kg/ha; and of an adequate supply of N, P and K 105 kg/ha *(Hanway [1962* b*])*.

The amount of potassium at silking time in maize plants that received no potassium fertilizer varied at 51 locations in the Corn Belt from 24 to 233 kg/ha, with an average of 85 kg/ha *[ibid.]*.

7.4.3 Critical growth period

Many investigations have shown that most mineral nutrients are absorbed during a period of approximately five weeks – starting 10 days before tasseling and lasting until 25–30 days after the start of tasseling. During this period the plant takes up 70 to 75 per cent of its nitrogen, 60 to 70 per cent of its phosphorus and about 65 per cent of its potassium.

In Table 31 are shown the relative amounts of dry matter and major nutrients taken up at two stages of development of the maize plant.

Table 31. Relative amounts of dry matter, P, N and K in maize plants at two stages of development (in per cent of total amounts at maturity) *(Hanway [1962])*

Period (number of days after emergence)	Total dry weight	P	N	K
38 days (stalks just beginning to elongate)	6	10	17	20
65 days (silking time)	44	50	65	75

Fifty per cent of the leaf growth take place during one two-week period just before tasseling, during which 31, 28 and 38 per cent of the total season's uptake by the crop of nitrogen, phosphorus and potassium respectively, also occurred. This indicates how extremely critical this period is from the point of view of mineral nutrition.

7.4.4 Patterns of distribution of nutrients within the plant

Hanway [1962 b] has made a detailed study of the distribution of the macroelements in different parts of the maize plant, as influenced by the soil fertility level **(Figure 45).**

7.4.4.1 Nitrogen

Though the total amounts of N taken up by the plants are markedly influenced by the available nutrient supply (cf. p. 258.), the pattern of distribution of nitrogen in different parts of the plant does not appear to differ markedly as a result of differences in nutrient supply. During the vegetative period of growth most of the nitrogen accumulates preferentially in the young, rapidly growing organs. Nitrogen accumulates in each plant part as it grows, and except for plants grown under conditions of extreme N-deficiency, which lose some nitrogen from the stalks prior to silking, little translocation of nitrogen from one plant part to the other was found to occur until after grain formation began. The accumulation of nutrient reserves in the developing grain triggers the breakdown of part of the proteins in the vegetative parts of the plant and nitrogen is translocated to the grain from all plant parts. Translocation of nitrogen from the cob, husk and stalk preceeds that from the leaves. In mid-July, 50 days after emergence, the leaves have nearly completed growth and their total content of nitrogen remains relatively constant for 30 days. During this period the leaves contain approximately 30 per cent of the total nitrogen accumulated by the plant, though they constitute only about 13 per cent of the final dry matter accumulation. At maturity

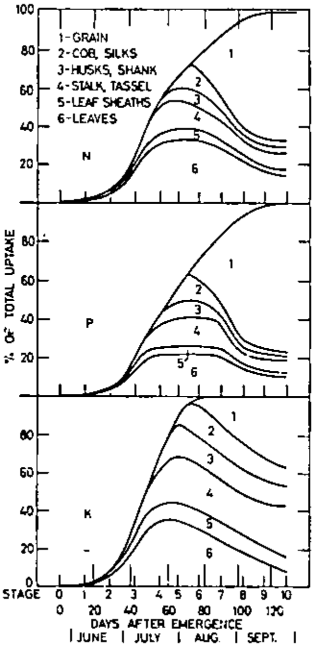

Fig. 45 Uptake of N, P, and K by corn plants and their distribution among the different plant parts in relation to the different stages of growth and dates after emergence *(Hanway [1962b])**. By courtesy of the American Society of Agronomy.

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* *Hanway [1962 c]* states that the plants grown on plots with no nutrient deficiencies and also those with extreme N-deficiencies lost potassium in mid-season, as indicated in the graphs. He assumes that these variations in K uptake with time are due to variability in potassium availability within the plots.

the grain contains about two-thirds of the total nitrogen absorbed. About one-half of the nitrogen in the grain appeared to be due to translocation from the above-ground parts of the plant.

In the Nigerian work mentioned above (p. 144), the nitrogen content of the ears increased uniformly, and at harvest (17 weeks after emergence) 66 per cent of the total nitrogen taken up by the crop was in the ears *(Bromfield [1969])*.

7.4.4.2 Phosphorus

The patterns of distribution of phosphorus in different parts of the plant are somewhat different from those of nitrogen: phosphorus tends to be distributed more uniformly in the different organs of the plant. Like nitrogen, the distribution of phosphorus in the plant is not markedly influenced by differences in nutrient supply. The total amount of phosphorus in the leaves remains fairly constant during the month after they have practically completed growth (50 to 80 days after emergence).

7.4.4.3 Potassium

The patterns of uptake and distribution of potassium in different parts of the plant are very different from those of nitrogen and phosphorus. The uptake of potassium is very rapid early in the season and slows down later on. Much less potassium is translocated from the above-ground parts to the grain than is the case with the other two macronutrients. About 30 per cent of the total K uptake was found in the leaves in mid-July, 50 days after emergence. However, under conditions of extreme N-deficiency, the leaves at this time, contain almost half of the total potassium taken up by the plants.

As the leaves age, proteolysis occurs and the potassium migrates in association with nitrogen compounds resulting from the proteolysis.

The departure of the potassium results in an increase in the relative content of calcium and magnesium. The levels of these two elements therefore rises with increased senescence.

The same process occurs in all plant organs that are depleted of nutrients in favour of young leaves, or of grain formation.

All the leaves begin to lose potassium prior to silking on plants grown under conditions of N- and P-deficiency, whilst plants that have suffered from K-deficiency or no deficiency at all lost their potassium only after silking. Loss of potassium from the leaves continues until maturity in all the nutrient regimes tested. However, there is relatively little loss of potassium from the cobs, husks, stalks and leaf-sheaths; after mid-August (80 days after emergence) the potassium that migrated from the leaves appears to accumulate in the stalks.

At maturity, the grain contained about one-third of the total potassium in the plants. In this investigation, no appreciable loss of potassium at maturity was recorded, as had been reported by *Sayre [1955]*. *Hanway* ascribes this difference in results to the lower level of potassium availability in the soil in his study; therefore, the plants studied by *Sayre* had a much higher K-content than those used by *Hanway*. Apparently as a result of the higher K-availability, the uptake of this nutrient was more rapid during July, accumulation ceased earlier in the season and potassium was lost from the plants toward the end of the growing period.

7.4.4.3 Secondary nutrients

Carlès et al. [1957], working in France, studied the evolution of dry matter production and nutrient uptake in maize at three stages of growth: at the end of the vegetative period (beginning of tasseling), at the end of flowering (four weeks after tasseling) when the grain is already in the milky stage, and at grain maturity (five weeks after the end of flowering). The results are shown in **Figures 46 a + b.**

The uptake of calcium is more active at an earlier stage than that of magnesium, but ceases at the beginning of grain maturation, whilst the uptake of magnesium is more constant and continues up to grain maturity. Most of the calcium is finally located in

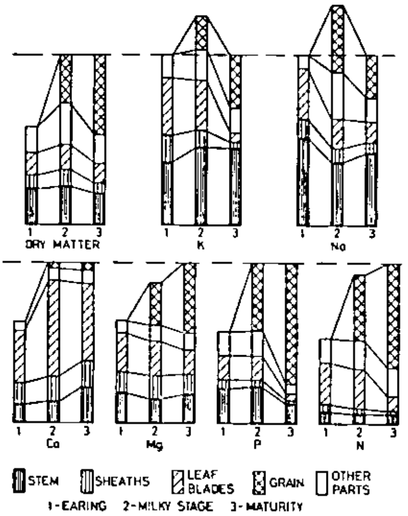

Fig. 46a Evolution of dry matter production and nutrient uptake by maize at three stages of growth *(Carlès et al. [1957])*. By courtesy of the Académie Française d'Agriculture.

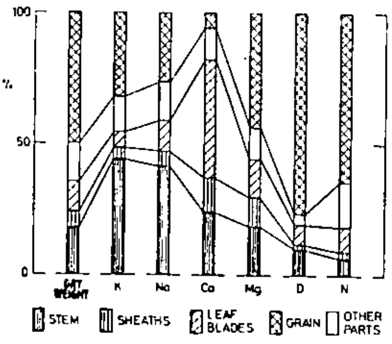

Fig. 46b Distribution of dry matter and mineral elements in different plant organs of maize at maturity *(Carlès et al. [1957])*. By courtesy of «Engrais de France».

the leaf blades, and the magnesium in the grain. About half the total magnesium and only a fraction of the calcium are translocated to the grain.

The uptake of sodium follows a very similar pattern to that of potassium. Sodium content of the plant was found to remain fairly constant from tasseling to maturity. Whatever uptake occurred during this period was apparently lost, mainly by leaching.

7.4.5 Migration of nutrients to the developing kernels

It is important that once grain formation has been initiated, all dry matter in excess of what is required for the maintenance of an efficient photosynthetic structure should be diverted to the developing grain. In addition, the maximum possible of nutrients should be translocated from the non-harvestable parts of the plant to the economic product during the later stages of maturation.

The assumption is justified that there exists a mechanism whereby the growing kernels are able to withdraw varying amounts of photosynthates from other parts of the plant. It is not known whether this is an active or passive process, but it appears from work by *Mothes [1956]* that certain substances, such as kinetin and benzimidazole, have a profound influence on the movement of nitrogen to different parts of the plant. There might therefore be an activating principle produced by the rapidly growing parts of the plant, in amounts which are genetically controlled, which affects the above mentioned process.

At the time of flowering, the maize plant has reached its maximum size and the vegetative parts gradually become senescent and the nutrients accumulated by these organs are progressively translocated to the developing ear.

The developing kernels of maize have two major sources of mineral nutrients; (a) those absorbed from the soil during the period from pollination to grain maturity, and (b) translocation of previously accumulated nutrients from different parts of the plant to the developing kernels. Nutrient re-distribution in the plant occurs at all periods of growth, but is particularly significant during the development and maturation of the grain.

There are considerable differences in the degree of mobility of the different nutrients which are translocated from the senescent organs of the plant of the grain. Nitrogen, phosphorus, potassium and magnesium are very mobile, whilst calcium and zinc are relatively immobile. It is interesting to contrast the mobility of phosphorus in the plant with its lack of mobility in the soil. This high mobility in the plant is mainly due to the fact that P-transport, in particular in the phloem, is in the organic form *(Mengel [1968])*.

The redistribution of five major mineral nutrients in the maize plant from the vegetative parts of the developing ear during the period from 12 days after silking to maturity was measured by *Kissel and Ragland [1967]:*

7.4.5.1 Nitrogen

Shortly after flowering a breakdown of the proteins by proteolysis occurs in all the vegetative organs, possibly including the roots. About 65 per cent of the nitrogen present in the vegetative parts is translocated to the ear, mainly from the bottom leaves and stalk *(Kissel and Ragland [1967])*. The tassels are the first to lose their nitrogen followed by the stalk, the sheaths and finally the lamina of the leaves.

According to *Hay et al. [1953]*, 40 per cent of the nitrogen supply to the grain results from direct absorption by the roots and 60 per cent from translocation from the above-ground parts of the plant.

The relative contribution of the different vegetative organs is shown in Table 32.

Table 32. Relative contribution of vegetative organs to the nitrogen supply to the grain. Percentage of total translocated from above-ground parts

	Hay et al. [1953]	*Carlès et al. [1957]*
Leaves	60	58
Cobs	2	12
Husks	12	11
Stems and other parts	26	19

7.4.5.2 Phosphorus

After pollination, the supply of phosphorus to the developing grain is very intensive. Absorption of phosphorus by the roots is still very active during the period from ear formation to maturity. The amounts of phosphorus absorbed by the roots during this period are 63 per cent of the total phosphorus uptake according to *Sayre [1955]*, and 43 per cent according to *Carlès et al. [1957]*; most of this finds its way to the developing kernels.

Translocation of phosphorus to the grain begins somewhat later than that of nitrogen, but is more complete.

The movement of phosphorus from the stalks, cobs and husks to the grain precedes that from the leaves. Seventy-five per cent of the total phosphorus present in the vegetative parts moves to the ear. Redistribution occurs about equally from leaves, stalks, shanks and husks *(Kissel and Ragland [1967])*. It is estimated that about one-half or more of the phosphorus in the grain is derived from translocation from the other above-ground parts *(Hanway [1962 a])*.

The rate of translocation of phosphorus to the grain depends to a large extent on the levels of nitrogen supply to the plant. In plants that have received adequate amounts of nitrogen, 90 per cent of the phosphorus accumulated in the vegetative parts migrates to the grain, whilst in N-deficient plants translocation starts later and only 40 per cent is translocated to the grain *(Carlès et al. [1957]). Bromfield [1969]* found that, at harvest, 78 per cent of the total P was in the ear.

7.4.5.3 Potassium

Smaller amounts of potassium than of nitrogen or phosphorus move from the vegetative parts to the developing ear. About 23 per cent of the potassium was found to move out of the vegetative parts to the developing ear. This element was apparently redistributed from all plant parts except the stalks, in which potassium content increased during grain maturation *(Kissel and Ragland [1967])*.

7.4.5.4 Calcium

Calcium redistribution in the plant is very slight. A small loss from the ear, and some gain in the top leaves and stalk, were actually recorded.

7.4.5.5 Magnesium

According to *Kissel and Ragland [1967]*, about 45 per cent of the total magnesium in the vegetative parts of the plant moved to the ear. The stalks contributed the highest percentage of their content to the ear.

Carlès et al. [1957], found that the above-ground parts of the plant contributed only about 20 per cent of their magnesium content to the grain and that it was the leaves that made the major contribution of magnesium to the grain (70 per cent).

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8. The effects of fertilizers on dry matter production, growth and morphology

8.1 Dry matter production

The first prerequisite for high yields is a high production of total dry matter per unit area.

Carbon compounds account for 80–90 per cent, of the total dry matter produced by the plants. Photosynthesis is the basic process for the building of organic substances by the plant, whereby sunlight provides the energy required for reducing carbon dioxide, with sugar as the end product of the process. This sugar serves as building material for all the other organic components of the plant.

The amounts of dry matter produced will therefore depend on the effectiveness of photosynthesis of the crop and on the efficient functioning of other vital activities.

The effectiveness of photosynthesis is dependent on (1) a large and efficient assimilating area, (2) an adequate supply of solar energy and carbon dioxide, and (3) favourable environmental conditions. The total products of photosynthesis throughout the life-time of the crop will depend on the size of the assimilating area, the efficiency with which it functions and the length of the period during which it is active.

A proportion of the organic substances produced by photosynthesis will be needed for the vital processes of the plant, and consumed – by respiration – by the plant itself. The total yield of dry matter will therefore be the total amount of dry matter produced, less the photosynthates used for respiration.

8.2 Assimilating area

The leaves are the main organs of photosynthesis, and the total area of leaves per unit area of land surface, called *leaf area index (LAI)*, has therefore been proposed by *Watson [1947]* as the best measure of the capacity of a crop for producing dry matter, – what he calls 'its productive capital.'*

Hanway [1962 a] has shown that the total dry weight of the maize plant and also the grain yield are directly related to and highly correlated with the weight of leaves on

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* In experiments in Rhodesia, it was shown that in maize most of the dry matter increase after flowering was produced by the upper leaves. The contribution from photosynthesis by the ear was negligible, probably because its surface area is only 2 per cent of that of the leaves *(Allison and Watson [1966])*.

these plants **(Figure 47).** The slope of the line for the total dry matter produced is almost exactly double that for the grain; this is not surprising as the grain, at maturity, constitutes about half the total dry weight of the plant.

Variation in *total leaf area (LA) of a plant* may result from changes in leaf number or in leaf size. The number of leaves present at any time equals the total number of leaves produced less the number of leaves that have been lost by abscission.

Leaf number depends on the number of growing points, the length of time during which leaves are produced, the rate of leaf production during this period, and the length of life of the leaves. Leaf size is determined by the number and size of the cells of which the leaf is built, and is influenced by light, moisture regime and the supply of nutrients.

8.3 Effect of fertilizers on the assimilating area

8.3.1 Leaf number

The initiation of leaf primordia ceases with the initiation of tassel, about 21 days after sowing *(Kiesselbach [1949]).*

It is therefore reasonable to assume that factors which affect the number of leaves formed, do so either by affecting the time of tassel initiation or by influencing the rate of leaf initiation before initiation of leaf primordia ceases. The fact that close spacing affects the number of leaves per plant suggests that competition between seedlings is already noticeable about two weeks after sowing. In the experiments of *Eik and Hanway [1965]* starter fertilizers generally increased the average number of leaves per plant. The range of number of leaves was narrower and greater proportion of plants had leaf numbers in the upper part of the range, where starter fertilizers had been applied **(Figure 48).**

8.3.2 Leaf area

In hybrids WF9 × B14 and AES 704 it was found that at the time when the 12th leaf was completely unfolded, practically all leaves had attained their full area *(Eik and Hanway [1965]).* Most of the leaves above the 12th were not yet functional at this stage. It therefore appears that the sizes of the individual leaves cannot be influenced after the time when the 12th leaf is completely unfolded, which is about 7 weeks after emergence. Starter fertilizers generally increased the mean lengths and the mean widths of all leaves, resulting in consistent and statistically significant increases in total leaf area per plant **(Figure 49).** Plow-under fertilizers also generally tended to increase the sizes of individual leaves **(Figure 50)** *(Eik and Hanway [1965]).*

Nitrogen in particular has a considerable influence on leaf growth. Under conditions of N-deficiency, the embryonic bud of the plant does not develop to its full potential, cell division in the growing tips is retarded and a reduction in leaf area and plant size results.

It is well-known that leaves of potassium-deficient plants have a subnormal rate of photosynthesis. Increases in yield resulting from potassium fertilization are not due solely to the improved photosynthetic activity of the leaves, but also to increases in

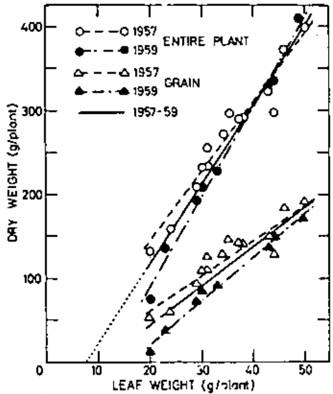

Fig. 47 Relation between leaf weight and (A) weight of the entire plant and (B) grain weight of nearly-mature maize plants *(Hanway [1962b])*. By courtesy of the American Society of Agronomy.

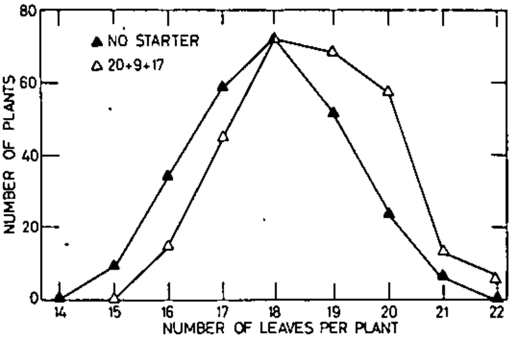

Fig. 48 Effect of starter fertilizer on the number of leaves per plant *(Eik and Hanway [1965])*. The starter fertilizer generally increases the average number of leaves per plant, and a greater proportion of the plants have leaf numbers in the upper part of the range. By courtesy of the American Society of Agronomy.

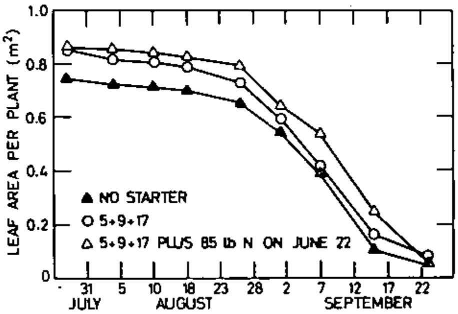

Fig. 49 Effect of starter fertilizer and nitrogen top-dressing on total leaf area per plant *(Eik and Hanway [1965])*. By courtesy of the American Society of Agronomy.

the total leaf area per plant or per unit area. In cereals, the increase in leaf area due to potassium fertilization is mainly the result of greater expansion of the individual leaf; the number of leaves per plant is not much affected *(Watson [1956])*.

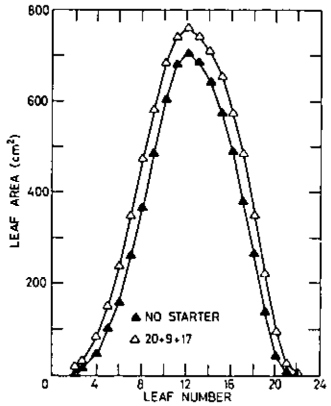

Fig. 50 Effect of starter fertilizer on the areas of individual leaves *(Eik and Hanway [1965])*. By courtesy of the American Society of Agronomy.

In field trials in the N. E. Ukraine, combinations of organic and mineral fertilizers increased the leaf surface of maize plants from 2970 cm^2/plant (unfertilized) to 4070–4080 cm^2, increased the coefficient of utilization of late-season, photosynthetically active, radiation from 0.376 to 0.436, increased productivity of photosynthesis over a 17-day period from 14.74 g/m^2 to 15.64–16.04 g/m^2, and increased yields of maize grain from 2880 to 6400 kg/ha *(Afendulov [1969])*.

8.3.3 Rates of leaf emergence

Where no plough-under fertilizer was applied, starter fertilizer generally increased the rate of leaf emergence in maize. Plough-under fertilizer had the same effect. Nitrogen side-dressed in June did not have an appreciable effect on the rate of leaf emergence *(Eik and Hanway [1965])*.

8.3.4 Leaf area development

The rate of expansion of the total leaf area was consistently increased by starter fertilizers, when no plough-under fertilizer had been applied *(Eik and Hanway [1965])*.

8.3.5 Growth curve of leaf area index – Optimum LAI (Figure 51)

After germination, LAI increases very slowly at first, over a fairly long period; then follows a period of rapid expansion of LAI. As LAI increases, light absorption and the rate of dry matter production increases, until the foliage becomes sufficiently dense to cause mutual shading. Less light penetrates to the lower leaves, whose photosynthetic activity is therefore reduced. As shaded leaves respire just as actively as leaves receiving full sunlight, their contribution to the total assimilation effort of the crop becomes negative. There is therefore an optimum LAI for maximum dry-matter production, which is reached when the lowest leaves receive just sufficient light for photosynthesis to balance respiration, e. g. when the lower leaves are at the compensation point, and the canopy as a whole has reached maximum net assimilation. Below LAI opt. light energy is not being fully intercepted; above LAI opt. the leaf area is not being utilised at maximum efficiency.

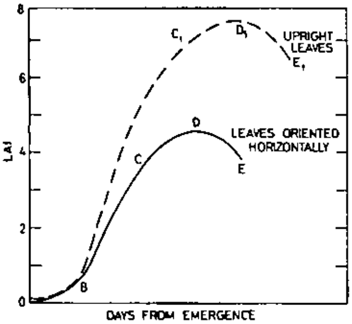

Fig. 51 Schematic presentation of growth curve of leaf area index (LAI). AB = Period after emergence (LAIs increase slowly); BC and BC_1 = Period of rapid growth (steep increase in LAIs); C and C_1 = optimum LAI, when lower leaves are at compensation point; D and D_1 = maximum leaf LAI.

When LAI increases beyond the optimum, the lower leaves lose carbohydrates and eventually die, long before the leaf canopy as a whole reaches the compensation point *(Donald [1961])*. When LAI exceeds its optimum, many of the leaves of the lower levels will actually be parasitic even under conditions of full light intensity.

The rate of loss of the lower leaves increases as LAI increases, until a point is reached at which it equals the rate of production of new leaves; at this point LAI has become static, and leaf area is at its maximum. At this stage dry matter production is still increasing, though usually at a somewhat lower rate than at 'optimum LAI'.

Optimum LAI values for maize will depend on a number of factors, such as plant type and light intensity. The plant density required to give optimum LAI values will also vary accordingly. The following example will make this clear.

Locally-adapted maize hybrids were grown at densities of 4.9–14.3 plants/m^2 in England and 2.3–7.4 plants/m^2 in Rhodesia. When sown at similar densities, plants grew more rapidly in Rhodesia than in England, and leaf area/plant at flowering was more than twice as large. The faster growth in Rhodesia was apparently due to the higher temperature and solar radiation there. For maximum dry matter production after flowering, and thus maximum grain yield, a LAI of 5–6 was found to be required in Rhodesia, and of about 4 in England. Plant densities giving these LAI values were 5–6 and 9–10 plants/m^2, respectively *(Allison and Eddowes [1968])*.

The development of leaf area (expressed in LAI) in maize at different plant densities is shown in **Figure 52** *(Williams et al. [1968])*. During the period of stalk elongation the internodal elongation increases the vertical separation between successive leaves. Maximum LAI had developed by tasselling from the beginning of August to mid-August depending on population density, with a range for LAI max. from 3.5 to 8.5, for densities of 1.75 to 12.50 plants/m^2.

The time course of relative light interception was studied by *Williams et al. [1968]*. Relative light interception was closely associated with LAI until the inception of tasseling, around August 5. At that time, all canopies were practically closed, intercepting more than 90 per cent of the sunlight. With the exsertion of the tassel, the uppermost leaves unfolded from the tassel-containing whorl to a more or less horizontal position. From this stage on, the tassels, which do not make a substantial contribution to photosynthesis, intercepted significant amounts of light *(Duncan et al. [1967])*. The pollen accumulation on the leaves may also interfere with the utilization of light by the leaves.

The relative light interception as a function of LAI at different growth periods is shown in **Figure 53** *(Williams et al. [1968])*. It is clear that an increase in LAI resulted

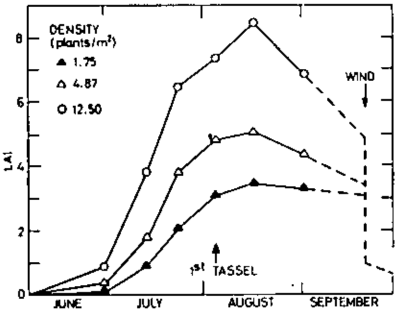

Fig. 52 The development of leaf area index (LAI) in maize at three different densities *(Williams et al. [1968])*. LAI max. ranged from 3.5 for a density of 1.75 plants/m^2 to 8.5 for a density of 12.50 plants/m^2. By courtesy of the Crop Science Society of America.

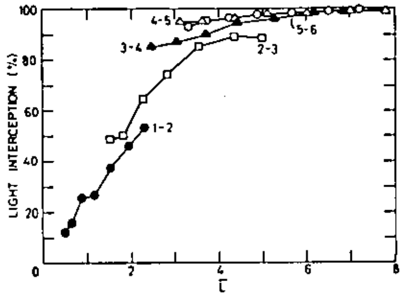

Fig. 53 Relative light interception as a function of leaf area index (LAI) for five growth periods *(Williams et al. [1968])*. The figures indicate stages of growth as follows: 1 = 2 weeks after emergence; 2=4 weeks after emergence; 3 = 6 weeks after emergence; 4 = Beginning of tassel emergence; 5 = 2 days prior to pollen shedding; 6 = Dough stage; 7 = Harvest dent stage. By courtesy of the Crop Science Society of America.

in an approximately proportional increase in relative light interception up to LAI = 3 and then approached the apparent asymptote of 99 per cent with further increases in LAI.

8.3.6 Importance of high initial rate of growth

For most annual crops, LAI is lower than optimum during most of the growing period. As long as LAI < 1, some of the incident solar energy is not intercepted by leaves, but reaches the soil.

In the temperate cereals, LAI increases rapidly to a peak and falls again rapidly; in maize, a high LAI is maintained for a much longer time. A hybrid which flowered 82 days from sowing, when grown with an ample supply of nitrogen, maintained a LAI of over 4 for 60 days from an age of 2 months, and reached a peak of 5–6 a few days before flowering *(Bunting and Drennan [1966])* **(Figure 54,** *Mueller [1964]).*

If the crop could achieve an optimum LAI (3–4) within a very short period, and then maintain it during most of the growing season, enormous yields could be achieved *(Niciporovic [1960]).*

In maize, it might be possible to shorten the period of very low LAI by fertilizer treatments which promote a high initial rate of leaf growth. Another objective of fertilization would be to maintain a large, photosynthetically-active leaf at the time assimilates are being stored in the economic product.

Fertilization practices can be effective in increasing the leaf area per plant produced early in the season and in preventing premature death of leaves due to nutrient deficiencies. Hence the importance of considering nutrient uptake by the plants and the translocation of the nutrients within the plant in relation to their effect on these factors.

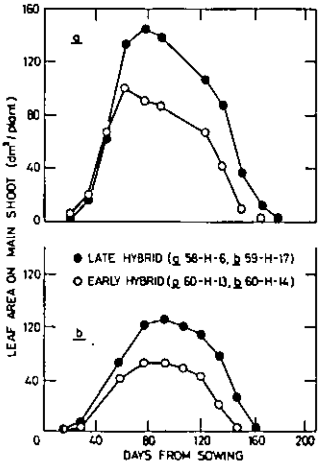

Fig. 54 The course of leaf area development in early and late-maturing maize hybrid plants in two experiments *(Mueller [1964])*. Courtesy University of London.

In a study by *Hanway [1962 b]* it was found that more than half the leaf growth occurred in the two-week period starting July 2 (38 days after emergence). The percentage of the nutrients taken up during this two-week period, in relation to the total accumulated throughout the growing season, was 31 per cent for nitrogen, 23 per cent for phosphorus and 38 per cent for potassium. This high rate of nutrient uptake indicates that these two weeks constitute a critical period in the life of the plant in regard to its mineral nutrition. If leaf growth is not to be restricted during this period by nutrient deficiencies, it is essential that nutrient availability be relatively high so that a rapid rate of uptake, which is essential, can be maintained.

Nutrient uptake both before and after the critical period is also important. Although leaf growth and nutrient uptake during the first five weeks in the life of the plant are relatively slow, the amount of leaf area produced during this period will undoubtedly affect the amount of growth that occurs during the subsequent critical period of rapid growth *(Hanway [1962 b])*.

8.3.7 Efficiency of photosynthesis

The efficiency of the photosynthetic system can be estimated in the field by determining the rate of increase of dry matter per unit leaf area at short intervals throughout the growth period *(Watson [1956])*. This method, called 'growth analysis', does not give a pure measure of photosynthesis per unit leaf area, but only the excess of dry matter gain due to photosynthesis over loss by respiration. This value has been called 'net assimilation rate' (NAR), and is calculated according to the following equation:

$$\text{NAR} = \frac{\text{Increment in dry weight,}}{\text{Mean leaf area x days}} \quad \text{in g/m}^2\text{/day.}$$

8.3.8 The significance of NAR

NAR cannot be considered a measure of the intensity of photosynthesis, as it is also affected by changes in respiration rates. NAR varies between and within species and is influenced by mineral nutrition, water supply and seasonal climatic conditions.

Hanway [1962 b] has shown that although the N, P and K contents of the leaves of maize varied considerably according to the levels of fertility of the plots on which the plants were grown, the relationships between leaf weights and total dry matter of the entire plant and of the grain were linear over the entire range of values obtained (cf. Figure 47, p. 159). This indicates that the nutrient levels of the soil and the corresponding chemical composition of the leaves have relatively little influence on the *rate of photosynthesis in the leaves.*

The data in table 33 show that the highest NAR value, 0.12, was obtained when there were no nutrient deficiencies, and the lowest value 0.9 with severe N deficiencies; P and K deficiencies gave intermediate values. This indicates that NAR is influenced somewhat, but to a small extent, by the nutrient supply to the plant. The low NAR value for the extremely N deficient plants is at least partly due to the premature death of some of the leaves and the NAR of the living leaves is therefore actually higher than is evident from the figures in table 33.

Table 33. Net assimilation rates of maize plants as affected by soil fertility levels *(Hanway [1962 a])*

Nutrients status of plots	Leaf analysis at silking (% dry matter) N	P	K	Daily dry matter production (kg/ha)	Leaf weight (kg/ha)	NAR (kg/day per kg of leaves)
No deficiencies	2.9	0.3	1.5	245	2048	0.12
P-deficient	2.7	0.2	1.2	204	1193	0.11
K-deficient	2.8	0.3	1.0	200	1237	0.11
Extremely N-deficient	1.4	0.14	1.6	82	957	0.09

From the foregoing, it appears possible to conclude that the rate of supply of nutrients affects dry matter yields mainly by its influence on leaf growth, whilst variations of NAR due to this cause are usually of less importance.

Thus, while total dry matter production and grain yield are primarily functions of leaf area, the latter is a function of the nutrient status of the plant. The nutrient content of the leaves at silking can indicate whether and which nutrient elements are deficient, and whether as a result leaf area has been or will be reduced, thereby causing a reduction in grain yield. Therefore, leaf analyses can be a valuable diagnostic tool, but their interpretation should be based upon their relation to leaf area and not to net assimilation rate *(Hanway [1962 b])*.

8.3.9 Fertilizers and photosynthetic rate

Not all investigators are agreed that nutrition has only a relatively small effect on the photosynthetic rate.

Peaslee and Moss [1966] have shown photosynthesis is strongly affected by the concentration of extractable potassium in the leaves of maize (**Figure 55**). The rates of photosynthesis decreased very rapidly as the concentrations decreased from 1.5 to 0.2 meq/g of fresh tissue, corresponding to a critical level of 1.1 to 1.5 per cent K on a dry matter basis. All the leaves appeared normal, and did not differ significantly in chlorophyll content. Thus, K-deficiency caused a marked reduction in photosynthesis before visible symptoms appeared on the leaf. On the other hand, when a K-deficient

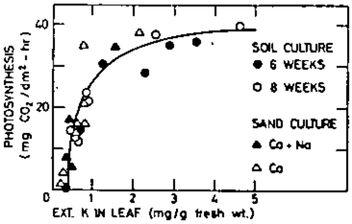

Fig. 55 Extractable K and rates of photosynthesis in maize leaves from plants grown in soil or in sand cultures containing Ca or Ca + Na as major cations *(Peaslee and Moss [1966])*. By courtesy of the Soil Science Society of America.

leaf was supplied with potassium, it regained appreciable photosynthetic ability within 24 hours. The recovery of photosynthetic activity was accompanied by increased transpiration (see table 34).

Table 34. Influence of K on photosynthesis and relative transpiration of excised leaves from normal and K-deficient maize plants *(Peaslee and Moss [1966])*

Initial K level	Post-excision treatment*	Photosynthesis** after excision 0 hours	24 hours	Total transpiration g/leaf
Low	Control	4	3	2.0
Low	K	5	12	4.6
High	Control	32	22	7.5
High	K	29	18	7.3

* Control = Hoagland's '-K' solution; K = Hoagland's solution

** Photosynthesis expressed in mg $CO_2dm^{-2}hr^{-1}$ (single measurements)

The authors conclude that the lower photosynthetic activity of K-deficient leaves is associated with the closure of the stomata.

Humble and Hsiao [1969] have shown that potassium has a highly specific effect on the opening of stomata, both in the dark and in light. However, light lowered the concentration of K^+ required for maximal opening more than 100-fold. No specific anion was required in association with K^+.

Whilst K is an activator for many metabolic reactions, it can generally be substituted with similar physiological ions. Stomatal opening appears to be the first physiological process in higher plants in which a highly specific requirement for K^+ is demonstrated *[ibid.]*.

Peaslee and Moss [1966] have shown that the rate of photosynthesis in maize leaves is also closely related to magnesium concentration in the leaf tissue **(Figure 56)**. Although deficiencies appeared early in the plants, the rates of photosynthesis were reduced only after the plants were about 11 weeks old and already fairly large. The range of concentration of magnesium causing rapid increases in photosynthesis was about 50–200 ug/g of fresh tissue, whilst the initial level was 0.15 per cent on a dry-matter basis. On a meq basis the critical K/Mg ratio is therefore 3:11.

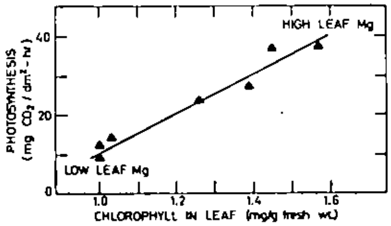

Fig. 56 Rates of photosynthesis and chlorophyll contents of maize leaves having different Mg concentrations *(Peaslee and Moss [1966])*. By courtesy of the Soil Science Society of America.

Leaves with slow photosynthesis rates showed the yellowish-green and light yellow streaks typical of Mg-deficiency. The relation between chlorophyll concentrations of the leaves and their rate of photosynthesis is shown in Figure 66 (correlation $r^2 = 0.96$).

In contrast to the reversible effect of K-deficiency on photosynthetic activity (cf. p. 166)*, leaves deficient in magnesium fail to recover after fertilizer applications. *Peaslee and Moss* conclude that the deterioration of the chlorophyll appears to be the major cause of decreased photosynthesis in Mg-deficient leaves, even though it becomes important only at advanced degrees of chlorosis.

In field trials in Rumania with hybrid maize grown at a density of 3–3.3 plants/m^2, it was found that an application of 80 kg N + 20 tons farmyard manure/ha increased chlorophyll content of the leaves at flowering by nearly 30 per cent. A direct relationship was established between leaf chlorophyll content at flowering, and grain yield *(Hurduc and Stefan [1966])*.

In trials in Trinidad, the application of nitrogen at the rate of 154 kg N/ha increased NAR from 0.446 to 0.530 g/dm^2/wk. The respective values of the crop growth rate were 0.827 and 1.194 g/dm^2/wk *(Gibbon [1966])*.

Whilst there may be differences of opinion on the magnitude of the effect of fertilizers on the rate of photosynthesis, the available evidence indicates that nutrient deficiencies do reduce photosynthetic efficiency to some extent. Even small increases in the rate of photosynthesis can result in fairly large increases in dry matter production, because the latter accumulates according to the principle of compound interest.

8.3.10 Respiration rates

Actually, NAR does not reflect only photosynthetic rates, but is also influenced by respiration rates.

The proportion of the photosynthates that is used for respiration varies widely with the crop and the environment but is generally quite substantial, amounting to as much as 40 per cent *(Muller [1964])*. Not all of the dry matter used for respiration can be considered as wasted. *Wilson [1969]* distinguishes among the following three components of total respiration:

(a) constructive respiration

Respiratory energy is required for the synthetic processes on which structural growth depends. A close relationship has been shown to exist between relative growth rate and respiration rate in a number of crop plants, indicating that for each gram of tissue synthesised, about half a gram of substrate is respired to provide energy.

(b) maintenance respiration

In addition to providing energy for growth, respiration is necessary to maintain the existing organisation, such as maintaining the concentration of mineral salts in the tissues.

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* *Pflüger [1970]* states that plants suffering from an inadequate supply of K are unable to close their stomata rapidly or completely under conditions of moisture stress, and are therefore unable to reduce water losses under an unfavorable moisture regime. Apparently, K-deficiency impairs the mechanism of stomatal adjustment to moisture conditions both as regards the opening and the closing of the stomata.

(c) substrate-induced respiration

Respiration also occurs that is not related to productive metabolic processes. For example, respiration is known to increase when the sugars in the tissues exceed a certain level.

Many studies have shown that even moderate K-deficiency causes an increase in the respiration rates of all tissues of higher plants. An inadequate supply of potassium may influence respiration at the cellular level in many ways; a specific metabolic role for potassium in respiration has not yet been clearly established *(Jackson and Volk [1968])*.

8.3.11 Photorespiration

Most higher plants release a considerable amount of CO_2 when they are photosynthesizing, a phenomenon known as photorespiration. The rate of oxidation of photosynthetic products by photorespiration is about five times the rate of respiration in the dark. Photorespiration appears to confer little or no benefit on the plant, and the reverse is even probably true. Maize is one of the cultivated crops* in which photorespiration does not seem to occur, and this may be one of the reasons for the rapid growth rate and productivity of this crop, among the greatest of the higher plants *(Goldsworthy [1969])*.

8.3.12 Relationship between NAR and LAI

The results of various experiments have suggested that NAR is almost independent of LAI when the latter does not exceed a certain value, but decreases when LAI increases beyond this value.

If NAR decreases with increases of LAI beyond a certain range, crop growth rate cannot be linearly related to LAI, but must increase more and more slowly with increasing LAI, eventually reaching a maximum and subsequently falling *(Watson 1947])*. In investigations by *Hoyt and Bradfield [1962]* the NAR of maize was found to be a linear function of the leaf area, when LAI was less than 2.7. At higher LAI values, NAR declined rapidly and showed a tendency to level off. At a LAI of 4.0, a decrease in rate of dry matter accumulation occurred even under ideal moisture conditions and with an ample supply of soil nutrients.

The dry matter produced per m^2 of leaf surface from grain initiation to maturity showed that the top leaves were much more productive than the bottom leaves. In a stand with a LAI = 3, the amount of dry matter produced per m^2 of leaf area by the top, middle, and bottom leaves was of the ratio 4:2:1. The bottom leaves produced less dry matter because of lower light intensity as a result of shading. It was the reduced production in the lower leaves that caused the decreasing NAR values at high LAI *(Hoyt and Bradfield [1962])*.

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* Maize and sugar cane are two crops that have some unusual features relating to photosynthetic rates, leaf anatomy, the morphology and other characteristics of the chloroplasts. These unique features are accompanied by a unique process of CO_2 fixation, called the C_4 – dicarbolic acid pathway. Photorespiration is apparently inoperative in plants having this pathway *(Hatch and Slack [1970])*.

8.3.13 Length of the growing period

Yield of dry matter can be derived from the following formula:

$$Y = LA \times NAR \times t,$$

in which Y = total production of dry matter,
LA = assimilating area,
NAR = net assimilation rate, and
t = time

The length of the vegetative period (t) is obviously of great importance in determining the effect of LAI on yields. Fertilizer treatments aimed at the most efficient use of the available growing season may contribute considerably to increased productivity. An integral of LAI over the growth period is a measure of the combined action of LAI and time and has been called 'leaf area duration' (LAD) by the English workers and 'photosynthetic potential' by the Russians. LAD is a measure of the opportunity for assimilation throughout the life of the plant. In fertilizer trials in Trinidad, LAD and grain yield were found to be linearly related *(Gibbon [1966])*.

Grain yields of maize have been shown to be linearly related to leaf area indexes at silking time and to the leaf area index days* over the grain formation period (**Figure 57,** *Eik and Hanway [1966])*. Values that did not fit this general relationship were obtained from maize grown without fertilizer or with insufficient fertilizer.

The quantity of dry matter accumulated per plant on any date was proportional to the accumulated leaf area days (**Figure 58**). About 45 days after emergence, there started a period of rapid dry matter accumulation, during which the curves representing dry-matter accumulation as well as those representing leaf area days were practically linear *(Eik and Hanway [1966])*.

The importance of the longevity of the leaves was well demonstrated by a study in Nigeria of the development of two varieties of maize which have very different yielding performance, in spite of a rather similar vegetative development *(Van Eijnatten [1963])*.

The lower yielding variety (Lagos White) had a more rapid loss of leaf by senescence, from the eighth week onwards, i. e., from shortly before the period of rapid develop-

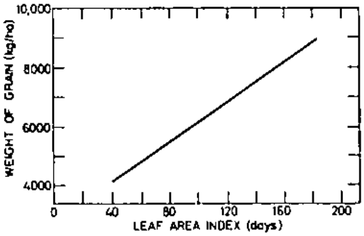

Fig. 57 Relationship between the treatment means of the final grain weights and the leaf area index days from silking to 45 days after silking. Four experiments in 2 years combined *(Eik and Hanway [1966])*. By courtesy of the American Society of Agronomy.

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* Leaf area index days: the integrals of the values of LAI over the period from silking date to 45 days after silking.

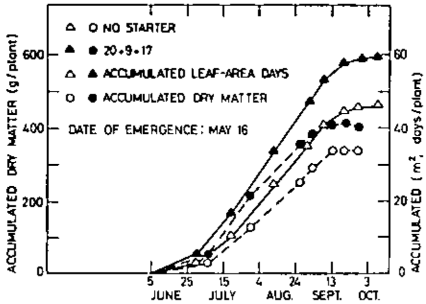

Fig. 58 Relation between accumulated dry matter and accumulated leaf-area days *(Eik and Hanway [1966])*. Note that the quantity of dry matter accumulated per plant on any date is proportional to the accumulated leaf area days. By courtesy of the American Society of Agronomy.

ment of the ear. The retention of a larger functional photosynthetic area by the higher yielding variety (ES2), during the development of the ear, therefore appears to be the major factor responsible for its higher production of dry matter in the latter period of development, when compared with the lower yielding variety **(Figure 59)**.

In the investigations by *Eik and Hanway [1965]* it was found that starter fertilizers generally tended to result in the formation and maintenance of larger leaf areas from silking date until about 50 days after silking, but occasionally increased the rate of leaf drying, where no plough-under fertilizer had been applied **(Figure 60)**. The longevity of the leaves was therefore influenced mainly by the continued availability of nutrients, particularly of nitrogen. *Hanway [1962 b]* has also shown that extreme N- and K-deficiencies cause the premature death of a number of leaves on maize plants, thereby shortening the period during which these leaves are photosynthetically active.

Continued accumulation of nutrients fairly late in the season is therefore essential for maintaining minimum levels of nutrients in the leaves, as otherwise translocation of nitrogen and potassium from the leaves would cause premature death in at least some of the leaves. The loss of P from the leaves, following translocation to the grain, does not appear to cause chlorosis and necrosis of the leaves as does the loss of nitrogen and potassium. Premature death of leaves due to N-deficiencies may occur at any stage of growth, whilst necrosis due to a K-deficiency appears most likely to develop prior to the period of grain formation since most of the potassium has been taken up prior to that time *(Hanway [1962 b])*.

Moss and Peaslee [1965] have found that normal-appearing older leaves of maize, suffering from a potassium deficiency, had lower photosynthetic rates even in ample light, and that this disability could be largely removed by ample K fertilization. They concluded that the lower leaves of maize, if supplied with adequate moisture and nutrition, could assimilate CO_2 at nearly the same rate as younger, higher placed leaves when they received the same intensity of light, and that leaf senescence is therefore not determined by age alone.

8.3.14 Biological and economic yield

We have discussed at length the ability of the plant to produce a high yield of carbohydrates. In maize grown for silage or forage, the total dry matter production or biomass has economic significance; however, this is not the case with maize for grain. That part of the biomass which is converted into the economic product has been called the 'economic yield' *(Nichiporovic [1960])*. The relationship of the economic yield to the total, or 'biological yield', is expressed as the 'coefficient of effectiveness' or 'harvest index' (K) according to the equation

$$Y_{\text{biol}} \times K = Y_{\text{econ}}.$$

There exist, therefore, two different, though not necessarily antagonistic, pathways that can be followed in achieving high yields of grain:

(a) increasing the total production of dry matter (Y_{biol}), which has already been dealt with, and
(b) increasing the proportion of the total dry matter produced that is accumulated in the parts of the plant of economic importance ($Y_{\text{econ.}}$) e. g. by increasing the coefficient of effectiveness (K).

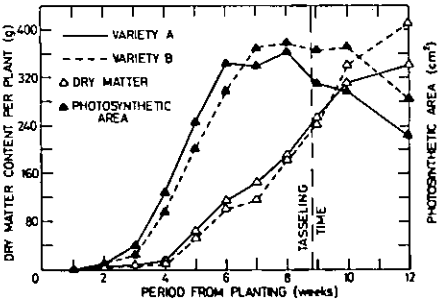

Fig. 59 Increase in dry matter and photosynthetic area in two varieties of maize (Lagos White; ES 2) *(Eijnatten [1963])*. By courtesy of the Cambridge University Press.

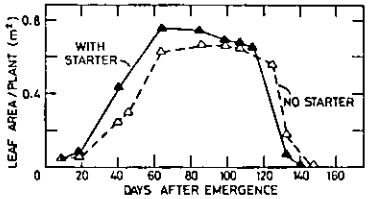

Fig. 60 Effect of starter fertilizer on total leaf area per plant throughout the growing season *(Eik and Hanway [1965])*. Note that whilst the starter fertilizer (where no plough-under fertilizer had been applied), resulted in a larger leaf area until about 50 days after silking, the rate of leaf drying was increased thereafter. By courtesy of the American Society of Agronomy.

A balance between the productive parts of the plant and the reserves which form the economic yield is essential. Experience has shown that a considerable increase in the yield of the economic product is usually dependent on an increase in the total dry matter produced. However, this is not an absolute relationship. In extreme cases, the opposite is true. In maize, high plant populations which produce the greatest biomass (and are therefore the most efficient in utilizing radiant energy), may produce little or no grain because of excessive competition between the plants for light.

In many cereals, most of the dry matter in the grain is produced by photosynthesis after the ears emerge. Grain yield therefore depends to a large extent on the photosynthetic activity of the parts of the plant that are still green after anthesis. One possible way to increase the effective yield would therefore be to extend the duration of the period of formation of the economic product. For example, the formation of grain in maize takes an average of about 35 days of the total growing period. It is estimated that with the varieties grown at present, every additional day of grain formation would increase yields by approximately 3 per cent *(Army and Greer [1967])*. Selecting or breeding for varieties or hybrids with a period of 50 to 75 days between fertilization and grain maturity, would make possible a yield increase of approximately 50 per cent. This is, of course, possible only in regions with a long, frost-free growing season.

8.3.15 Effect of fertilizers on the coefficient of effectiveness (K)

In a study with 11 maize hybrids *(Hanway and Russell [1969])*, it was found that the proportion of grain varied from 35 to 52 per cent of the total plant weight. On an average, grain constituted 42 per cent of the total dry weight of the mature plants. Each of the non-grain parts represents essentially the same relative proportion of the total non-grain weight in the different hybrids.

In contrast to the effect of nitrogen on the ratio of grain to straw in wheat and barley, in which nitrogen increases the straw component far more than the grain, the increase in grain yield in maize is proportionally greater than that of the vegetative parts of the plant. This is mainly because the maize plant is not capable of reacting to an increased supply of nitrogen by increasing the number of tillers to the same degree as is possible in wheat, for example. Therefore, the main response of the maize plant to applications of nitrogen is an increase in the number and weight of the kernels *(Collier et al.[1958])*. This is borne out by numerous experiments, of which a few examples follow:

The effects of nitrogen on the respective yields of grain and stover in experiments carried out by *Krantz and Chandler [1951]*, are shown in **Figure 61.** These results show that when the amounts of nitrogen applied were relatively low, 3 kg of stover were produced for every kg of grain, whereas on plots which received nitrogen at the rate of 176 to 198 kg/ha – only about 0.8 to 0.9 kg of stover were produced per kg of grain.

In 14 more recent fertilizer experiments in Nebraska on irrigated maize, fertilization increased stover yields by an average of 17 per cent, whilst the corresponding grain yield increase was 62 per cent. The grain-stover ratios were 1.0 for unfertilized maize and 1.4 for fertilized maize *(Olson et al. [1964])*.

In a spacing × fertilizer experiment carried out on a fine sandy loam in Mississippi, nitrogen was applied at rates of 0, 66 and 132 kg/ha, in combination with stands of

1.0 and 3.0 plants/m², respectively *(Jordan et al. [1950])*. The grain-stover ratios obtained are given in Table 35.

Table 35. Grain-stover ratios in spacing x fertilizer experiment *(Jordan et al. [1950])*

Nitrogen (kg/ha)	Number of plants per m²	
	1.0	3.0
0	1:1.570	1.476
66	1:1.150	1.142
132	1:0.840	1:0.97

At both plant densities the proportion of grain to stover increased as a result of nitrogen fertilization.

8.3.16 The components of economic yield

Attempts have been made to achieve better understanding of the economic yield of many crops by breaking down yield into a number of components.

The traditional breakdown into yield components

A familiar formula of yield is that for grain cereals:

$$Y = n \times a \times b \times c \times d$$

in which Y = grain yield per unit area,
n = the number of plants per unit area,
a = the number of fertile tillers per plant,
b = the number of ears per tiller,
c = the number of grains per ear, and
d = the weight of the individual grain.

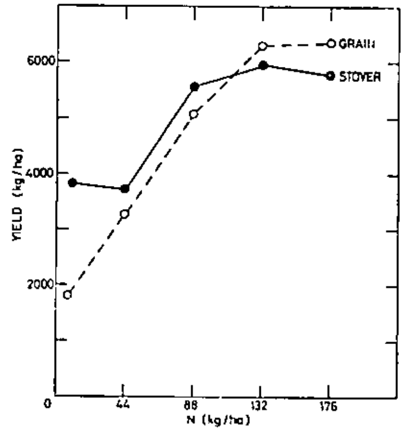

Fig. 61 Effects of nitrogen fertilization on the yields of grain and stover. (Based on data from *Krantz and Chandler [1951].)* Note that high rates of nitrogen actually favour grain production more than stover production.

At first sight, an increase in one of the components on the right hand side of the equation should lead to an increase in yield. This has led, in the past, to a considerable amount of attention being paid by agronomists to these factors in the hope that yields could be increased by achieving a combination of components such as more numerous ears, larger ears, heavier grain, etc. This requires an understanding of the influence of the various components on yield, and the effect of crop management in general, and of fertilization in particular, on each of them.

Number of plants per unit area (n)
This aspect has been dealt with in detail in chapter 4. The application of fertilizers makes it necessary to adjust population density upwards, in order to ensure efficient utilization of the higher levels of nutrient supply.

Number of fertile tillers per plant (c)
Most cereals have a considerable capacity to increase the number of fertile tillers per plant, when sufficient space and nutrients are available to the individual plant. However, most varieties of maize do not have this tendency, probably as a result of selection for large ears *(Mangelsdorf [1965])*. Whatever tillers are formed do not normally carry ears (cf. p. 23).

Number of ears per plant
It has already been mentioned (cf. p. 31) that single-eared maize was preferred in the past because of the popular emphasis on large ears and the greater ease of harvesting at a time when most maize was harvested by hand. Prolific varieties are now becoming popular.

At low nitrogen levels, most of the plants in prolific varieties are either single-eared or barren. As the nitrogen level is increased, ear size increases. However, in some plants the second ear develops long before the first ear has reached its average maximum size *(Krantz and Chandler [1954])*.

In **Figure 62** the effect of nitrogen fertilizers on the weight of ears is shown for single-eared and for prolific hybrids. It can be seen that with increasing rates of nitrogen, the bottom ear of a plant carrying two ears continues to increase in weight after the weight of single ears has leveled off.

In **Figure 63**, double-eared plants are seen to account for a much larger portion of the total yield at high nitrogen levels. Hence, in prolific varieties both ear number and ear size increase as nitrogen is added, the former more than the latter.

Number of grains per ear and weight of the individual grain
Increasing the productivity of the plant, in terms of increased carbohydrate production, will contribute to increased yields only if the total storage capacity of the plant is adequate. In the case of the cereals, this means that a sufficient number of grains is produced and their development is adequate; in other words, an adequate 'sink' is required, capable of receiving the carbohydrates in excess of the metabolitic needs of the plant.

It has been shown, in non-cereals, that there is a feed-back effect, in the sense that the size of the 'sink' affects the production and the movement of carbohydrates in the plant. It is therefore possible that in maize, also, too few grains, or their unsatisfactory development, may restrict the photosynthesis of the shoot *(Thorne [1966])*.

Hence, the importance of number of grains per ear and weight of the individual grain. Generally speaking, factors acting early in the season influence mainly grain number, whilst the size of grain is affected by the factors acting after anthesis. The number of rows of kernels per ear (or grain number per ear) can be increased significantly by small amounts of nitrogen fertilizer, provided the nitrogen is applied at a very early stage, i. e., before the plants are 20 cm tall. Even much larger amounts of nitrogen applied at later stages did not influence the number of rows *(Schreiber et al. [1962])*.

Weight of individual ears

In chapter 4, we have shown that maximum yields of maize are associated with average-sized ears*; large ears are an indication that the plant population was too low to utilize fully the productive potential of the field. Increased soil fertility as the

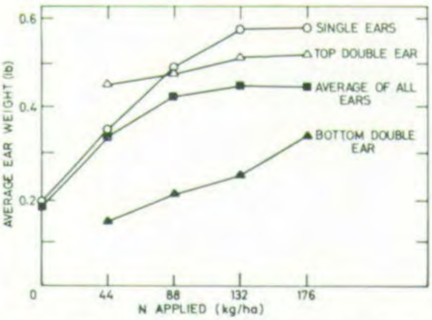

Fig. 62 Effect of nitrogen fertilizers on the weight of ears of single-eared and of prolific hybrids *(Krantz and Chandler [1954])*. Note that with increasing rates of nitrogen, the weight of the bottom ear of a plant carrying two ears continues to increase, after the weight of single ears has levelled off. By courtesy of the North Carolina Agricultural Experiment Station.

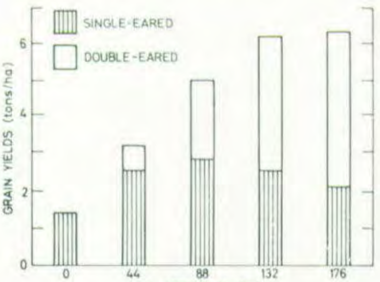

Fig. 63 Relative contributions to total yield of single-eared and double-eared plants at increasing levels of nitrogen application *(Krantz and Chandler [1954])*. By courtesy of the North Carolina Agricultural Experiment Station.

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* For prolific varieties, i. e. varieties producing more than one ear per plant, it would be more logical to consider *grain yield per plant* than average weight of ear.

result of a consistent and adequate supply of nutrients is therefore best exploited by adjusting plant density and not by aiming at increased size of weight of the ear (Plate 11).

For a given weight of ear, potassium nutrition has a considerable influence on the proportion of grain in the ear, as indicated by the husk to grain ratio. A deficiency of potassium markedly increases the proportion of husk relative to the rest of the ear. In experiments reported by *Loué [1963]*, the ratios of grain to husk were: 4.42 on potassium-deficient soil, 5.54 when K_2O was applied at the rate of 80–100 kg/ha, and 5.70 for K_2O applications of 120–160 kg/ha.

To recapitulate: Attemps to obtain high yields by combining in the individual plants a large number of ears per plant, large ears and large kernels, have generally not been successful. The maximum yield that can be achieved under given environmental conditions has a ceiling which cannot be surpassed. Any increase in one of the components is therefore usually accompanied by a parallel decrease of another component even when the growing conditions are optimal. Experience has shown that an inverse correlation exists among the yield components; and that the highest yields are not obtained from fields in which the plants have extremely large heads or heavy kernels, but usually from those in which these components attain average size.

It should not, however, be assumed that no worthwhile significance can be attached to the traditional yield components. It is true that yields cannot be increased *beyond* an upper limit by manipulating individual yield components, but much can be done to approach this limit by achieving yield components that are well-balanced and adjusted to the environmental conditions under which the crop is to be grown.

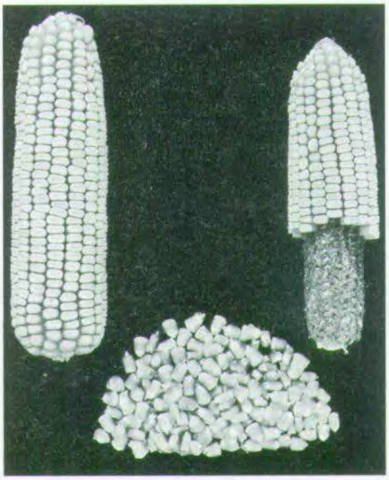


Plate 11

Typical well-formed, medium sized-ear of single-cross maize obtained from well-fertilized optimum stand of 5 plants/m², grown under irrigation. Amounts of fertilizer applied (in kg/ha): Sulphate of ammonia 1200, superphosphate 1000, muriate of potash 600; amount of water applied 500 mm. Photo *A. Shlomi.*

The role of fertilizers in this respect is (a) in raising the ceiling for the maximum yield that can be achieved under given environmental conditions, and (b) in ensuring that each of the individual yield components can make its maximum contribution to the achievement of the maximum yield.

8.4 Growth and morphology

8.4.1 Germination

The effect on maize germination of fertilizer salts that come in contact with the seed, will depend on the kind and rate of application of fertilizers and on the soil moisture level.

The effects of commercial fertilizers on the germination of maize, obtained in experiments by *Cummins and Parks [1961]*, are shown in Table 36.

Table 36. The percent concentration of selected fertilizers which resulted in detrimental effects to maize germination *(Cummins and Parks [1961])*

Fertilizer	Concentration (%)
Anhydrous ammonia	0.10
Urea	0.05
Sodium nitrate	1.00
Ammonium nitrate	1.00
Ammonium sulphate	2.00
Muriate of potash	1.00
Potassium sulphate	2.00
Concentrated superphosphate (48%)	5.00
Ordinary superphosphate (16%)	10.00
6 – 12 – 12	2.00

Nitrogenous fertilizers differed as to the concentration at which they caused reduced germination. Most injurious were anhydrous ammonia and urea. The injurious effect was probably due to a high concentration of NH_4^+ ions in the vicinity of the seed, resulting from the reaction of the anhydrous ammonia with water and from the release of NH_3 during urea hydrolysis. Sodium nitrate and ammonium nitrate were much less injurious than the former N-carriers mentioned; least injurious was ammonium sulphate.

The potassium fertilizers were similar to the three latter nitrogen fertilizers in their effect on seed germination. Muriate of potash was more detrimental than potassium sulphate of potash, probably because of the Cl ion.

Germinating maize seeds tolerated far higher concentrations of phosphorus fertilizers than of nitrogen or potassium fertilizers. Concentrated superphosphate was twice as injurious to germination as ordinary superphosphate.

The effect of the mixed fertilizer (6–12–12) on germination was probably due to the additive effects of its components.

8.4.2 Root growth

A high level of soil fertility is usually conducive to the proliferation of the root system; penetration in depth is frequently limited as a result of an unsatisfactory nutrient status underneath the ploughed layer, and hence a favourable nutrient regime may be even more important than a favourable physical environment for the deep rooting of the plant.

Fehrenbacher and Rust [1956] reported that in a well-fertilized rotation, corn roots penetrated to a depth considerably greater than in unfertilized controls (Plate 12 – see page 179).

The total approximate weight of dry roots per hectare of maize on fertilized soils was found in Illinois to range from 2200 kg to 2900 kg, and that of maize grown on unfertilized soil amounted to only 820 kg **(Figure 64)** *(Fehrenbacher and Snider [1954])*.

Roots are generally the first part of the plant to suffer from a shortage of nutrients. At any one time, the root systems of the plants are in contact with no more than 1 per cent of the total soil area in the root zone. However, as the roots continue to grow, root hairs die and are replaced by new ones, so that throughout the life of the plant, a considerable proportion of soil may be explored by the roots.

Fertilizers that are broadcast and incorporated in the soil promote a considerable proliferation of the root system in all directions, whilst fertilizers applied in the band encourage intensive growth of fine fibrous roots around and within the band. Both types of root growth are essential for maximum efficiency in nutrient uptake and for high yields *(Burson et al. [1962])*.

Any influence on root development by fertilizers has relevance to the water relationships of the plant. As water movement in unsaturated soils is both limited and slow, an extensive proliferation of roots is essential to enable the plant to utilize soil moisture effectively. The extent of the root system also determines the depth of the reservoir from which plants can absorb water, and hence their ability to make use of water and nutrients stored in the sub-soil **(Figure 65,** *Smith [1953])*.

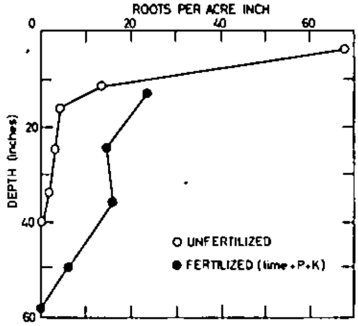


Fig. 64

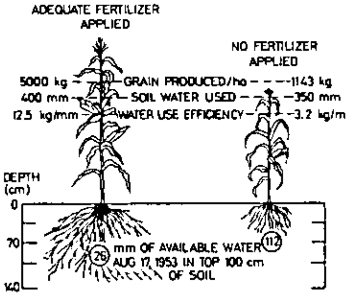


Fig. 65

Fig. 64 Distribution of maize roots in profiles of fertilized (O) and unfertilized (●) soil *(Fehrenbacher and Snider [1954])*. By courtesy of the State University, New Brunswick, N.J.

Fig. 65 Effect of fertilization on root development of maize and on efficient use of soil moisture *(Smith [1957])*. The maize grown with inadequate nutrients does not develop sufficient root system to utilize subsoil moisture. By courtesy of the Missouri Farmers' Association.

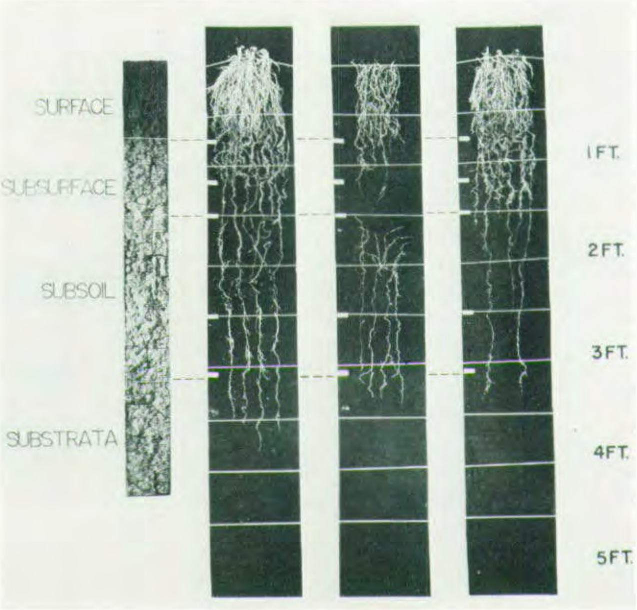
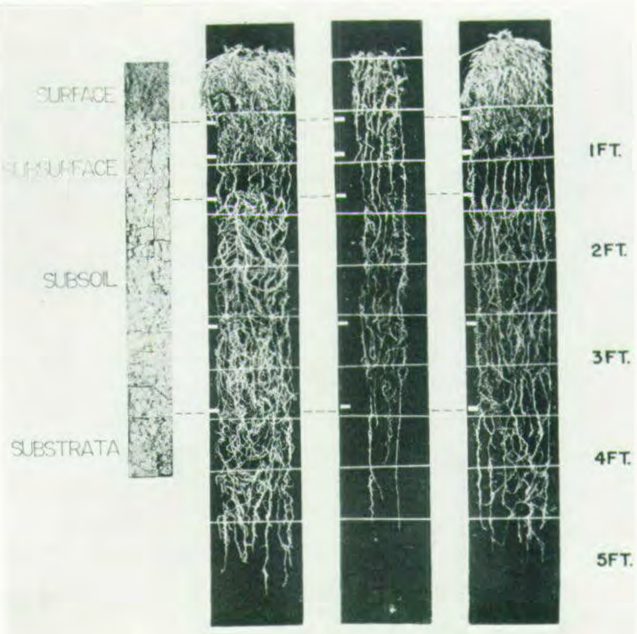


Plate 12
Effect on maize root development of fertilizer application to a silt-loam:

(a) Unfertilized plots.



(b) Fertilized plots.

By courtesy of
J.B. Fehrenbacher.

8.4.3 Nitrogen

Under favourable conditions, roots of maize will penetrate the soil to a considerable depth. In trials in Nebraska, nitrogen fertilization produced a deeper and more extensive root system during the early part of the growing season.

The greatest difference in root production between nitrogen-fertilized and unfertilized plants was observed when the maize was 50 days old, at which time the fertilized plots contained nearly three times as many roots by weight as did the non-fertilized plots; maximum root penetration at this time was 130 cm for the fertilized maize and 95 cm for the unfertilized plots. These differences disappeared with increasing maturity, possibly because root penetration was impeded below 1 m by the high bulk density of the soil and nutrient deficiencies at this depth *(Linscott et al. [1962])*.

Entirely different results were obtained by *Dormaar and Ketcheson [1960]*, who have shown a linear decline in the weight of roots (dry matter) with increasing N rates. NH_4 – N produced more root dry matter than NO_3 – N at the lower levels of N – application **(Figure 66).** These investigators, however, point out that the active absorbing surface may vary independently of root weight. Roots in the soils to which NH_4 – N had been applied tended to be more finely branched than those in NO_3 – N treated soils.

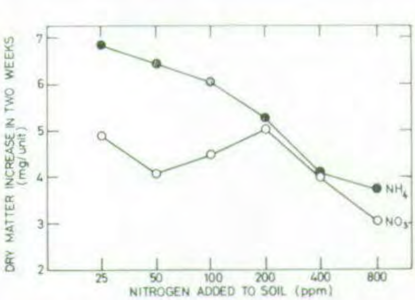


Fig. 66 Effect of nitrogen level and form on the increase in total dry matter in roots of maize plants grown in soil over a 2-week interval *(Dormaar and Ketcheson [1960])*. By courtesy of the Agricultural Institute of Canada.

8.4.4 Phosphorus

Long-term experiments in Virginia showed that phosphates had a beneficial effect on root development by maize. When the plants where grown in sand cultures, phosphate-deficient plants produced roots with 43.7 g of dry matter, whilst plants supplied with ample amounts of phosphate had 88.5 g *(Pettinger [1933])*.

8.4.5 Potassium

The effect of potassium fertilizers on low-potassium soils, on decreasing the lodging of maize due to weakness of the root system, is discussed on p. 185. *Hoffer and Krantz [1949]* have shown that as a result of potassium deficiency, iron accumulates at the nodes of the stalk, thereby interfering with the translocation of nutrients to the roots;

the roots become weakened and susceptible to root rots, and hence the subsequent lodging.

8.4.6 Sulphur

Root growth of maize is particularly sensitive to sulphur deficiencies. For example, at the 150 ppm level of N, the amount of roots was increased by 230 per cent, when 1 ppm S was added for every 30 ppm added N. No effect similar was noted for wheat roots *(Stewart and Porter [1969])*.

8.4.7 Interactions between fertilizers

Burson et al. [1962] investigated the effects of fertilizer application on root growth of maize in field trials in Minnesota, on a slightly acid silt loam soil, medium to high in organic matter and medium in phosphorus and potassium contents. The best root proliferation was obtained when all three macronutrients – N, P and K – were applied in the starter fertilizer. As high levels of nitrogen with normal levels of phosphorus were found to stimulate root growth in the band, increased amounts of potassium were also required in order to maintain a balanced supply of nutrients. At least 66 kg N/ha in the starter were required to obtain maximum root growth. Adding this amount of nitrogen in a starter containing phosphorus and potassium was much effective than adding higher rates of nitrogen with no potassium.

In long-term experiments in Virginia, on a soil slightly deficient in nitrogen and very deficient in potassium and phosphorus, the effect of nitrogen on root development appeared to be determined largely by the simultaneous status of potassium. In the absence of potassic fertilizers, the application of nitrogen generally reduced root development; where potassium was applied simultaneously with nitrogen, the latter had a slight beneficial effect on root development *(Pettinger [1933])*.

It was assumed that under conditions of K deficiency, the rate of carbohydrate synthesis is relatively low; adding nitrogen under these conditions increased utilization by the tops of the reduced supply of carbohydrates, so that the amount available for translocation to the roots became insufficient for normal development. Where both nitrogen and potassium were deficient, root development was somewhat better, because of a better distribution of the available carbohydrates between tops and roots *[ibid.]*.

In soils deficient in P and K, phosphate fertilizers were also found to be most effective in promoting root growth when applied together with a nitrogen fertilizer *[ibid.]*.

Since both phosphorus and potassium markedly increased root development, and nitrogen is slightly beneficial in the presence of potassium, it follows that root development should be greatest where complete fertilizers are applied to soils deficient in all these elements. This assumption was found to be justified by the results of these long-term experiments *[ibid.]*.

8.4.8 Nutrient content of roots

In Illinois, the chemical composition of maize roots grown in soil that had been treated with limestone, finely ground rock phosphate and muriate of potash, was compared with that of roots grown in untreated soil. Only slight differences in the concentration of nitrogen, phosphorus, calcium and magnesium in the roots grown in the two media were observed. By contrast, there were rather large differences in percentages of potassium in the roots in a comparison between the treated and untreated plots *(Snider [1953])*.

Table 37. Effect of fertilization on potassium content of roots (in percent of dry matter) *(Snider [1953])*

Soil layer (cm)	K in roots (%)		Total amount of K in roots (kg/ha)	
	Treated plots	Untreated plots	Treated	Untreated
0– 15	1.61	0.34	64.8	5.5
15–140	0.95	0.51	10.3	0.9

Nitrogen, phosphorus and calcium contents of roots were found to vary within very narrow limits in three soil types in Illinois. In contrast, the potassium content varied considerably, especially between fertilized and unfertilized soils. *(Fehrenbacher and Snider [1954])*.

Table 38. Nutrient content of roots (%) at two soil depths *(Fehrenbacher and Snider [1954])*

Soil layer (cm)	N	P	K	Ca	Mg	Mn
0– 25	0.92	0.12	1.20	0.35	0.26	0.018
25–180	1.22	0.15	1.15	0.41	0.28	0.022

8.4.9 Effect of direct contact of fertilizers on anatomical and growth responses of primary roots

Isensee et al. [1966] have studied the effects of several fertilizers on the growth and anatomy of the primary root of maize. Nitrogen (ammonium nitrate), phosphorus (triple superphosphate) and potassium (muriate of potash) were used in all possible combinations, at the rate of 33 kg/ha on the elemental basis and placed in bands 2.5 and 5 cm from the seed. Roots that came in contact with any of these fertilizers were shortened and showed deformities. Ammonium nitrate caused the greatest deformity and the shortest roots, while phosphorus and potassium were the least detrimental.

The deformities consisted in the enlargement of the root tips, due to abnormal swelling of the individual cortical cells. The epidermal cells in the affected area were also enlarged, deformed and ruptured. Extensive cellular breakdown and necrosis also occurred in the meristemic region, though the root tips appeared to the eye to be unaffected.

8.4.10 Effects of fertilizers on root anchorage

The effects of fertilizers on root anchorage were investigated on a slightly acid, silt loam soil, medium to high in organic matter, medium in phosphorus and potassium. The results are shown in Table 39 *(Burson et al. [1962])*. The highest degree of root anchorage was obtained when all fertilizers were in balance.

Table 39. Effect of fertilizer treatments on root anchorage *(Burson et al. [1962])*

Treatment	Pounds of pull per stalk*
Effect of potassium	
NPK	259
K in starter + K broadcast	251
K broadcast, none in starter	217
Effect of N in starter	
Over 44 kg/ha N	250
23 to 44 kg/ha N	282
Less than 11 kg/ha N	200
No fertilizers (control)	179

* Root anchorage was measured by the pounds of critical pull on each stalk of maize required to release the roots from the soil.

8.4.11 Root development in relation to top growth

Pronounced changes occur in the ratio of tops to roots during the growing season. Early development of the plants is characterized by a rapid growth of both tops and roots: At first the weight of the tops increases more rapidly than of the roots, so that the top-root ratio increases. Subsequently, the extensive development of brace roots causes a decline in the top-root ratio **(Figure 67)** *(Foth [1962])*.

It is well known that heavy nitrogen fertilization tends to increase the top-root ratio, since a smaller quantity of carbohydrates is translocated to the roots. For example, in trials by *McLean [1957]*, increasing nitrogen levels produced increased top growth in maize seedlings. Root growth did not increase in proportion to the increased top growth induced, so that top-root ratios generally increased with higher increments of nitrogen (Table 40).

Table 40. Yields of roots and tops and the top-root ratio of maize seedlings grown in solutions with three nitrogen levels *(McLean [1957])*

Nitrogen level	Yields Roots	Tops	Top-root ratio
Low	2.17	1.93	0.9
Medium	2.00	2.52	1.3
High	2.47	3.23	1.3

Since leaf growth is more sensitive to adverse conditions such as an unfavourable water balance, than photosynthesis, these induce an accumulation of carbohydrates in the plants, which is favourable to the *relative* growth rate of the roots and also effects the equilibrium between transpiring and absorbing surfaces *(Brouwer [1967])*.

8.4.12 Relationship between root development and grain yields

Grain yields of maize have been shown to be directly proportional to the weight of roots in a 70 cm layer of soil *(Phillips and Kirkham [1962])* **(Figure 68).**

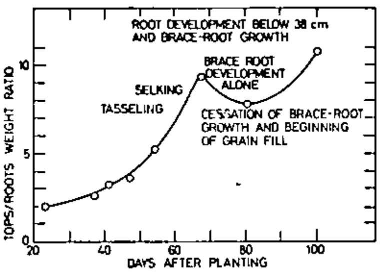


Fig. 67 The variation in the top-root ratio during growth of maize *(Foth [1962])*. By courtesy of the American Society of Agronomy.

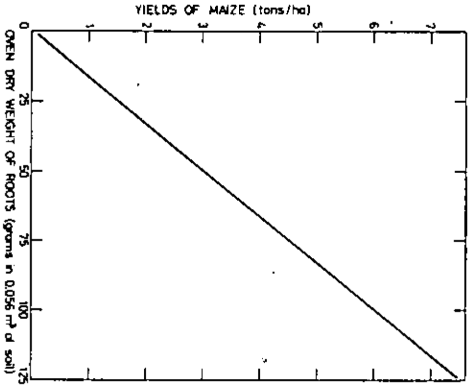


Fig. 68 Yields of maize in relation to dry weight of roots, in a clay soil *(Phillips and Kirkham [1962])*. By courtesy of the American Society of Agronomy.

8.4.12.1 Lodging

Lodging in maize causes difficulties in harvesting and considerable losses in yield. A number of factors contribute to increased lodging:

1. Several pathogens which cause stalk rots, such as *Diplodia, Pythium, Rhizoctonia* and *Gibberella*, weaken the stalks and cause lodging. The pathogens are found in most soils, and are particularly destructive under the conditions of high temperature and high moisture which usually prevail in the period from flowering to maturity. The effects of fertilization on the incidence of root rots will be discussed on pp. 387—390. Insect damage, especially from corn borers, generally causes breakage above the ear, whilst root worms may cause early lodging of the plants.

2. An excessively high plant population increase the rates of lodging; this is particularly marked in certain hybrids which have not been selected for adaptability to dense stands.

One of the major factors in increasing the susceptibility of maize plants to stalk rot is the depletion of food reserves in the stalk, as well as early senescence of leaves. This may be the direct result of excessive interplant competition following very dense planting *(Mortimore and Wall [1965])*.

3. Too early cessation of irrigation, and the ensuing moisture stress on the ripening plant, generally increase lodging.

4. However, numerous investigations have shown that the main factor responsible for lodging in maize is undoubtedly a shortcoming in the nutrition of the plants. For example, much premature dying and subsequent breakage have been observed in high yielding maize following legumes, and in particular lucerne, which are known to be heavy feeders on potassium. Applications of up to 91 kg K/ha were found to reduce dead stalks and lodging significantly under these circumstances *(Josephson [1962])*.

Influence of fertilizers on lodging

Many experiments in the United States and elsewhere, have demonstrated that lodging of maize is considerably influenced by fertilizers. In most cases the lodging can be attributed to potassium deficiency. Nitrogen and phosphorus may increase lodging, especially when the rates of application of these nutrients is increased, and the potassium level remains low.

Burkersroda [1965], in fertilizer experiments in Rhodesia, was able to demonstrate a considerable reduction in lodging of maize grown on a K-deficient soil, by providing sufficient potassium to balance heavy applications of nitrogen (**Figure 69**).

The relationship between N:K_2O ratios in fertilizer and the percentage of lodging in maize for different fertilizer combinations under Rhodesian conditions (**Figure 70**) and the amounts of K_2O required to offset the effects of increasing rates of nitrogen (**Figure 71**) have been calculated by *Cunard [1967]*, from the data provided by *Burkersroda [1965])*.

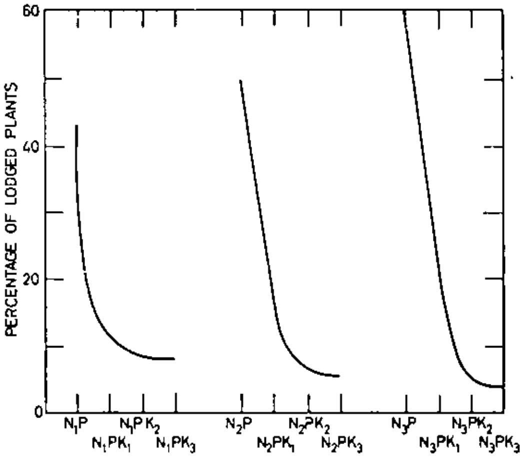


Fig. 69 Effect of N:K interactions on the lodging of plants of a Rhodesian double hybrid *(Burkersroda [1965])*. The rates used were N_1 = 44 kg N/ha, K_1 = 33 kg K_2O/ha, N_2 = 88 kg N/ha, K_2 = 66 kg K_2O/ha, N_3 = 132 kg N/ha, K_3 = 132 kg K_2O/ha, P = 66 kg P_2O_5/ha. By courtesy of the American Potash Institute.

How various combinations of N, P and K affect lodging is shown in **Figure 72**, which is based on the results of an experiment by *Murdock et al. [1962]*). The most striking effect is the high rate of lodging on plots that received nitrogen and phosphorus at the rate of 176 kg N/ha and 176 kg P_2O_5/ha, respectively, and the steep decrease in lodging when 176 kg K_2O/ha is added to these plots.

Microscopic examination of sections of the stalk showed that the pith at the first and second internodes of plants that were badly lodged was almost completely disintegrated.

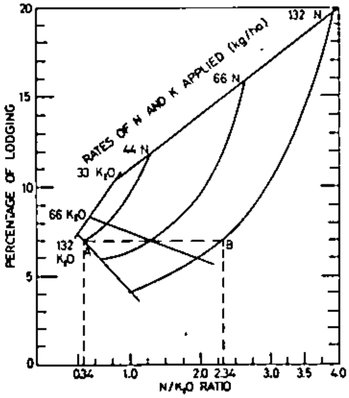


Fig. 70 The relationship between the N:K_2O ratio (fertilizer) and percentage of lodging in maize for different fertilizer combinations under Rhodesian conditions *(Cunard [1967])*. By courtesy of the Editor, World Crops.

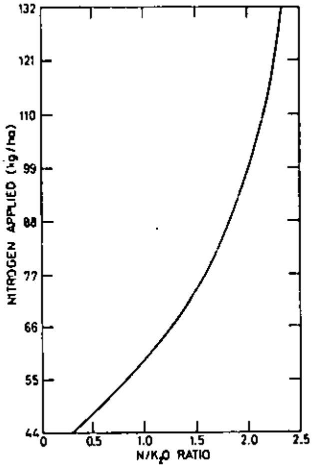


Fig. 71 N:K_2O ratios (fertilizer) permissible at increasing rates of nitrogen, in order that the percentage of lodging in maize may be limited to 7 per cent, in Rhodesian soils (Data from *Burkersroda [1965]* by *Cunard [1967]*). By courtesy of the Editor, Better Crops with Plant Food.

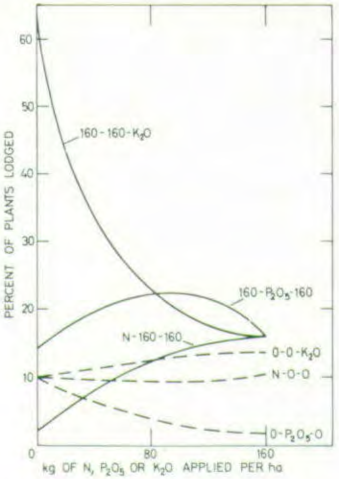


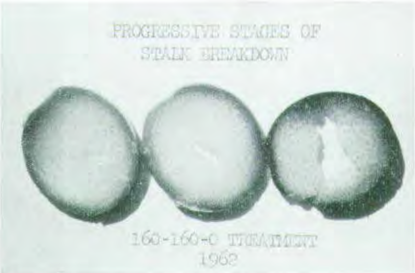
Fig. 72 The influence of level and balance of fertilization on the incidence of stalk breakage *(Murdock et al. (1962))*. By courtesy of the American Potash Institute.

Similar results were obtained by *Liebhardt and Murdock [1965]*, who found that nitrogen alone caused lodging of maize at the rate of 38 per cent, whilst nitrogen plus phosphorus increased lodging to 78 per cent. These rates of lodging were reduced to 3 and 11 per cent, respectively, by adding potassium (see Table 41).

Table 41. Influence of fertilizer treatments on lodging and brace root development of maize *(Liebhardt and Murdock [1965])*

Treatment (kg/ha)			Lodging (%)			Brace root (BR) characteristics		
						Plants with BR above ground	Average no. of above-ground BR/plant	Area above ground (cm²)
N	P	K	Root	Stalk	Total			
0	0	0	1.5	0.5	2.0	53	10.3	32
176	0	0	24.0	14.0	38.0	42	8.3	45
176	0	146	3.0	0.0	3.0	79	10.3	135
176	77	0	50.0	28.0	78.0	42	7.1	64
176	77	146	10.0	1.0	11.0	85	15.0	297

Liebhardt and Murdock [1965] observed two types of lodging in K-deficient plants: root lodging and stalk breakage. The root lodging was due to a restricted brace root system and subsequently, to the breakdown of parenchyma cells in the brace root. Stalk breakage resulted from parenchyma disintegration in the lower portion of the stalk (Plates 13–16). The breakdown of the parenchyma tissues could not be attributed to disease as no evidence of penetration of the plant tissues by patogenic organisms was found until the crop had matured. The breakdown was therefore the result of a severe nutritional deficiency and imbalance, which incidently also hastened maturity.



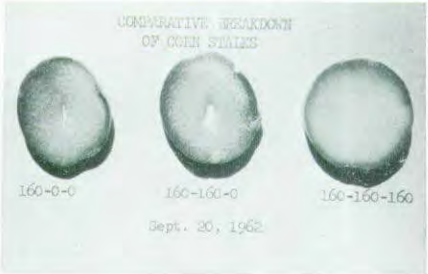
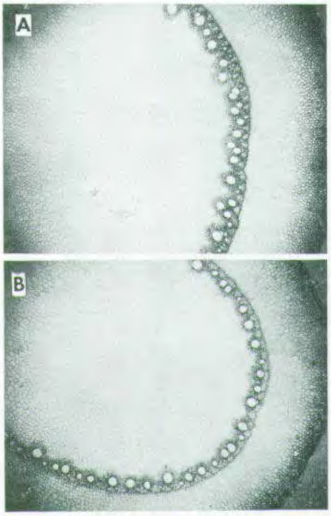


Plate 13
Photograph showing the progressive stages of stalk breakdown in plants grown under conditions of K-deficiency. (By courtesy of the authors: *Liebhardt and Murdock [1965])*.

Plate 14
Photograph showing the relative effects of nutrients on stalk breakdown. Note the characteristic breakdown of the parenchyma in the N-O-O and N-P-O treatments, whilst no such breakdown is apparent in the N-P-K treatment. (By courtesy of the authors: *Liebhardt and Murdock [1965])*.



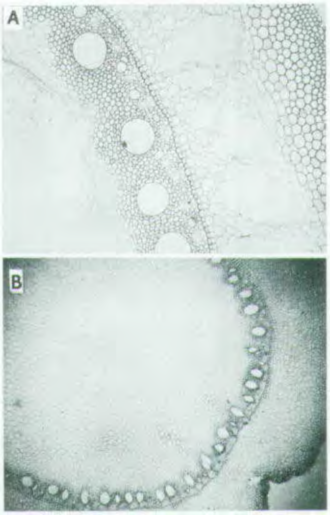


Plate 15
Photomicrographs showing the effect of (A) K-deficiency and (B) high level of K on the internal morphology of the brace root shortly after silking. Note the beginning of pith parenchyma disintegration for the N-P-O treatment, whilst there is none for the N-P-K treatment. These trends continued to maturity. (Magnification 50X) (By courtesy of the authors: *Liebhardt and Murdock [1965])*.

Plate 16
Photomicrographs showing the effect of (A) K-deficiency and (B) high level of K on the internal morphology of the brace root towards the end of the growing season. Note that by this time only the vascular cylinder and the epidermal layers of the brace root of the N-P-O treatment remained intact, whilst only a slight breakdown was observed in the N-P-K treatment. (Magnification: A - 100X, B - 50X) (By courtesy of the authors: *Liebhardt and Murdock [1965])*.

Potassium-deficient plants had N/K ratios greater than 3.5 at maturity, compared with ratios of less than one for plants adequately supplied with potassium.

Premature breakdown of parenchyma in the lower third of the stems of K-deficient maize was considered to be due to inhibition of protein synthesis. Maximum yield of dry matter and of starch plus sugar was attained at the early dent stage, and that of starch plus sugar between the early and late stages *(Liebhardt [1967])*. In another investigation a complete factorial experiment was designed to study the effects of fertilizers on lodging. The three-year experiment comprised four rates of nitrogen (0, 44, 88 and 132 kg/ha) and three rates each of P_2O_5 and K_2O (0, 44 and 88 kg/ha), on a fine sandy loam in Texas *(Fisher and Smith [1960])*. A heavy green manure crop was ploughed under prior to the start of the experiment. Lodging was significantly increased by nitrogen alone or in combination with phosphorus. The higher the rates of nitrogen applied, the greater the percentage of lodged plants **(Figure 73).**

Maximum lodging occurred when nitrogen and phosphorus were applied together. Up to 70 per cent of the plants lodged when the fertilizer treatment 133–88–0 was applied annually. Potassium, whether applied alone or in combination with nitrogen reduced lodging significantly **(Figure 74).**

A significant regression of yield on lodging was established for these trials: for each one per cent increase in lodging, yield was reduced by 34.4 kg/ha **(Figure 75).**

Nitrogen fertilizer application in this trial had no effect on yields, mainly because of the increased lodging, but also because the supply of nitrogen from the green manure crop was apparently adequate and moisture stress during certain periods of growth, restricted crop response to nitrogen.

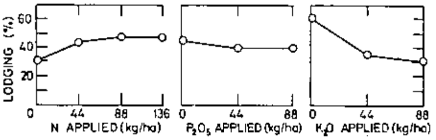


Fig. 73 Lodging of maize as influenced by rates of fertilizer nitrogen, phosphorus or potassium on a fine, sandy loam in Texas *(Fisher and Smith [1960])*. By courtesy of the American Society of Agronomy.

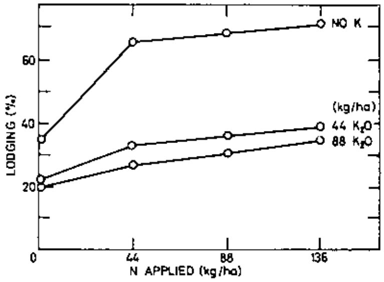


Fig. 74 The effect of potassium in reducing lodging due to applications of nitrogen fertilizer on a fine sandy soil in Texas *(Fisher and Smith [1960])*. By courtesy of the American Society of Agronomy.

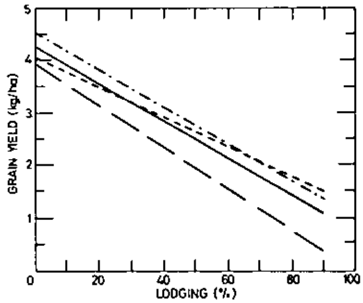


Fig. 75 Regression of grain yield on lodging *(Fisher and Smith [1960])*. For each one per cent in lodging, yields were reduced by 34.4 kg/ha. By courtesy of the American Society of Agronomy.

Phosphorus and potassium, alone or in combination, significantly increased yields. The greatest response from a single nutrient was from potassium, which increased yields from 2032 kg to 3365 kg/ha.

In experiments in N. Carolina, on six soil types of widely varying fertility levels, lodging was decreased and yields were increased by applications of 88 to 132 kg K_2O/ha on potassium-deficient soils, where visual potassium deficiency symptoms occurred in the plants. Potassium application did not affect lodging on soils which contained enough soil potassium so that no visual symptoms of deficiencies could be observed and in which yields were not increased by potassium fertilizer application. Nitrogen markedly increased yields, and at plant populations of 3.5 plants/m^2, it had only small, though consistent, effects on lodging. In three experiments, the mean increase in lodging was only 6.1 percent, while the yield increase from nitrogen application was 3700 kg/ha *(Krantz and Chandler [1951])*.

In Tennessee, potassium application of up to 44 kg K/ha were found to reduce stalk breakage of maize, when given in conjuction with high levels of nitrogen. Where nitrogen applications were low, potassium had no effect on the proportion of broken stalks *(Wittels and Seatz [1953])*.

In an investigation in which five maize hybrids were grown on a loam soil low in exchangeable potassium, at a plant population of 4 plants/m^2, the combined amount of root lodging and stalk breakage was reduced by K fertilization from 18.5 per cent to 5.8–6.5 per cent on an average for the five hybrids tested. In the hybrid most susceptible to lodging, the reduction was from 38.9 per cent to 5.2–11.1 per cent. The differences in lodging due to different levels of potassium were not significant **(Figure 76)** *(Boswell and Parks [1957])*.

In field trials in Honduras with two maize hybrids, Diacol H-205 and Zamorano H-I, sown in K-rich soil and treated with increasing rates of potassium fertilizer, it was found that applications at a rate of 40 kg K/ha reduced lodging in both hybrids, and gave a significant yield increase from hybrid Zamorano H-I, which had shown the greatest tendency to lodge *(Awan [1965])*.

Heavy fertilization rates increase the weight of the ear and hence increase the stress on the stalk of the plant.

Nitrogen fertilization of maize grown under irrigation increased lodging, in spite of the fact that the nitrogen actually increased the 'breaking strength' of the stalks and the diameter of the third internode. The increased resistance of the stalk to lodging was more than offset by increased ear weight and height on the stalk *(Nelson [1958])*.

The manner of applying the potassium fertilizer is also important: In field trials on a silt loam soil, with a high organic matter content and medium levels of available phosphorus and potassium, 140 kg K_2O/ha was applied as KCl, in addition to adequate amounts of nitrogen and phosphorus.

Where all the potassium was applied broadcast and ploughed under, 45 per cent of the stand was lodged. By contrast, where one-third of the KCl was applied with the starter fertilizer in the band and the remainder broadcast, there was no lodging *(Burson et al. [1961])*.

Reliable records on the effect of fertilizers on lodging cannot be obtained under conditions in which no or little lodging occurs. *Parks and Russ [1962]* therefore suggest that the amount and rate of stalk senescence would be a better criterion than the actual rates of lodging, for demonstrating the effects of fertilizers on lodging.

Prevention of lodging

Prophylactic measures follow logically from the causes inducing lodging: to control pathogens and insects as far as possible; to avoid unbalanced fertilizer applications and in particular potassium deficiencies; to sow adepted hybrids at the optimum plant density for yield and standability; to maintain a favourable moisture regime throughout maturation; and to avoid a delay in harvesting.

Indubitably, heavy nitrogen fertilization and increased plant populations required for maximum yield also increase lodging; however, it is not economically justified to reduce fertilization rates or plant density in order to reduce fertilization rates or plant density in order to reduce lodging. A more practical approach is to advance the harvesting date, as much of the lodging occurs during the maturation of the grain; to apply potassium fertilizers in quantities adequate to balance the nitrogen supply.

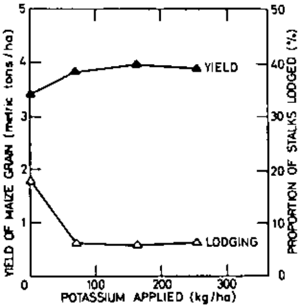


Fig. 76 Average yield and lodging of four varieties of maize with different applications of potassium to a loam soil in Tennessee *(Boswell and Parks [1957])*. Values for lodging are sums of lodging from root and stalk breakage. By courtesy of the Soil Science Society of America.

8.4.13 Maturity

A delay in maturity of the crop may have considerable economic significance to the farmer. In rain-fed maize it may prevent the grain from ripening fully before the available soil moisture is exhausted, resulting in shrivelled grain. In irrigated maize, harvesting difficulties and lowered grain quality may result from delaying maturity until after the autumn rain. In regions with short summers, it may prevent grain maturation entirely.

It is frequently stated that nitrogen fertilizers cause a delay in maturity of most crops. Actually, if there is a deficiency in available nitrogen, an adequate supply of this nutrient can advance maturity of maize by as much as two weeks *(Pesek et al. [1955])*. Properly balanced nitrogen applications, given at the right time and in the right amounts, will generally advance maturity, rather than the opposite. It is the heavy applications of nitrogen, out of balance with the supply of other major nutrients, that delay maturity.

It is known that phosphorus helps to hasten maturity in most cereals.

In an experiment on a typical silt loam soil of the Corn Belt, it was found that when either of the three major nutrients was applied alone, the percentage of stalks in silk at the beginning of August was slightly increased by the first increment of N, P or K. However, the second increment of each nutrient caused a decrease in the percentage of stalks in silk. Applications of N alone caused the greatest delay in silking (approximately two weeks). This delay carried through until grain maturity **(Figure 77)**. When adequate quantities of other nutrients were added, increasing the rates of N and P actually increased the percentage of stalks in silk. Increased rates of K, in conjunction with adequate amounts of N and P, had little effect on time of silking *(Murdock et al. [1962])*.

In experiments on a slightly acid silt loam soil, medium to high in organic matter and medium in phosphorus and potassium, fertilizer applications in sufficient amounts and in proper balance were shown to speed up maturity, reduce grain moisture content and

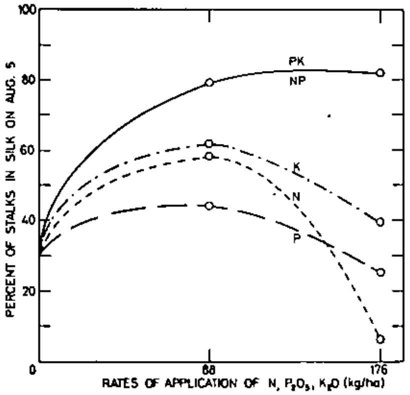


Fig. 77 Influence of level and balance of fertilization on the per cent of stalks in silk on August 5 *(Murdock et al. [1962])*. By courtesy of the American Potash Institute.

improve the quality of the grain. On unfertilized plots, only 50 per cent of the ears were in the milk stage and only 2 per cent in the nearly-mature stage, and therefore safe from frost damage, one month before the average killing frost. By contrast, on the same date, maize grown on plots that had received N – P – K fertilizer (44 N + 44 P_2O_5 + 44 K_2O kg/ha starter, plus 88 kg N/ha side-dressed) had only 2 per cent of the ears in the milk stage and 90 per cent in the nearly mature dent stage, and therefore safe from frost damage *(Burson et al. [1962])*.

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9. Effects of nutrients on plant composition and quality

9.1 Composition and quality of the grain

9.1.1 Proteins

The vital role of proteins in human nutrition, and the disastrous effects on human health of an inadequate balance between proteins and carbohydrates in the diet, are well known. Hence, the possibility of increasing, by the judicious use of fertilizers, the absolute and relative amounts of proteins produced in maize is of major importance, especially for those populations for whom maize is a major food crop and whose low standard of living makes them largely dependent on plant proteins. The protein content of the grain is also of considerable value to livestock feeders and to millers. The protein content on a dry basis may be changed considerably by selective breeding and is also markedly affected by weather conditions and management practices. Starting with a variety of maize containing 10.92 per cent protein, it has been possible, by selection through 50 generations, to produce respectively a high-protein strain averaging 19.45 per cent protein, and a low-protein strain averaging 4.91 per cent *(Woodworth et al. [1952])*.

– *Nitrogen*

The overall picture that emerges from a considerable volume of research is that after plants have used available nitrogen for growth processes related to maximum yield, fairly large doses of nitrogenous fertilizers increase protein content.

In a factorial experiment carried out in seven locations in Virginia with seven hybrids, in which nitrogen was applied at the rates of 66, 132 and 264 kg/ha, and P_2O_5 and K_2O at the rates of 0, 53 and 120 kg/ha, increased rates of nitrogen gave highly significant increases in protein content of the grain, whilst the levels of P_2O_5 and K_2O tested had no effect in this respect, though they caused significant differences in yield *(Genter et al. [1948])*.

These effects of nitrogen have been confirmed by many investigators; a few examples follow:

Bolhuis [1962] working in the Netherlands, found that increasing rates of ammonium sulphate up to 400 kg/ha, increased the protein content to 11.59 per cent, vs. 7.51 per cent for unfertilized maize **(Figure 78).**

Krantz and Chandler [1954], working in North Carolina, showed that ample nitrogen increased the protein percentage and nitrogen content of the grain even when the nitrogen was applied at rates above 132 kg N/ha **(Figure 79).**

Lang et al. [1956] found that increased levels of nitrogen fertilization gave an increase in protein content of the grain at all plant densities investigated **(Figure 80).**
The results obtained in Nebraska are shown in Table 42.

Table 42. Effect of nitrogen fertilizer rate on yield and protein content of irrigated maize *(Anon. [1960])*

Nitrogen applied (kg/ha)	*Maize yield* (kg/ha)	*Protein content* (%)
0	4700	7.5
88	6477	8.5
196	7048	9.2

Occasionally, a low rate of nitrogen may actually reduce the protein content to below that of unfertilized maize, as shown in Table 43.

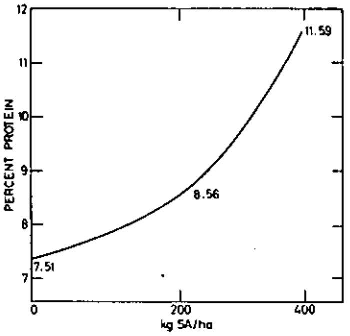

Fig. 78 The effect of nitrogen fertilizer on the protein content of maize *(Bolhuis [1962])*. By courtesy of the Editor, World Crops.

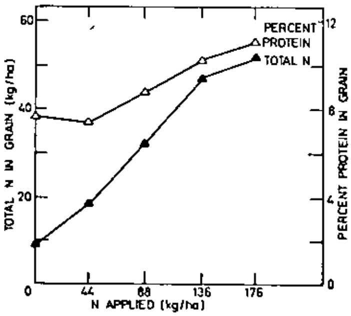

Fig. 79 Effect of nitrogen fertilizer on the protein content of the grain and of total nitrogen uptake by the grain *(Krantz [1949])*. By courtesy of the North Carolina Agricultural Experiment Station.

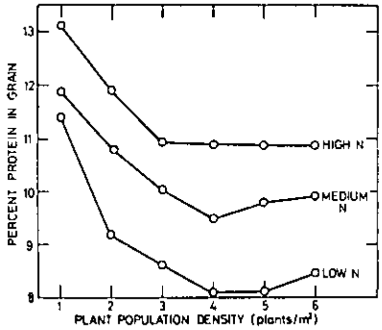

Fig. 80 Effect of plant population and nitrogen level on the percentage of protein in maize grain – average of 9 hybrids – *(Lang et al. [1956])*. By courtesy of the American Society of Agronomy.

Table 43. Effect of nitrogen fertilizer rate on protein content of maize *(Zuber et al. [1954])*

Nitrogen applied (kg/ha)	% protein in grain 1951	1952	
0	7.73	7.28	
55	7.25 (— 7%)	7.12 (— 3%)	
132	8.83 (+21%)	10.27 (+29%)	compared with N 50
275	9.64 (+33%)	10.27 (+44%)	

The addition of 55 kg N/ha gave a significantly lower protein content than the control without nitrogen. This was clearly a 'dilution' effect, due to the improved vegetative growth of the fertilized plants.

– *Nitrogen × sulphur interactions*

Thomas [1959] found that under conditions where neither nitrogen nor sulphur separately increased the yields of maize, combined applications of these two nutrients increased the protein content of the grain significantly.

He explains the significant interaction of nitrogen × sulphur on the basis of the generally accepted view that in the synthesis of protein, each kind of amino acid in the peptide chain recurs at constant intervals. Therefore, if either nitrogen or sulphur are limiting for the synthesis of a specific amino acid required for a given protein, this would also limit the synthesis of the protein. It also appears that the optimum amounts of nitrogen and sulphur required for protein synthesis are higher than those required for yield.

– *Potassium and phosphorus*

Intensive protein synthesis requires, in addition to fairly high levels of nitrogen, a balanced supply of potassium and phosphorus. The general effect of potassium, except when it is supplied at excessively high levels, is to increase the effectiveness of nitrogen and, in conjunction with phosphorus, to counteract the unfavourable effect of high N-fertilization on the quality of the protein (cf. p. 199).

In experiments in Rumania, the NPK treatment increased protein content by 1.68 per cent, in comparison to the NP treatment. This represents a relative increase of 17 per cent in the protein content of the grain. In other experiments, on a podsolic soil, potassium increased the total amount of proteins produced per ha by 174.2 kg, as compared to the unfertilized control, and by 87.8 kg, as compared to the NP treatment *(Davidescu [1965])*.

Keeney [1970] reports that while N fertilizer treatments increased the protein level of the grain by 10 per cent, the balanced N-K treatment increased the protein concentration by an additional 14 per cent.

– *Effect of fertilizers on protein quality*

The increased protein content of maize grain due to N-fertilization is usually accompanied by a reduced biological value* of the protein.

Nearly half the protein of maize consists of glutamic and aspartic acids, leucine, and proline. Several of the nutritionally most important amino acids (lysine, methionine, threonine) together constitute less than 10 per cent of the total *(MacGregor et al. [1961])*.

A direct relationship has been established between the amount of nitrogen applied to the soil and the contents of crude protein, zein and leucine in the grain *(Prince [1954])*. The ratio of zein to crude protein indicates that zein content increases at a faster rate than crude protein. The effect of nitrogen on tryptophane content was not found to be pronounced, but there was a tendency for tryptophane to increase with nitrogen application; however, when the tryptophane content was expressed as a percentage of total crude protein, it was found to decrease with increased nitrogen rates. Nitrogen applications tend to decrease both the total amount of isoleucine and its percentage of the crude protein.

Table 44. Effect of varying nitrogen application to the soil on the protein composition of maize grain (means of 3 varieties) *(Prince [1954])*

Nitrogen applied	Crude Protein	Zein fraction	Ratio Zein to Crude Protein	Grams amino acid per 100 grams maize			Tryptophane	Grams amino acid per 100 g protein	
(kg/ha)	(%)	(%)		Tryptophane	Leucine	Isoleucine		Leucine	Isoleucine
15	7.81	1.84	0.236	0.045	1.63	0.59	0.58	21.1	7.6
60	9.37	2.45	0.261	0.049	1.84	0.49	0.61	20.0	4.3
105	8.97	2.52	0.281	0.052	2.47	0.43	0.57	27.8	4.0
150	9.53	2.93	0.307	0.050	2.67	0.52	0.52	28.0	5.5

Similar results have been obtained by a number of other investigators:

In trials in which nitrogen fertilization substantially increased grain yields, protein content of the grain and protein production per ha, it consistently lowered the pro-

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* *Biological value:* The degree to which protein is able to replace body protein degraded in the course of the functioning of the organism.

portional concentrations of arginine, lysine, methionine, and valine *(MacGregor et al. [1961])*.

Sauberlich et al. [1953] found that the protein content of maize grain receiving a low rate of nitrogen application ranged from 6.8 to 8.3 per cent, as compared with a range of 9.3 to 12 per cent for a high nitrogen rate. The amounts of all amino acids increased with an increased protein content of the maize, but the rate of increase was not the same for each amino acid: some increased at a fast rate, some at a slow rate and some at an intermediate rate. Similarly, *Schneider et al. [1952[*, working in Illinois with six different strains of maize, found that all nitrogen fractions of the whole kernel usually increased when the total nitrogen of the kernel was increased by nitrogen fertilization; however, the alcohol-soluble nitrogen (zein) increased at the fastest rate. For protein contents of up to 14 per cent, each increase of 1 per cent in the total protein of maize increased the proportion of zein by 5.2 percentage units on the average *(Mitchell et al. [1952])*. Since zein is a low-quality protein, the biological value of the protein as a whole is reduced when total protein content is increased.

Biological assays confirm the poorer nutritional quality of the protein from high-protein maize, although digestibility increases slightly. However, the low biological value of the proteins of maize in general, and the decreasing value as the protein content increases, need not always have great practical significance. The advantage of increased protein production generally offsets their lower biological value. For feeding animals, this drawback can be partly overcome by using maize in farm rations in combinations with feed proteins relatively rich in the essential amino acids lysine and tryptophane *(Mitchell et al. [1952[)*.

However, maize is also a very important constituent of human diets in many parts of the world. In Central America alone, maize is the basic food of half the 200 million people. A very important recent development with regard to the nutritive value of maize is the discovery by a group of scientists at Purdue University, that two recessive genes called opaque-2, and floury-2, respectively, change the amino-acid distribution in maize protein, ensuring significantly higher levels of lysines than in ordinary maize.

The endosperm of opaque-2 contains twice as much lysine and tryptophane, 50 per cent more arginine, aspartic acid and glycine, and 30 per cent less alanine and leucine. The two recessive genes apparently act as prolamine (zein) suppressants in the developing endosperm. This upsets the normal balance between prolamine and glutelin synthesis, the latter becoming dominant. In the endosperm of normal maize, prolamine accounts for about 50 per cent, and glutelin for about 25 per cent of the total protein. In opaqua-2 and floury-2 endosperm, these values are reversed.

In addition, there are relative increases in the amounts of non-zein, non-glutelin proteins of free amino acids. All these fractions which increase contain substantially higher levels of lysine and trypotaphane than does zein *(Mertz 1968])*.

The high lysine character is being incorporated into many hybrids, in order to improve protein quality without sacrificing yield.

No research data are yet available, on the specific effect on the protein quality of the new-types maize, but there is every reason to assume that it will be easier to increase their yields without causing the same degree of lowering of biological value, as is the case with the normal maize types.

9.1.2 Oil content and oil yield

In a number of experiments in Illinois the effect of nitrogen, phosphorus and potassium fertilization on the oil content of maize kernels was studied on a soil deficient in nitrogen, highly deficient in available phosphorus and not deficient in available potassium *(Welch [1969])*.

– *Nitrogen*

Nitrogen added at the rate of 67 kg N/ha significantly increased oil content by 9 per cent. Higher rates of nitrogen had no additional effect. Grain yields were increased by 35 per cent, so that total oil yield was increased by 48 per cent *[ibid.]*.

In trials in Illinois, *Lang et al. [1956]* also found that oil content increased with increasing amounts of available nitrogen **(Figure 81).**

– *Phosphorus*

Phosphorus applied at the rate of 20 kg P/ha significantly increased oil content by 3 per cent; grain yields were increased by 36 per cent, so that oil yield was increased by 40 per cent *(Welch [1969])*.

– *Potassium*

Although the soil was high in available K, the application of potassium fertilizer at the rate of 448 K/ha increased the oil content of the grain by 5 per cent. Smaller applications had no effect on oil content, although the greatest increase in grain yield was obtained with 112 kg K/ha. Oil yield was increased by 14 per cent with the 448 kg/ha rate.

Since both yield and oil content of the grain were increased by the potassium fertilizers, the effect on oil yield was greater than that on oil content *(Welch [1969])*.

9.1.3 Vitamin content

The effect of fertilizers on the vitamin content of maize kernels was investigated by *Hunt et al. [1950]*. NPK fertilization of unlimed soil increased the thiamine content of the kernels in two out of three years and consistently decreased the nicotinic acid

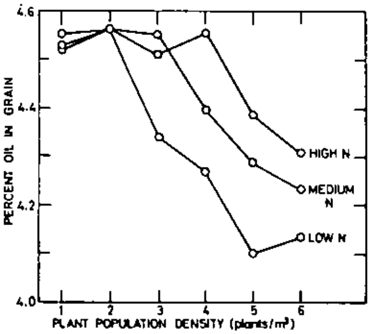

Fig. 81 Effect of plant population and nitrogen levels on the percentage of oil in maize grain. Average of 9 hybrids *(Lang et al. [1956])*. By courtesy of the American Society of Agronomy.

content. Liming the soil in addition to the NPK fertilization, had no additional effect on the thiamine content, but brought about an increase in nicotinic acid in one year out of three. *Earley et al. [1952]* found that heavy applications of nitrogen and phosphorus resulted in an increase in thiamine and a decrease in nicotinic acid in mature kernels.

In general, it appears that a high level of nutrient supply increases the thiamine content of maize kernels and decreases the nicotinic acid content.

9.1.4 Mineral content

The mineral constituents of grains can vary considerably, both in quantity and in proportion to each other.

Many factors, of which fertilizers are the most important, control the uptake of minerals by the plant (chapter 7). However, absorption and accumulation of ions by plants are really two separate processes and they can be influenced in different ways by similar chemical environmental conditions *(Nielson et al. [1963])*. The observed differences in mineral content of various parts of the plant are not always understood *(Lawton and Cook [1954])*. When nutritive elements are applied to a low-fertility soil, the percentage of the respective elements in the plant tends to increase until a complete, well-balanced treatment is achieved. Subsequently, the more luxuriant growth generally causes a reduction, through dilution, in the level of these elements.

A considerable proportion of the mineral nutrients absorbed by the plant may accumulate in the mineral form as a result of an unbalanced nutrient supply, a deficiency in catalysts or insufficient photosynthetic activity. These non-metabolized elements may reach toxic levels *(Routchenko [1965])*.

– *Potassium*

The potassium content of plants is more directly influenced by the potassium content of the soil solution than are other elements, because it is not converted into organic substances like the others.

K-content of the seed of most crops is usually far less affected by K-fertilization than is that of the vegetative parts. Stems of maize may contain three times more potassium than the grain *(Stubblefield and de Turk [1940]*, and variations in K-content under the influence of manuring is far more evident in the former than the latter.

– *Phosphorus*

Whilst there is a considerable body of research on the effect of phosphorus fertilizers on the mineral composition of forage crops, in which an increase in P-content as a result of P-fertilization had been conclusively demonstrated *(Nehring [1965]*, much less work on this subject has been carried out on food crops. However, here, too, there is a general tendency for phosphorus applications to result in an increase in P-content of the produce. This was found to be generally true in cereals *Wenzel [1957]*, in which the major proportion of the phosphorus is in the form of phytin and only a small amount is present in the inorganic form.

In field experiments in North Carolina, where maize yields were increased by phosphorus fertilization, the average phosphorus content of the grain was increased from

0.51 to 0.57 per cent P_2O_5, by fertilizer application. Where there was no yield response, the P_2O_5 content.was increased only 0.2 per cent on an average by phosphorus fertilization *(Krantz and Chandler [1954])*.

When relatively large quantities of calcitic lime, phosphorus and potassium were added to an infertile sandy loam, the phosphorus content of maize grain grown on this soil was increased by 39 per cent.

The calcium content of the grains remained unchanged by liming so that the application of phosphorus resulted in a narrower Ca : P ratio in the seed. As a result, the grain was deficient in calcium, whilst adequate in phosphorus for an animal diet. The calcium therefore becomes limiting for bone development, so that the increased content of phosphorus has no significant nutritional effect *(Rutherford and Pretty [1960])*.

Climate and soil fertility may, of course, mask the effect of phosphoric fertilizers. Heavy nitrogen applications, in conjunction with phosphorus, may reduce the P-content of the crop as a result of dilution due to increased growth.

– *Overall nutrients supply*

Hamilton et al. [1951] investigated the effect of cropping systems on the composition of the maize kernel. They wished to ascertain whether 'the penalty of poor yield associated with poor soil and poor crop management carried with it a further penalty of a seed crop of impaired value as food.' They found that maize, grown continuously year after year without fertilizers for almost three-quarters of a century, on a soil type that is naturally productive and representative of a vast area of prairie land in central and northern Illinois, produced kernels about 26 cent smaller than the kernels of fertilized maize.

The poorly developed kernels had the following physical and chemical characteristics, as compared with those of kernels from the same varieties of maize grown under the same climatic conditions, but with a favourable supply of plant nutrients: the germ was about 17 per cent smaller than normal, and therefore the nutrients that are largely concentrated in the germ – oil and phosphorus – were present in subnormal proportions. The endosperm was rich in starch but had 30 per cent less protein than normal kernels.

After application of fertilizers to this soil, the weight of the kernel increased, as did the protein, fat and total phosphorus contents. The nicotinic acid content was slightly depressed.

9.1.5 Hectoliter weight or bushel weight

The quality of grain plays an important role in the commerce of maize. Quality is frequently defined and governed by strict official regulations stipulating various criteria which may finally have a marked influence on the cash return of the farmer. One of the more important is hectoliter weight, or bushel weight, on which certain minimum limits are imposed for each grade. The beneficial effects of potassium and nitrogen applications on a K-deficient soil in raising the bushel weight and the interaction of potassium and nitrogen were demonstrated by *Burkersroda [1965]* **(Figure 82).**

9.2 Nutritive value of forage maize

Research on the effect of fertilization on the nutritive value of maize has been carried out by *Davidescu [1965]* in Rumania, and is summarized in Table 45.

Table 45. Effect of fertilization on nutrient content and value of maize leaves (all data in per cent of fresh weight of leaves) *(Davidescu [1965])*

Treatment	Concentration of elements in leaves			Effect on hydrolisis of nitrogen and phosphorus					
				Nitrogen (N)			Phosphorus P_2O_5		
	N	P_2O_5	K_2O	Hydrolized (h)	Non-hydrolized (nh)	Ratio (nh/h)	Hydrolized (h)	Non-hydrolized (nh)	Ratio (nh/h)
No-deficiencies	0.78	0.35	0.92	0.28	0.50	1.7	0.07	0.28	4.0
N-deficient	0.39	0.73	1.50	0.09	0.30	3.3	0.60	0.13	0.21
P-deficient	0.61	0.27	1.60	0.30	0.31	1.0	0.06	0.14	2.3
K-deficient	0.67	0.97	0.28	0.35	0.32	0.91	0.50	0.46	0.94

From the data presented in Table 45 the following conclusions can be drawn:

(a) Concentration of nutrient elements in the leaves:

- Nitrogen deficiencies caused an accumulation of phosphorus and potassium in the leaves, resulting in unbalanced nutrient composition.
- Phosphorus deficiencies caused decreased accumulation of nitrogen and increased accumulation of potassium in the leaves of maize.
- Potassium deficiency caused an increased accumulation of phosphorus and tended to reduced nitrogen concentration in the leaves.

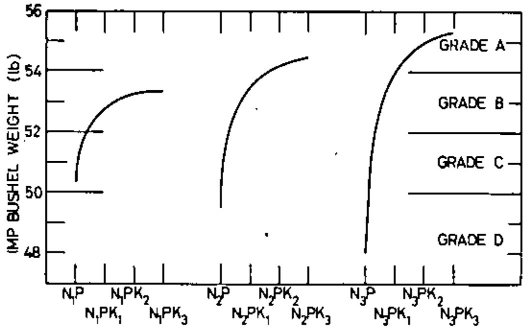

Fig. 82 Increase in bushel weight due to rising potash applications (N:K interactions) *(Burkersroda [1965])*. Nitrogen-potash fertilizer experiment with Rhodesian double hybrid II. Fertilizer levels applied: N_1 = 44 kg N/ha, K_1 = 33 kg K_2O/ha, N_2 = 88 kg N/ha, K_2 = 66 kg K_2O/ha, N_3 = 132 kg N/ha, K_3 = 132 kg K_2O/ha, P = 66 kg P_2O_5/ha.
By courtesy of the American Potash Institute.

These effects are of particular significance for maize grown as fodder or for ensiling. However, total nutrient content can only give a very superficial appreciation of the qualitative modifications that have occurred as a result of mineral nutrition. Increases in the P or N-content of the leaves may be the result of the inhibition of vital processes of synthesis transformation or migration of synthates from the leaf to other parts of the plant.

The effect of fertilizers on the ratio between hydrolized and non-hydrolized nitrogenous and phosphoric components, the former bound in protein and the latter to phosphatides and nucleoproteins, was investigated. The data presented in Table 45 indicate that nitrogen deficiency caused an increase in the ratio of non-hydrolized to hydrolyzed nitrogenous components, and to a decrease in the ratio of non-hydrolyzed P to hydrolized P. Phosphorus and potassium deficiencies cuased a decrease in both the ratios:

$$\frac{\text{Non-hydrolized N}}{\text{Hydrolized N}} \text{ and } \frac{\text{Non-hydrolized P}}{\text{Hydrolized P}}$$

and this decrease was most marked for K-deficiencies.

9.2.1 Proteins

The nitrogen content of the stover is influenced by the same factors as that of the grain, but is generally more variable. In general, mature stover contains 0.5 to 1.0 per cent N (3 to 6 per cent protein).

In trials by *Zuber et al. [1954]* nitrogen fertilizer, applied at the rate of 250 kg N/ha, increased protein content of the stover from 2.07 to 4.68 per cent in 1951, and from 2.91 to 6.52 per cent in 1952.

9.2.2 Nitrate accumulation in plant tissues

Under conditions of limited soil moisture supply and low atmospheric humidity, the plant may take up more nitrate than it requires, as a result of the high concentration of the soil solution and the high rate of transpiration.

Before the nitrate can be used in amino acid and protein synthesis, it must be reduced to ammonia. The first step in the reduction process is conversion of the nitrate to nitrate by the nitrate reductase enzyme. When the reduction process is slowed down because of an inadequate supply of carbohydrate energy or because of reduced activity of the nitrate reductase system, the metabolisation of NH_4 is retarded and the danger of toxic levels being reached in the plant is increased.

Unbalanced nutrition resulting from high rates of nitrogen application under conditions of P deficiency, is also conducive to excessive nitrate accumulation in the plant tissues.

One of the roles ascribed to potassium is that of a regulatory factor in nitrogen metabolism. Plants deficient in K usually contain a higher concentration of soluble N compounds and have a lower amount of protein than plants that are adequately supplied with potassium *(Barker and Bradfield [1963])*. Increasing the supply of nitrogen, particularly in the form of NH_4, was found to cause an increase in the total amino-acid content of the soluble fraction and in particular in the concentration of asparagine (the predominant amino acid) and other free amino acids in the maize plant. High rates of potassium application had the opposite effect *[ibid.]*. The higher the concentration of NH_4 in the nutrient solution, the larger the amounts of K that were required to counteract the inhibitory effect of the NH_4 ion on protein formation. Adequate supplies of K have also been shown to lessen the danger of ammonium toxicity.

In trials in Maryland, an application of 225 kg N/ha increased dry matter and protein yield per hectare and also increased the level of nitrate in the forage. However, much of the nitrate was reduced from the time of harvest to the time of removal from the soil and the reduction increased with the length of the ensiling period. As a result, the silage from the heavily fertilized forage did not show any detrimental effect on the performance of dairy cattle *(Hemken and Vandersall [1969])*.

9.2.3 Carbohydrates

An adequate supply of potassium is essential for condensing sugar into starch.

In Azarbaidzhan, field trials were carried out to study the sugar content in maize leaves at different stages of growth, in relation to mineral nutrition *(Safaralieva and Lyatifov [1969])*. At the 2-or 3-leaf stage, NP was the most effective combination in increasing the sugar content from 3.87 (in the unfertilized control) to 5.26 per cent (air-dry basis). At the 5-leaf stage NPK gave the highest further increase: from 4.77 (no fertilizers) to 6.05 per cent. At full flowering, sugar content had again decreased to 3.99 per cent in the unfertilized control; P was the most effective nutrient at this stage and caused an increase to 5.68 per cent. The addition of N tended to decrease the sugar content. Sucrose was the major sugar fraction and the one most affected by nutrient supply.

9.2.4 Minerals

Loué [1963] found that increasing amounts of potassium fertilizers applied to the soil caused corresponding increases in the K-content of maize forage. The effect of the K-status of the soil on the K-content of forage is shown in Table 46.

Table 46. Effect of potassium level in the soil on K-content of maize at harvest *(Loué [1963])*

K-status of the soil	Per cent K_2O in dry matter
Acute deficiency	0.30–0.50
Grave deficiency	0.50–0.75
Low K supply (no foliar deficiency symptoms)	0.85–1.10
Average K supply	1.10–1.60
High K supply	1.60–2.50

The potassium content of maize leaves is highly correlated with the exchangeable K-content of the soil. At low levels of exchangeable K in the soil, the application of K fertilizers increased the K-content of the leaves significantly; on the other hand, at high levels of exchangeable K in the soil, the K-content of the leaf was not appreciably affected *(Hanway et al. [1962])*.

The effects of four levels of K fertilization (0, 82, 192 and 302 kg K_2O/ha) applied to a loam soil low in exchangeable potassium, on the K-content of the maize leaf, were investigated by *Boswell and Parks [1957]*. Potassium content was increased by K fertilization, but decreased as the season progressed and tended to level off after 53 days. Part of this decrease can be attributed to dilution effects, but the small decline in the potassium-deficient treatment, as compared with the fertilized plots at all levels, suggests that at least part of the potassium has been translocated from the lower leaves to the meristematic region at the time of ear formation, and re-utilized in carbohydrate synthesis.

9.2.5 Overall effects of fertilizers on the quality of maize silage

The results of work in Wisconsin, on the effects of fertilizers on the quality of maize silage are shown in Table 47 *(Stangel [1965])*.

Table 47. Effects of fertilizers on maize silage quality and losses during fermentation *(Stangel [1965])*

Treatment			Protein		Carotene	Fermentation losses
N	P	K	(%)	kg/ha	mgm/kg DM	(% DM)
0	77	0	5.9	278	*	7.0
0	77	145	5.9	334	18.9	7.3
176	77	0	11.1	924	46.2	6.8
176	77	132	10.9	1001	126.3	2.1

* Not measured but assumed to be similar to values for the crop receiving the 0–77–145 treatment.

The percentage of most of the N fractions in the silage increased as the rates of nitrogen fertilizer were increased. In general, fermentation accentuated the specific fertilizer effects on the N fractions. Nitrogen fertilization lowered the fibre and lignin contents of the silage, but potassic and phosphoric fertilizers had no effect on them. High application rates of nitrogen fertilizer and low rates of potassic fertilizer resulted in an exceptionally low carotene content. Nitrogen and potassic fertilizers increased the amounts of carotene in the silage but the highest amounts were obtained from a complete fertilizer application. Although K-fertilization did not markedly affect the content of the nitrogenous and carbohydrate fractions in the fresh green forage, it greatly increased the yields of dry matter, protein, and fermentable carbohydrates per hectare.

The actual fermentation process was influenced by the fertilizers applied to the crop, and the highest quality silage and smallest losses were obtained when balanced fertilizer applications were given to the crop. Potassium fertilizer lowered the amount of lactic acid and CO_2 produced on ensiling *(Keeney et al. [1967])*.

The effects of two fertilizer rates (61–52–52 and 122–104–104, N-P-K) on the composition and digestability of silage were also evaluated by *Alexander et al. [1963])*. It was found that the higher fertilizer rate increased protein content, showed little effect on crude fibre, ether extract or energy, and decreased NFE and digestible protein. Digestible protein, digestible energy and TDN were increased following the application of the higher rate by 65, 39 and 36 per cent, respectively.

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10. Interactions between nutrient elements

10.1 Nutrient balance and its importance

The statement that a balanced supply of nutrients is essential for optimum production is commonplace, yet it is unfortunately true that this is not always reflected in agricultural practice. The high fertilizer rates required to ensure high yields of hybrid maize increase the probability of creating an imbalance. It is also a moot question whether a balance among only the three main macronutrients N-P-K is adequate. Actually, the N-P-K balnce is not really more critical than any other balance.

'Plant growth is a function of two variables: of nutrition intensity and balance' *(Shear et al. [1946])*. Not only is maximum yield dependent on optimum intensity occurring in combination with a proper balance of all the nutrients, but the effect of changing the level of supply of one or more nutrients on yield and quality characteristics will clearly depend on the imbalance created in relation to the other essential elements. In many cases, the minimum amount of a nutrient for normal growth is not an absolute value, but may depend on the relative amounts of certain other elements that are available.

The physiological effects of plant nutrients therefore cannot be considered in isolation from each other. As interactions occur, changes are initiated at the subcellular level which may affect phothosynthesis, respiration, utilisation and translocation of carbohydrates and organic acids *(Munson [1968])*.

The balance between nutrients may be quite satisfactory at a given level of yields but may prove inadequate when a higher yield level is made possible, e. g. by irrigation, by heavier fertilization rates or a combination of factors.

In a paper summarising the results of eight irrigated field experiments with maize, carried out in the Lebanon over five seasons *(Fuehring et al. [1969])* present evidence showing that as grain yields increase to levels in the range of 12 to 18 tons/ha or more, a high degree of nutrient balance is involved, as well as a balance between population density and nutrient supply.

Nutrient balance is achieved within a plant 'when no nutrient is limiting yields because of being in suboptimum concentration in the plant' *(Donald et al. [1963])*.

10.2 Factors which influence interactions among ions

Practically all factors which influence the uptake of nutrients by the crops will also affect the relationships between nutrients.

10.2.1 The crop

Crops are capable of being highly selective in cation uptake, so that there are large differences between them in the amounts of individual cations taken up, in their concentrations in the tissues of the plant and in the ratios between them. *Collander [1961]* studied the uptake of cations by 13 different crops grown in solution cultures with equal concentrations of each cation (4 meq/l).
Table 48 shows the range of variations in concentrations among the crops investigated and the values for two contrasting crops.

Table 48. Cation content and interrelations in crops grown in cultures with equal concentrations of each cation *(Collander [1941])*

	Cations (meq/100 gr)					Ratios		
Crop	K	Na	Ca	Mg	Total	K/Ca	K/Mg	Ca+Mg
Maize	169	7	27	39	242	6.2	4.3	0.43
Spinach	339	29	85	202	655	4.0	1.7	0.93
Range for 13 crops	109–339	3–125	16–116	26–202				

In the case of maize, potassium constituted 70 per cent, sodium 2.9 per cent, magnesium 16 per cent and calcium 11 per cent of the total cation uptake.
Collander found that the range of variation in the content of individual cations in the plant species grown in the same solution cultures was very unequal. The differences observed appear to be truly specific in character: single plant species were found to be generally rich in certain cations and poor in others. The smallest range of variation was found to occur with potassium.

10.2.2 Fertilizers

Plant nutrients may either aid or compete with each other for entry in the plant, and improve or impair their respective availability.
The application of a particular nutrient usually increases the content of that nutrient in the dry matter of the plant. Where this application causes an increase in growth, this will frequently result in a decreased content of the nutrient, as a result of dilution. There are cases in which the application of a nutrient not only increases growth, but also the content of other nutrients, and finally, there are cases in which the application of a nutrient actually decreases the content of certain other nutrients.
Whenever the effect of one nutrient on the uptake of another cannot be explained by dilution due to increased growth, it is probably the result of metabolic associations – either synergistic or antagonistic – between nutrients.
In a study of nutrient uptake by maize, *Nielsen et al. [1963]* found that increases in applications of nitrogen had a synergistic effect and resulted in higher concentrations of phosphorus and calcium. By contrast, specific antagonisms appeared to exist in the following cases: Nitrogen, on the content of potassium; phosphorus on the content of potassium; potassium, on the content of nitrogen; and phosphorus, calcium, and

chloride on the content of sulphur. The antagonisms were not always mutual; for example, sulphate had no effect on chloride concentration.

In an experiment on irrigated maize, a study was made of the effects of increased rates of nitrogen on nutrient ratio in the plant at maturity *(Viets et al. [1954])*; the results are presented in Table 49.

Table 49. Effect of rates of N on maize yield, leaf cation content and N/K ratios of Iowa 939 maize grown under irrigation *(Viets et al. [1954])*

Nitrogen rate (kg/ha)	Grain yield (kg/ha)	N/K (%)	Cation sum (meq/100 g)	K/Ca	K/Mg	$\frac{Ca+Mg}{K}$
Control	4 782	0.50	88.1	2.34	3.53	0.71
Ammonium sulphate						
45	6 972	0.42	108.4	2.87	5.95	0.52
90	9 024	0.69	99.7	3.47	5.90	0.43
180	10 028	0.78	98.9	3.87	5.92	0.43

• Grown on a virgin Ephrata sandy loam. Soil analyses were as follows: pH 7, CEC, 13 meq/100 g, Ca, 7.78 meq, Mg, 2.80 meq, Na, 0.10 meq, and K, 1.14 meq/100 g.

With increasing rates of nitrogen application, N/K(%) ratios were reduced with the first increment of nitrogen (dilution effect) and then markedly increased with subsequent increments of nitrogen. The K/Ca ratio increased progressively with an increased rate of nitrogen; K/Mg ratios were considerably increased by nitrogen fertilization, but equally at all levels of nitrogen applied. The $\frac{Ca+Mg}{K}$ ratio was decreased by nitrogen application.

10.2.3 Age of plant or of individual organs

The nutrient content of the crop changes with the age of the plant (cf. 142); as these changes are not the same for all the nutrients, the ratios between nutrients also change with the age of the crop, as shown in the following examples.

In studies in Ohio, nutrient content of maize leaves was sampled on four dates during the growing season. The results are shown in Table 50 *(Sayre [1955])*.

Table 50. Effect of age on leaf dry matter yield, cation content and ratios of maize *(Sayre [1955])*

Sampling date	Dry weight of leaves (g/plant)	N/K (%)	Cation contents (meq/100 g)				Cation ratios		
			K	Ca	Mg	Sum	K/Ca	K/Mg	$\frac{Ca+Mg}{K}$
June 20	5	0.71	107	22	13	142	4.9	8.2	0.33
July 20	46	1.07	72	14	15	101	5.1	4.8	0.40
August 19	62	1.35	51	17	20	88	3.0	2.6	0.72
September 18	61	1.12	43	15	20	78	2.9	2.2	0.81

The potassium content of the leaves dropped sharply between June 20 and July 20, resulting in a marked increase in the N/K ratio. The K/Ca and K/Mg ratios decreased with age, while the $\frac{\mathrm{Ca+Mg}}{\mathrm{K}}$ ratio increased during the same period.

10.2.4 Moisture status of soil

In experiments on a fine, sandy loam in Nebraska, the nutrient content of maize grown with and without irrigation was sampled at different periods during the growing season *(Jenne et al. [1958])*. The results are shown in Table 52.

Table 52. Effect of irrigation on maize grain yield and cation content and ratios of leaves at tassel* *(Jenne et al. [1958])*

	Grain yield (kg/ha)	Cation contents (meq/100 g)				Cation Ratios		
		K	Ca	Mg	Sum	K/Ca	K/Mg	$\frac{\mathrm{Ca+Mg}}{\mathrm{K}}$
Nonirrigated	4330	84,4	54,8	40,4	179.6	1.54	2.09	1.13
Irrigated	9601	65.5	37.9	34.5	138.9	1.75	1.93	1.09

* Very fine sandy loam. Soil pH, 7.3; CEC, 16.5 meq/100 g and Exch. K, 2.1 meq/100 g. Fifteen tons of manure and 90 kg N were applied per hectare.

Irrigation decreased the cation contents (dilution), slightly increased the K/Ca ratio and decreased the K/Mg ratio. The $\frac{\mathrm{Ca+Mg}}{\mathrm{K}}$ ratio was hardly affected by irrigation.

Lawton [1945] studied the effect of soil moisture status on the uptake of cations and their ratios on loam and silt soils in Iowa. The results are shown in Table 53.

Table 53. Effect of K and soil moisture on cation content and ratios, and yields of maize grown in a greenhouse* *(Lawton [1945])*

Nutrient treatment	Soil moisture %	Cation contents (meq/100 g)				Cation ratios			Maize yield (g/pot)	
		K	Ca	Mg	Sum	K/Ca	K/Mg	$\frac{\mathrm{Ca+Mg}}{\mathrm{K}}$	tops	roots
NP	15	50	16	29	95	3.2	1.8	0.8	20.8	12.9
NP	25	44	22	34	100	2.0	1.3	1.3	20.9	9.9
NP	40	24	18	33	75	1.4	0.7	2.0	13.3	5.6
NPK	15	80	18	23	121	4.4	3.5	0.5	24.5	14.2
NPK	25	78	18	26	122	4.5	3.0	0.6	23.9	11.5
NPK	40	53	24	30	107	2.2	1.7	1.0	18.1	9.0

* Loam soil having the following analyses: pH, 5.6, moisture equivalent 25%, Exch. K, 123 kg/ha, and extractable P, 15 ppm.

Differences in soil moisture supply caused shifts in the cation contents and ratios of the plants. Excessive moisture reduced potassium content, the K/Ca ratio and the

K/Mg ratio, whilst it increased the $\frac{\text{Ca}+\text{Mg}}{\text{K}}$ ratio. The application of potassium fertilizer increased the total amount of cations, but did not change the effect of excessive moisture on the cation ratios.

10.2.5 Soil temperature

The effect of soil temperature on the cation contents and ratios of maize grown on a silt loam was studied by *Nielsen et al. [1961]*. The results are presented in Table 54.

Table 54. Effect of soil temperature on maize yield, cation contents and ratios of whole maize plants at 31 days *(Nielsen et al. [1961])**

Soil temperature (°C)	Yield (g/pot)	Cation contents (meq/100 g)				Cation ratios		$\frac{\text{Ca}+\text{Mg}}{\text{K}}$
		K	Ca	Mg	Sum	K/Ca	K/Mg	
5	10.3	101	44	42	187	2.30	2.40	0.85
26.6	51.5	23	21	47	91	1.10	0.49	2.96

* All treatments received NPK.

At higher temperatures, a five-fold increase in dry matter production was accompanied by drastic reductions in the concentration of potassium and calcium in the plant tissues (dilution effects) whilst the magnesium content remained unaffected. The $\frac{\text{Ca}+\text{Mg}}{\text{K}}$ ratio was increased more than three-fold by the higher soil temperature.

10.3 Interactions between pairs of nutrients

10.3.1 Effect of nitrogen on phosphorus uptake

The addition of nitrogen fertilizers has been shown by many investigators to enhance considerably the utilization of fertilizer phosphorus by maize. These effects were most marked on soils low in available nitrogen.

In trials with maize grown for fodder in Moscow Province, it was found that the uptake of phosphorus by maize roots was greatly increased by the application of nitrogen. This was most effective when the nitrogen was introduced at a depth of 4–8 cm as $(NH_4)\ NO_3$ or at a depth of 8–12 cm as KNO_3 *(Yakovlev [1969])*.

In experiments in the North Central Region of the USA, the application of nitrogen increased the percentage of plant phosphorus from the P-fertilizer, by amounts ranging from 6.4 per cent in a broadcast application to 220 per cent with banded application. These values are in comparison with no nitrogen application or with nitrogen applied separately. In all cases, increasing the rate of nitrogen application caused a progressive increase in the utilization of the fertilizer phosphorus. The effect of the concomitant supply of nitrogen and phosphorus in increasing phosphorus utilization was found to be especially important in the early growth stages of the crop **(Figure 83)** *(Fine [1955])*.

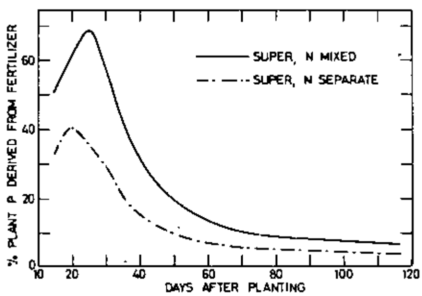

Fig. 83 Effect of phosphate and nitrogen association on the rate and time of utilization of phosphate by maize *(Fine [1955])*. By courtesy of South Dakota Agricultural Experiment Station.

Miller and Ohlrogge [1958] obtained a 100 per cent increase in phosphorus uptake per plant at all soil levels of phosphorus, when nitrogen was mixed with phosphorus fertilizer in a band. *Bennett et al. [1953]* report that phosphorus percentage in the maize leaf was significantly increased in a number of experiments following nitrogen application; these increases were associated with yield responses which proved to be independent of the nitrogen effect. In a study on the effect of fertilizer applications on the yields of maize on irrigated soils low in nitrogen and high in available phosphate, a high positive correlation was found between N and P in the leaves *(Viets et al. [1954])*. Yields were closely related to both N and P contents of the leaves. The N applications actually increased P uptake faster than dry matter production, so that P concentration in the plants increased. The investigators conclude that P concentrations in the leaf have little value for diagnosis of the P-status of the plant unless they are related to the N-status of the leaves *(Viets et al. [1954])*. *Dormaar and Ketcheson [1960]* have established that there is an optimum nitrogen level for growth and for the uptake of phosphorus by maize plants. Both growth and uptake of P increased with initial increments of nitrogen, passed through a maximum at about 200 ppm and then declined with higher applications **(Figure 84).**

The influence of nitrogen fertilizers on the availability of phosphate differs with the form in which the nitrogen is applied as well as with soil conditions. Generally, NH_4-N increased P uptake more than did NO_3-N. This effect was more pronounced as soil temperature increased **(Figure 85)** *[ibid.]*.

– *Factors involved*

The effect of nitrogen in increasing the uptake of phosphorus has been variously ascribed to three groups of factors: morphological, chemical and physiological, or a combination of these three *(Grunes [1959])*.

There are probably circumstances in which one or the other of these mechanisms is operative and others where two or more operate together. Whatever the mechanism, the effects have been proved and are of considerable practical importance.

– *Morphological effects on root area*

One possibility is that the effect of nitrogen on root growth and distribution is great enough to increase the area of uptake of phosphorus. The response of root growth to nitrogen is well known, and it is logical to assume that phosphorus uptake will be approximately proportional to root distribution in the soil.

Increased proliferation of roots in the fertilizer band has been frequently observed. *Duncan and Ohlrogge [1958]* have demostrated that the number of roots of maize plants was considerably increased by combined N and P fertilization when applied in a fertilizer band. In addition, the roots were finer and more hair-like, so that a considerable increase in root surface area resulted.

The growth rate of the roots under these conditions was very high: the total length attained by one secondary root with all its branches in less than two weeks was 250 cm; the rate of growth was therefore nearly 1 cm per hour!

Other investigators have shown that P uptake from a solution was not related to dry matter production of roots *(Doormaar and Ketcheson [1960])*. These authors actually found that total dry matter production in roots of maize seedlings was inversely related to nitrogen application and to P uptake.

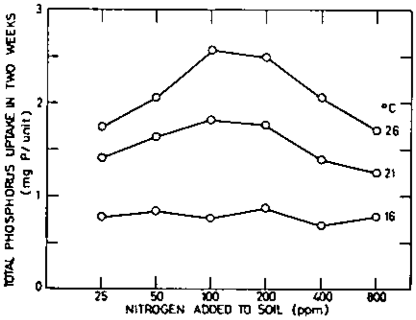

Fig. 84 Effect of temperature and nitrogen level on total phosphorus taken up by maize plants from soil over a 2-week interval *(Dormaar and Ketcheson [1960])*. By courtesy of the Agricultural Institute of Canada.

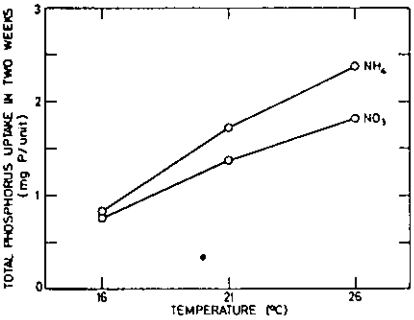

Fig. 85 Effect of temperature and nitrogen form on total phosphorus taken up by maize plants from soil over a 2-week interval *(Dormaar and Ketcheson [1960])*. By courtesy of the Agricultural Institute of Canada.

In three experiments carried out by *Miller [1965]*, the addition of $(NH_4)_2SO_4$ to a P band consistently increased the absorption of fertilizer P by the individual root of maize. Increased root growth was obtained in only one experiment. *Miller* therefore concluded that the latter was not a prerequisite for the increased uptake of P observed, but that the $(NH_4)_2SO_4$ had some specific physiological effect that increases the absorption of P.

Thien and McFee [1970], by pretreating maize seedlings with nitrogen, obtained a 30 per cent increase in P uptake above the values for seedlings pretreated with phosphorus, and yet there were no significant differences in the dry weights of the roots due to the different treatments investigated, indicating that the absorptive capacity as measured by root mass was similar in each treatment.

Blanchar and Caldwell [1966] also found that P uptake could not be explained on the basis of root development. They observed that increases in root concentration in fertilizer bands were nearly the same, whether NH_4Cl or KCl was associated with the monocalcium phosphate in the band **(Figures 86 a and b).**

The increased root concentration could therefore not be ascribed to the effect of ammonium on P uptake. In both cases the maize roots were growing in solutions of extremely high P concentration. The investigators estimate that the zones described by the 100-to-500 on the 500-to-1000 ppm P line in **Figure 86,** each contain about 50 mg of water-soluble P. The water-soluble P content of the soil zones was shown to be nearly ten times the amount required to supply the plant with the phosphorus actually taken up from the fertilizer. A further increase in fertilizer P solubility would not be expected to increase P utilization by the plant.

They conclude that (a) root development may be the result, rather than the cause of increased P uptake, and that (b) P uptake may not be related to the amount of roots present, when diffusion of P to the root surface is not limiting its uptake.

– *Increased efficiency of the roots in absorbing P*

Nitrogen increases the growth of the aerial portions of the plant more than it does root growth, thereby increasing the requirements of the plants for phosphorus more

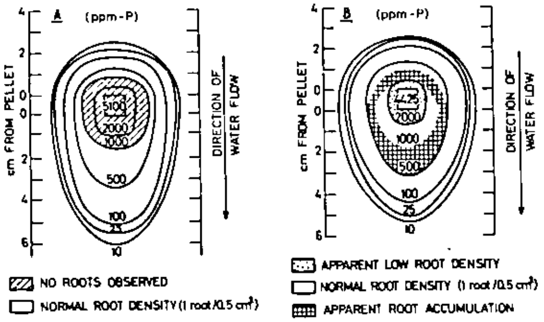

Fig. 86 Root density in various P concentration zones around monocalcium phosphate fertilizer pellets leached with 4 cm water *(Blanchar and Caldwell [1966])*. Left: Pellet of MCP only. Right: Pellet of MCP + NH_4Cl. By courtesy of the Soil Science Society of America.

than it increases the P-absorbing surface. Therefore the P-stress in the vicinty of the roots of N-fertilized plants will be greater than for N-deficient plants. As the P concentration at the root surface decreases, concentration gradients develop between the P sources in the soil and the root, and the rates of transfer of P from the sources to the roots increases. More P will therefore be absorbed per unit area of root surface as a result of N fertilization *(Grunes [1959])*.

– *Chemical effects*
Chemical effects might influence the preferential absorption of phosphorus by plants, by affecting P solubility or residual acidity.

Preferential absorption
It has already been pointed out that young maize plants absorb ammonium-N in preference to nitrate N (p. 215). According to *Coïc et al. [1961]*, the rapid metabolisation of ammonium-N in the roots favours its more rapid uptake from the soil at the expense of other cations. This is accompanied by an increased uptake of anions, in particular phosphorus. The opposite occurs when N-nitrate is taken up from the soil: the selective absorption of the nitrate is at the expense of other anions and the uptake of phosphorus in particular is depressed.

– *Increased solubility of phosphorus*
The presence of certain salts is known to affect the solubility of phosphate. The increased solubility may be due either to a pH change caused by the nitrogen carrier or to a mutual solubility enhancement resulting from the contact of the two chemicals. A preferential effect on the solubility of the soil phosphorus or the fertilizer phosphorus would presumably affect the percentage of the phosphorus derived from the fertilizer *(Grunes [1959])*.

In greenhouse tests it was established that, in general, salts such as ammonium sulphate, which in laboratory tests markedly increase the solubility of dicalcium phosphate with increasing ionic strength, also give the greatest crop response to phosphorus. By contrast, salts such as ammonium nitrate, which only give a moderate increase in solubility, leveling off at ionic strengths between 2 and 4, only occasionally give increased crop response. Finally, salts such as calcium nitrate, which cause decreases in solubility with increasing strength, usually give a negative crop response to phosphorus **(Figure 87)** *(Starostka and Hill [1955])*.

Caldwell [1960] showed that the solubility of the phosphorus fertilizer applied in the band together with ammonium salts was also a factor involved in the interaction between phosphorus and nitrogen. It was only with the more soluble monocalcium phosphate that ammonium increased the uptake of P by the plant, whilst no such effect was recorded with the less soluble di- or tricalcium phospahtes.

Rennie and Mitchell [1954] first assumed that the lowering of the pH in the vicinity of a phosphorus fertilizer band, due to the addition of acid-forming materials such as ammonium nitrate or sulphate, may be the reason for the increased availability of phosphorus to plants. The lower pH may increase the solubility of the phosphorus or it may slow down the reversion of soluble phosphorus to a more insoluble form *(Grunes [1959])*. However, subsequently, it was found in greenhouse and field studies that the addition of an acid salt, $KHSO_4$, to phosphorus carriers did not increase the uptake of phosphorus, but rather decreased it. They therefore concluded that their initial supposition was not substantiated *(Rennie and Soper [1958])*.

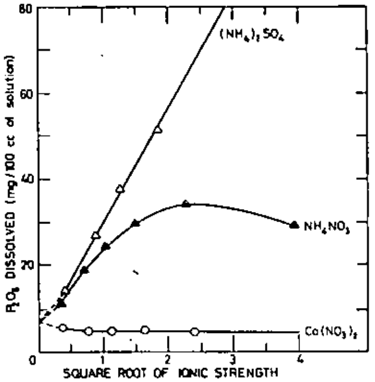

Fig. 87 Influence of salt concentration on the solubility of dicalcium phosphate in solutions of type salts *(Starostka and Hill [1955])*. (0.4 gm. of No. 3100 agitated with 100 cc. of salt solution at 30° C. for 30 minutes.) By courtesy of the Soil Science Society of America.

Blancher and Caldwell [1966] found that when the pots in which maize was grown were not leached, only trace amounts of fertilizer P were absorbed and the addition of ammonium was therefore ineffective. When pots were leached with 4 cm of water, P uptake was increased nearly three-fold by the addition of ammonium chloride. The authors concluded that the need to dilute the fertilizer zone in order to obtain the interaction between ammonium and phosphorus, may explain why results of experiments in the field have not always been consistent.

– *Residual acidity*

In an investigation by *Yuen and Pollard [1957]* it was found that the effect of various forms of nitrogen on the uptake of phosphorus is closely related to the pH of the soil, its available phosphate content and phosphate-fixing capacity – thereby explaining many inconsistent results reported in the literature.

In a slightly acid soil (pH 6.4), which had a moderately high level of available phosphorus and medium P-fixing capacity, the repeated use of physiologically acidic nitrogen (ammonium sulphate or chloride) increased the uptake of native and added phosphate more effectively than did the physiologically basic nitrogen (sodium or potassium nitrate). On a very acid soil (pH 4.9), which had a low level of available phosphorus and a high phosphate-fixing capacity, the same fertilizers had exactly the opposite effects.

The change in pH of the soil in turn affects the diffusion of phosphate through root membranes. Plants are assumed to prefer P in the form of $H_2PO_4^-$ for nutritional purposes, and this is the dominant form in which P is absorbed at pH < 5. At high pH (8–9), $HPO_4^=$ ions are dominant. At an intermediate pH (6.8), soluble P is present in the two forms in about equal concentrations and proportions. Of the two forms,

$H_2PO_4^-$ has a higher rate of diffusion through a permeable membrane, so that a reduction in pH of the soil from neutral to slightly acid, facilitates the uptake of phosphate by the plants, by shifting the proportion of phosphate ion from HPO_4^{--} to $H_2PO_4^-$. An increase in pH from acid to neutral would have the opposite effect. This change in the nature of the phosphate ion is particularly critical in the range of pH 6–7.

Briefly: the repeated use of physiologically acidic nitrogen on soils with $pH > 6.2$ favours the increased uptake of phosphorus, whilst the reverse is true of physiologically basic nitrogen. On soils with $pH < 5.5$, these nitrogen fertilizers behave in exactly the opposite manner.

– *Physiological factors*

In an investigation by *Blanchar and Caldwell [1966]*, chemical measurements of the root environment indicated that the phosphorus level and other conditions were nearly the same whether NH_4Cl or KCl was added to the monocalcium in the band. These authors conclude that the effect of ammonium on phosphorus uptake is probably due to its effect on plant functions and not to changes in availability of phosphorus in the soil.

Other investigators have reached the same conclusion, and the cause of increased P absorption is increasingly being attributed to the effect of nitrogen on the physiological processes that control the absorption of phosphorus *(Thien and McFee [1970])*.

– *Increased transfer of phosphorus across the root symplast into the xylem.*

Leonce and Miller [1966], in a series of soil and solution experiments with maize, showed that NH_4^+ + P gave increased P concentrations in maize tops, when compared with NO_3^- + P or P alone. They found that the NH_4^+ ion appeared to have a specific effect on the movement of phosphorus across the root symplast into the xylem, and concluded that this was the main mechanism responsible for the increased P absorption observed when nitrogen was added to phosphorus in their experiments. They suggest that the NH_4^+ ion increases the rate at which the phosphate-carrier complex releases the phosphate ion into the xylem.

– *Effects of N on metabolic processes that control the rate of P uptake*

Bennett et al. [1962] found that applications of nitrogen increased phosphorus uptake even under conditions in which neither enhanced P solubility, nor a greater ramification of the root system was involved. The results of their study provided some evidence that applied nitrogen results in larger amounts of nitrogen compounds being formed in the plants, some of which either contain P (such as the nucleoproteins), or require P for their formation. Hence, increased uptake of nitrogen results in an increased need for, and uptake of, phosphorus.

Cole et al. [1963] found that nitrogen pretreatments of one-month-old maize plants stimulated the rate of P uptake per gram root more than did a tenfold increase in P-concentration in the external solution. The N treatments caused a significant increase in growth rates of the tops without increasing the growth rates of the roots. The investigators therefore assumed that the stimulation in rates of P uptake cannot be ascribed to the promotion of growth rates by the roots, but rather to metabolic changes within the plant, thereby suggesting a connection between P uptake and N metabolism. They assume that nitrogen caused a stimulation in the metabolic system resulting in a greater turnover of NADH and ATP coupled to P uptake reactions.

Thien and Mc Fee [1970], in apparent contradiction to previous investigations, demonstrated that the form of the nitrogen associated with phosphorus has no significance on the interaction between nitrogen and phosphorus, when the roots of two-week old maize plants were pretreated with nitrogen. The pretreated plants, irrespective of whether the nitrogen was in the ammonium or nitrate forms, accumulated about 30 per cent more labelled P in their tops and roots, than did those plants that received a phosphorus or a water pretreatment. This indicates that the stimulation due to nitrogen affects both total P absorption and translocation. The nitrogen accompanying the phosphorus in the absorption solution had no further significant effect on the ability of the plants to absorb or translocate phosphorus during the actual absorption stage. Rather, those plants already high in metabolic N showed the greatest affinity for P uptake. The authors therefore conclude that phosphorus uptake and translocation are dependent on nitrogen pre-conditioning of the roots and not on simultaneous N and P absorption **(Figure 88).**

The fact that metabolic N was found capable of stimulating both translocation as well as absorption, but not in a similar manner for both processes, appears to indicate the presence of an N intermediate, acting in *two* transport systems: one across the initial cellular barrier and the other responsible for moving P to the xylem.

If a single carrier system were involved, in both initial uptake and lateral transport for translocation, total uptake and translocation would presumably be stimulated by metabolic N in a similar manner. As already observed, this was not the case in these investigations.

Thien and Mc Fee explain the apparent contradiction between their findings, namely, that N accompanying P in the treatment solution had no stimulating effect on mizae seedlings already pretreated with N, and those of previous investigators showing that

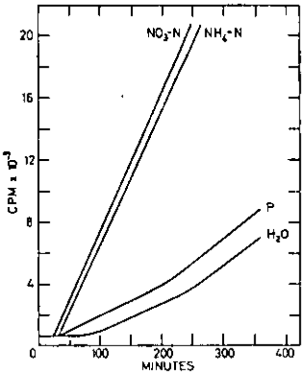

Fig. 88 Effect of pretreatment on the rate of labelled phosphorus accumulation in maize tops treated with NH_4N + P *(Thien and Mc Fee [1970])*. The two upper lines are significantly different from lower lines. By courtesy of Soil Science Society of America.

N is extremely effective in increasing P absorption when the fertilizers are placed together in the band, as follows:

In the soil, external movement of nutrients is extremely restricted. It is only those sections of the roots growing in the soil where the nitrogen concentration is present – i. e., the fertilizer band – that are likely to be conditioned for increased phosphorus absorption and translocation at the location where phosphorus concentration is the greatest. As nitrate nitrogen is more easily leached than ammonium nitrogen from the fertilizer band, it is less likely, under field conditions, to be effective in conditioning the roots than is ammonium nitrogen – and hence the greater effectiveness of the latter, as reported in most soil studies.

10.3.2 Nitrogen – potassium interrelationships

Maize is one of the many crops which take up nitrogen and potassium in nearly equal amounts.

– *Yields*

The interactions of nitrogen and potassium on yields, frequently observed in field studies, are evidence that nitrogen-potassium balance is of considerable practical importance.

For example, on a prairie soil in Wisconsin, with an adequate phosphorus supply, the application of nitrogen alone increased grain yields of maize by 3750 kg/ha, that of potassium alone by 323 kg/ha, whilst the combined effect of nitrogen and potassium was to produce an increase of 5240 kg/ha (Table 55) *(Stangel [1965])*.

Table 55. Effect of nitrogen and potassium applications on nitrogen content and yields of maize *(Stangel [1965])*

Treatment* (kg/ha) N	K	Whole plant 47 days (ppm NO_3 N)	82 days	Early dent % N	% K	Grain N (%)	Yield (kg/ha)
0	0	1417	Trace	0.95	0.94	1.18	2908
0	145	784	Trace	0.94	1.62	1.28	3232
176	0	6650	2050	1.78	0.66	1.58	6140
176	145	7119	2538	1.75	1.79	1.55	8147

* All treatments received 77 kg P/ha.

It is of interest to note that potassium applied alone actually led to a marked decrease in the N-content of the young plants; when applied in conjunction with nitrogen, potassium increased the N level. A further point of interest is that K fertilization delayed the depletion of potassium from the plant at an advanced stage of growth. The potassium had no effect on the final nitrogen content of the grain.

Another interesting example is provided by experiments on a K-deficient soil in Rhodesia. A marked response of maize to nitrogen was observed on this soil, provided it was applied together with adequate amounts of potassium fertilizer **(Figure 89)**. When applied without potassium, nitrogen fertilizer actually reduced yields. The combined application of both nitrogen and potassium also improved the quality of the marketed grain. One of the more important criteria for the quality of the grain is bushel weight, in which certain minimum limits are imposed for each grade. As shown in **Figure 82**, bushel weight was markedly increased by combined applications of nitrogen and potassium *(Burkersroda [1965])*.

– *Effect of nitrogen on potassium uptake*

Increased rates of either nitrogen or potassium were found to cause substantial increases in K-uptake, when adequate amounts of the other two major nutrients were supplied **(Figure 90**, *Murdock et al. [1962])*.

– *The recirculation of potassium and its importance for adequate nitrate nutrition*

Ben Zioni et al. [1971] have proposed a hypothesis that explains the large requirement for K^+ ions by plants, notwithstanding the fact that K^+ is not an organic constituant of any structural compound in the plant. According to these authors K^+ plays an essential role in the nitrate nutrition of the plant, in particular in the regulation of nitrate uptake, the latter depending to a large extent on the metabolic utilization of the anion in the shoot.

In the model proposed by *Ben Zioni et al.*, the nitrate taken up by the plant migrates through the xylem to the above-ground parts of the plant in association with potassium. In response to the reduction of nitrate in the leaves, malate is formed. Part of the malate, in the form of potassium salt, is then traslocated to the root, where the malate is oxidized and its degradation product, HCO_3^-, is given off to the medium where it exchanges with NO_3^-, which is taken up by the roots. Potassium therefore circulates in the plant moving upwards as KNO_3 und downwards as K^+ malate, and nitrate uptake is regulated by this circulation process.

Roots of plants actively reducing nitrate would be expected to take up a large excess of NO_3^- over K^+. The ratio of NO_3^-/K^+ should decrease in nitrate depleted leaves because malate is not synthesised under these conditions.

Consequently, plants during periods of peak nitrogen requirements will be reducing large amounts of nitrate, and will have at their disposal more malic acid to facilitate preferential uptake of nitrate. Conversely, during periods of low nitrogen requirement (such as the period of seed maturation), little malate is produced.

In view of the intimate relationship between malate production and nitrogen metabolism, the level of malates in the leaf tissue might constitute an important tool in diagnosing nutrition deficiencies in plants *(Vaadia, Y. [personal communication])*.

No direct evidence for K^+ recirculation is yet available, but a number of experiments provide correlative evidence for the proposed model *[ibid.]*.

10.3.3 Effects of N supply on microelement levels

In field experiments on a dark-brown clay (pH 5.8) in Southern Rhodesia, increasing the N supply depressed Al levels but increased Cu, Zn and Mn contents *(Thompson [1962])*.

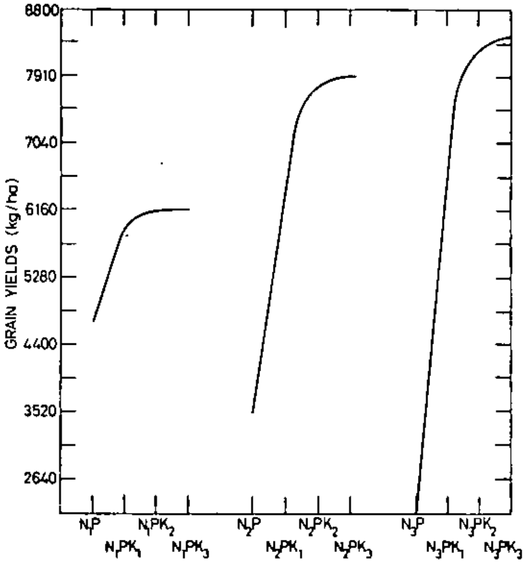

Fig. 89 Interactions of nitrogen and potassium in increasing yields of a double-hybrid maize on a K-deficient soil in Rhodesia *(Burkersroda [1965])*. Fertilizer levels applied: $N_1 = 44$ kg N/ha, $K_1 = 33$ kg K_2O/ha, $N_2 = 88$ kg N/ha, $K_2 = 66$ kg K_2O/ha, $N_3 = 132$ kg N/ha, $K_3 = 99$ kg K_2O/ha. By courtesy of the American Potash Institute.

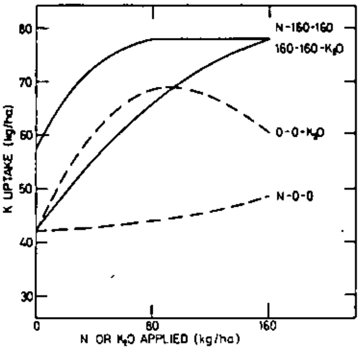

Fig. 90 The influence of level and balance of fertilization on total potassium uptake at maturity *(Murdock et al. [1962])*. By courtesy of the American Potash Institute.

– Nitrogen-sulphur relationships

The nitrogen-sulphur ratios in the tops and roots of maize were studied in relation to nitrogen and sulphur supplies in the soil. Greenhouse studies by *Stewart and Porter [1969]* showed that when sulphur became limiting, additional nitrogen did not affect either the yield or protein level of the plants, but the nonprotein N (nitrates, amides, and amino acids) increased.

There is a close relationship between the amounts of nitrogen and sulphur metabolized in the plants. The data indicated that one part of sulphur was required for every 12 to 15 parts nitrogen to ensure maximum production of both dry matter and protein. As the use of nitrogen fertilizers on maize increases, the possibility that sulphur may become limiting also increases, and adequate consideration of this element becomes necessary *[ibid.]*.

Sulphur applications, in the form of elementary sulphur or gypsum, have been shown to increase the nitrogen content of the leaves of maize, whilst phosphorus, boron and copper concentrations in the plant are reduced *(Caldwell et al. [1969])*.

10.3.4 Phosphorus and zinc interactions

Many investigators have established that the application of phosphorus fertilizer may depress the uptake of zinc by maize. This effect is most marked on soils rich in native P, on calcareous soils and on exposed subsoils containing free lime. Low soil temperatures and poor soil aeration enhance the depressant effect of phosphorus on zinc uptake. The application of phosphorus fertilizers under these conditions will depress maize yields only if the available soil zinc is at a marginal level; the deleterious effect of phosphorus can then easily be corrected by light applications of Zn fertilizer *(Bingham [1963])*.

A few examples of investigations on P × Zn interactions follow:

Starter fertilizers containing phosphate have frequently given poor results when applied to maize. It was at first assumed that a toxicity factor, present in the P fertilizer, was involved. Recent investigations indicate that the depressed growth and reduced yields following P fertilization of maize under certain soil and climatic conditions, may be due to a disturbance in micronutrient utilization by the young maize plant, and in particular reduced uptake of zinc.

The P-induced Zn deficiencies were found to be enhanced when the soils were cold and wet at the time the plants were still small, so that root growth was restricted *(Ellis et al. [1964])*.

In field experiments in which zinc deficiencies in maize were induced by P-fertilization, severe chlorosis and stunting of the plants resulted. In these cases, foliar spraying with $ZnSO_4$ corrected the chlorosis. Maize that had not been fertilized with P was normal in colour but did not grow so well as plants receiving micronutrients in addition to a complete NPK application. Conversely, phosphorus uptake was reduced by zinc applications. When both Zn and P were applied, the uptake of both nutrients was reduced. The more effectively the applied P is utilized by the plant, the more severe is the induced Zn deficiency *(Burleson et al. [1961])*.

Langin et al. [1962] found that the problem was greatest on calcareous soils, where Zn solubility is restricted because of the high pH. This is particularly so in soils of high inherent P supply, where Zn levels are already near-critical. If the plant is already existing at a marginal Zn level to begin with, this reduction in Zn content may be the cause of reduced yields.

The P level of the soil therefore appears to be as important as its Zn level when determining the need for Zn fertilization. The P-induced Zn deficiencies are aggravated by high clay and low organic matter contents of the subsoil, by soil compaction and by excessive soil moisture. For these reasons, the problem may become acute on irrigated maize grown on land that had been recently levelled. There are two possible explanations for the depressant effect of phosphorus on zinc uptake: (a) the micronutrient is immobilized within the plant because of abnormally high concentrations of P in the plant; and (b) excessive P in the soil-water system leads to the immobilization of the micronutrients within the soil system */ibid./*.

In order to investigate this problem, *Bingham [1963]* used sand cultures, which have the advantage that it is possible to separate the effects due to the soil from those associated with the physiology of the plant. *Bingham* found that even when P supply was varied from 1 to 100 ppm P, the Zn content of maize was not depressed and the growth of the plant was normal. The highest P-concentration of the sand culture was similar in magnitude to that of the solution phase of soils that have received excessive amounts of P-fertilizer, and on which P-induced Zn deficiencies have been observed. From these results, *Bingham* concludes that P-induced Zn deficiencies are connected with the soil system and are not due to precipitation or inactivation of Zn by P within the plant.

The results obtained in greenhouse experiments by *Terman et al. [1966]* indicate that the effects of large applications of P fertilizers on the response of maize to $ZnSO_4$ applications, were mainly related to the effects of these fertilizers on soil pH. Whether this resulted in influencing Zn solubility in the soil or influenced competition within the plant between Zn and Ca, or other cations, could not be ascertained from these experiments.

However, in recent investigations in greenhouse and field, *Stukenholtz et al. [1966]* have established that the effect of phosphorus appears to be largely physiological in nature, expressed at the root surface and/or in the root cells. Translocation of Zn from the roots to the tops was found to be inhibited at high concentrations of phosphorus, so that Zn concentration in the nodal and internodal tissues was sharply reduced.

Burleson et al. [1961] also assume that the P-induced Zn-deficiency is largely physiological in nature. Most probably a plant root-cell absorption phenomenon is involved and not a chemical reaction in the soil which would result in Zn phosphate precipitation. If external precipitation were involved, supplemental P at a given rate would be most harmful when mixed with Zn, and this was not found to be the case. The fact that Zn applications counteract the harmful effects of P, supports the assumption that an absorption process in the root-cells is involved, whereby increasing levels of P block the absorption of Zn and vice-versa. It is also possible that a secondary effect is due to an enzyme, activated by Zn.

Other elements were found to counteract the depressive influence of phosphorus on Zn uptake. Nitrogen applied with the phosphorus promotes Zn uptake and also improves P utilization. The application of potassium fertilizers was also found to be beneficial in this respect; this was ascribed to the depressant action of potassium on phosphorus and possibly also to improved manganese uptake, which in turn is beneficial to Zn utilization *(Bingham [1963])*.

In addition to soil P and Zn levels, the K saturation of the soil may have an influence on the P-Zn relationship within the plant. The higher the per cent K saturation of the soil, the less does the application of fertilizer P reduce plant uptake of Zn **(Figure 91).** Apparently, a high exchangeable K percentage exerts a favourable action on the plant in its utilization of Zn in the presence of applied P, for which no explanation could be derived from the available data *(Ward et al. [1963])*.

10.3.5 Interrelations between phosphorus and other micronutrients (except zinc)

Excessive phosphorus fertilization has generally been found to reduce the availability of Cu, increase that of Mn, and to have variable effects on concentrations of Fe, B and Mo in the plant. The magnitude of these effects appears to depend on soil, crop and management practices *(Bingham [1963])*.

Investigations were carried out in Rajasthan (India) on the effects of superphosphate, applied at different rates, on the uptake of micronutrients by maize plants grown on five different soils in pot culture experiments. P applications were found to have no significant effect on Mn uptake; they increased the uptake of Fe and decreased the uptake of Cu and B, on certain soils *(Baser and Deo [1967])*.

The interactions of P and Fe were studied in maize grown in a calcareous sulution culture *(Watanabe et al. [1965])*. Increasing P supply at the intermediate Fe levels first caused an increase in dry matter production, then P-induced Fe deficiency symptoms started to appear and dry matter production was depressed. This effect was not related to changes in Fe concentration but to the high P content of the tissues, resulting in a P Fe ratio larger than 60.

The addition of Fe did not affect the Fe concentration but corrected the depression of yield of dry matter *[ibid.]*.

10.3.6 Interactions between iron and zinc

The interactions between Fe and Zn were studied in maize grown in a calcareous solution culture *(Watanabe et al. [1965])*. The addition of Zn, when Fe was supplied at an intermediate level, accentuated Fe deficiency symptoms and decreased dry matter production. This adverse effect on productivity of the plants was not related to Fe concentration in the plant but was associated with a decreased Fe/Zn ratio.

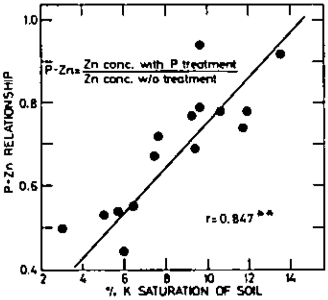

Fig. 91 Relation between K saturation of the soil and P-Zn relationship in maize grown on 15 soils in the greenhouse *(Ward et al. [1963])*. By courtesy of the Soil Science Society of America.

The antagonistic effect of Zn on Fe resulted in reduced dry matter production when the Fe/Zn ratio in the tissues dropped below 1.5. Additions of Fe corrected the adverse effect on dry matter production.

10.3.7 Effect of sulphur applications on the uptake of phosphorus and of certain micronutrients

Sulphur applied to neutral and calcareous soils definitely increased the availability of phosphorus. The uptake of manganese, zinc and copper was improved on soils ranging from acid to calcareous, and that of iron on calcareous soils *(Hassan and Olson [1966])*.

10.4 Interrelationships between potassium and other nutrients

10.4.1 Total cations uptake

Competitive phenomena in cation uptake were usually explained by assuming that the sum of cations was constant. This has not always been found to be the case for maize. *Blanchar and Hossner [1968]* have shown that the sum of inorganic cations in maize can be regulated by the form of nitrogen applied and by the amounts of $CaCl_2.2H_2O$ that are added.

K-fertilization at very high levels may cause an imbalance in the supply of other essential nutrients, thereby indirectly causing some physiological deficiencies in plants. However, since cation content of the plant generally tends to be rather constant, an excessive increase in K-supply will reduce the uptake of Ca and Mg *(Barber [1968])*. and an adequate potassium supply will limit sodium uptake. Conversely, when irrigation water high in magnesium is used, it was found that poor growth of plants resulted from a decreased uptake of potassium *(Ignatieff and Page [1958])*.

The total amounts of Ca+Mg+K measured at the time of silking average from 85 to 105 meq per 100 g of dry matter for maize plants that are well supplied with nutrients. Nitrogen deficiencies lower this figure, and a deficient supply of K, Ca, or Mn increases it.

The normal levels for K appear to vary between 31 and 51; below 31 deficiency symptoms rapidly appear and above 51 there is usually no yield response to K-applications.

The optimal levels for Mg are between 10 and 20; variations in this element, within fairly wide limits, have little effect on maize yields.

A level of 5.5 will cause Mg deficiency symptoms; Mg levels may reach 36, under conditions of K-deficiency.

Normal values for Ca are between 30 and 45; higher values are usually an indication of premature senescence, or of a deficiency of K *(Calmés [1965])*.

In investigations by *Loué [1963]*, it was found that the milliequivalents of total cations decreased at a given stage of growth as the rate of potassium fertilization increased. The greatest difference was found between the treatment without K fertilizer and those which received K fertilizer. At the lower levels of available K, the milliequivalents of total cations increased with age, but remained essentially constant throughout the life of the plant at the highest level of K-fertilization.

The sum of the K, Ca and Mg percentage contents of the plant was essentially a constant at all stages of growth, notwithstanding the considerable variability in the content of the individual cations */ibid./*.

10.4.2 Interrelationships between potassium, calcium and magnesium

The most frequently observed interaction of potassium with other cations is with calcium and magnesium. The interrelationships between potassium content and levels of calcium and magnesium in the tissues of maize plants have been thoroughly investigated in France by *Loué [1963])*.

In general, high negative correlations were established between the K-concentration in the leaves of maize and the corresponding levels of calcium and magnesium. From **Figure 92** it is apparent that the zone of K-deficiency is one of K-Mg antagonism, while the zone of high K-content is one of K-Ca antagonism.

The intermediate zone corresponds to a high positive correlation between Ca and Mg; this decreases as the level of K increases. Very high levels of K are associated with calcium and magnesium deficiencies, though severe deficiencies following the application of potassic fertilizers at rates that do not exceed 180 kg K_2O/ha, are exceptional.

The sum of the major cations (K + Mg + Ca) was found to be remarkably constant.

The triangular diagram of **Figure 93** is representative of many K/Ca/Mg equilibria, ranging from acute K-deficiency to moderate Mg deficiency. These equilibria do not occur at random, but are grouped in an extended zone, represented by a continuous line, which can be divided into five sections:

Section AB is the zone of acute K-deficiency where K represents only 25 per cent, Mg 25 to 40 per cent and Ca 45 to 50 per cent of the total sum of cations. In this zone, K-Mg antagonism is most apparent.

Section BC is a zone of intermediate K-level, with K making up 25 to 40 per cent of the total sum of cations. In this zone, both K-Mg and K-Ca antagonisms are apparent.

Section CD: In this zone, K accounts for 40 to 60 per cent of the total cations, Ca for 42 to 30 per cent, and Mg for 18 to 10 per cent. The K percentage increases mainly at the expense of Ca, whilst K-Mg antagonism is less marked.

Section DE: In this zone, K accounts for 60 to 70 per cent of the total cations, Ca has been reduced to 30–22 per cent and Mg to 12 to 8 per cent. Theoretically, this is the most favourable zone for yield responses to cation nutrition.

Section EF: At these high levels, K accounts for more than 70 per cent of the total cations, Ca produces less than 22 per cent and Mg less than 8 per cent. When Mg falls below 6 per cent, there is a danger of Mg-deficiency.

Sections DE and EF are the zones in which K-Ca antagonism is most marked.

A number of other investigations carried out in different parts of the world confirm that potassium fertilization and lime and magnesium applications are intimately interrelated.

In investigations on acid, sandy loam soils in northern Indiana, it was found that potassium applications induced widespread magnesium deficiency symptoms on maize, confirmed by low levels of magnesium and high levels of potassium in the leaves. Concurrently, additions of magnesium to the soil prevented the appearance of

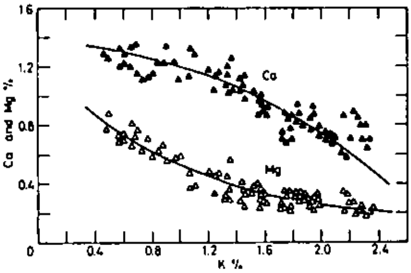

Fig. 92 Ca and Mg levels in relation to K content of maize leaves *(Loué [1965])*. By courtesy of International Potash Institute.

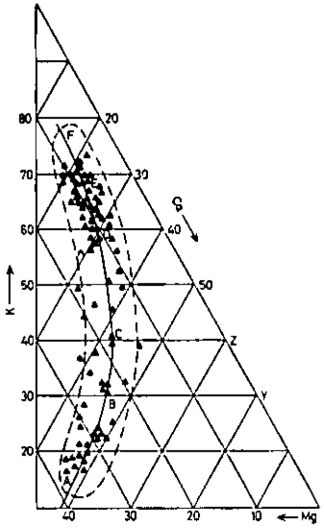

Fig. 93 K-Ca-Mg balance in the leaf of the cob *(Loué [1963])*. By courtesy of the Editor, World Crops.

the symptoms, increased the levels of magnesium in the leaves and reduced the levels of potassium *(Foy and Barber [1958])*.

The effects of four levels of K fertilization (0, 82, 192 and 302 kg K_2O/ha) applied to a loam soil low in exchangeable potassium, on the cation content of maize leaf tissue, was investigated in Tennessee by *Boswell and Parks [1957]* **(Figure 94).**

Increased potassium fertilization generally caused a decrease in calcium and magnesium contents were inversely related to the potassium content of the plant **(Figure 95).**

In field experiments in Southern Rhodesia, with maize grown on a dark-brown clay (pH = 5.8), it has been shown that as the potassium supply was increased, and in consequence K content of the leaves also increased, the Mg content of the leaf fell steadily **(Figure 96).** By contrast, indications of a possible K-Ca antagonism appeared

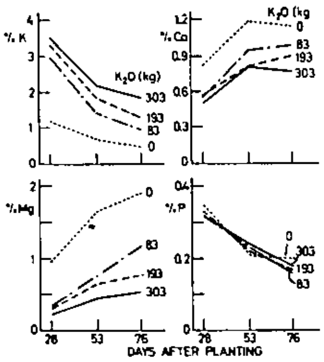

Fig. 94 Per cent K, Ca, Mg and P in maize leaf tissue at 4 levels of K_2O, and at 3 dates after sowing *(Boswell and Parks [1957])*. Note the small decline in K content of leaves from maize grown without potassium application, to the far steeper decline in the K-treated plants, which seems to indicate translocation to other plant parts, probably to the meristemic region. Potassium fertilization generally decreased the leaf content of calcium and magnesium, but did not appreciably affect phosphorus content. By courtesy of the Soil Science Society of America.

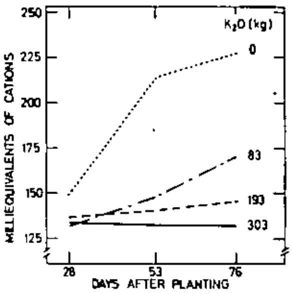

Fig. 95 Total cations (K, Ca, Mg) per 100 g of oven-dry tissue in maize leaves at 4 levels of K_2O, and at 3 dates after sowing *(Boswell and Parks [1957])*. With the exception of the first planting date, the meq of cations in the plant were inversely related to the potassium content of the plant. Because of the extreme differences in equivalent rates (39 for K, 20 for Ca, and 12 for Mg) the meq of total cations were very high for the treatment without K.

only at high K levels. At low K levels, increasing the supply of potassium actually tended to improve Ca uptake *(Thompson [1962])*.

Wilson and Weir [1970], using the *Homés method* of systematic variation in sand culture experiments with maize, found that the total absorption of potassium and magnesium was directly related to dry weight yield (**Figure 97**). It follows, therefore, that maximum yield was a function of the capacity of maize seedlings to maximize absorption of potassium and magnesium, while maintaining a constant sum of the tissue concentration. These conditions were best achieved, under experimental conditions, with an optimum ratio of 1:1 for K/Mg. Their results also suggested that magnesium antagonism over potassium absorption was greater than potassium antagonism over magnesium absorption.

Overstreet et al. [1952] have shown that calcium may increase or decrease K absorption by maize, depending on the level of potassium. The stimulating effect of calcium on K absorption has been explained by *Nielsen and Overstreet [1955]* as due to the fact that calcium is a co-factor in the utilization of the K-carrier complex.

In *Thompson's* experiments, the reciprocal effect of potassium on Ca absorption is demonstrated, indicating that potassium is also a co-factor in the absorption of calcium.

Key et al. [1962] found that the yields of maize were generally not significantly affected by Ca : Mg ratios, provided sufficient quantities of calcium or magnesium were present, except where magnesium exceeded calcium in the growth media. Under these conditions, severe Ca-deficiency symptoms were observed.

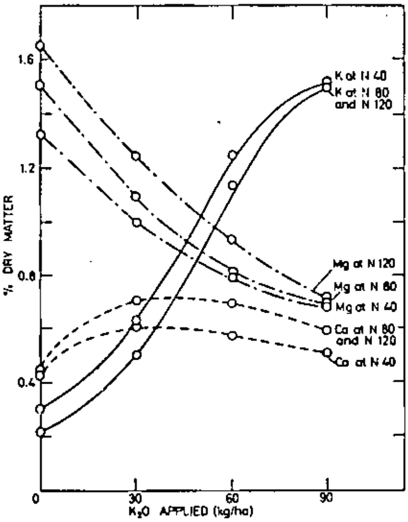

Fig. 96 K, Ca and Mg levels in maize leaves with increasing applications of K *(Thompson [1962])*. By courtesy of the State University, New Brunswick, N.J.

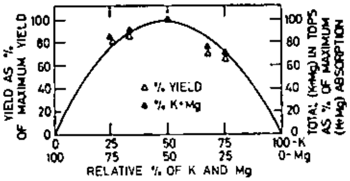

Fig. 97 Relationship between potassium/magnesium nutrient treatments and yield and tissue content of K and Mg *(Wilson and Weir [1970])*. The curve obtained is of similar shape to the theoretical yield curve for reciprocal antagonism between two cationic elements. By courtesy of the Faculty of Agriculture, University of the West Indies.

Maize grown on high-lime soils may show poor growth and low absorption of potassium, even on soils that contain over 220 kg/ha of exchangeable K. This is due to the antagonistic effect of Ca and Mg in the soil solution *(Allaway and Pierre [1939])*. *Bower and Pierre [1944]* working in Iowa on a high lime loam soil, found that, in agreement with numerous other trials, applications of potassium fertilizer markedly increased the K content of maize and decreased the contents of the other cations. The decrease was greater with Mg than with Ca. Low absorption of K on high lime soils may therefore be due more to Mg than to Ca antagonism (Table 56).

Table 56. The effect of potassium fertilization on the yields and K, Ca, Mg and Na contents of maize grown in a high lime loam soil *(Bower and Pierre [1944])*

KCl (kg K_2O/ha)	Yield per pot (g)	Response to K (%)	Chemical composition (meq/100 g)				$\frac{Ca+Mg}{K}$	$\frac{(Ca+Mg)}{-K}$ (mrq/100 g)
			K	Ca	Mg	Na		
0	4.5		10.9	58.0	104.7	< 1	14.9	151.8
165	6.8	51.5	16.5	56.8	92.0	< 1	9.0	132.3
495	9.6	110.0	69.2	46.7	53.3	< 1	1.4	30.8

In North Central Iowa are found intrazonal high-lime soils of low natural productivity. They occur in many fields in an irregular fashion and depress average yields of maize and reduce the quality of the crops.

It has been established that these non-productive high lime soils contain much less exchangeable potassium than productive, high-lime soils. They also contain more calcium and magnesium carbonates. A close relation was found to exist between the yield of maize and the amounts of exchangeable potassium in these soils.

Generally, by applying adequate amounts of potassium fertilizers, the yields of the naturally non-productive soils are increased to a level near that of the productive soils. Both greenhouse and field experiments have shown that applying potassium fertilizers to these soils reduces the uptake of calcium and magnesium by the maize plants. Apparently normal plants had Ca + Mg/K ratios of 3.5 or less, whilst in plants with marked K deficiencies the rates exceeded 5 *(Stanford et al. [1941])*.

10.4.3 Effect of liming the soil on potassium uptake

The graphs in **Figure 98** show clearly that increased K application enhances the K content of the leaf considerably, but at any one level of K application it is also influenced by the rate of liming. At higher rates of liming, less potassium may be found in the leaf in spite of a slight increase in exchangeable K. This suggests that either calcium or magnesium are competing with potassium for absorption on the root surface, or that liming somehow reduces the availability of potassium. Although K concentration in the leaf may be reduced by liming, the total amount of potassium may be increased due to higher yields *(Koch et al. [1970])*.

Stanford et al. [1941] found that maize growing on soils with a high lime content needed relatively more potassium fertilizer to counteract the high calcium level **(Figure 99)**. Normal plants had a Ca–Mg: K ratio of about 2:1. In potassium deficient plants the ratio was greater than 3.5:1.

The influence of calcium and potassium on the yield and cation composition of maize and of other crops was also investigated on a silt loam in the greenhouse, by *York et al. [1954]*. It was found that irrespective of whether potassium fertilizer was applied or not, an application of 5 tons of lime per ha increased dry matter production of maize; however, heavier applications reduced yields. The first two increments of lime reduced the potassium content, whereas the highest level of liming (10 000 ppm of soil) increased the potassium content. Lime also tended to increase the magnesium content. Applications of potassium at the rate of 220 kg K/ha reduced both Ca and Mg contents of the maize plants. The sum of cations in maize increased with each

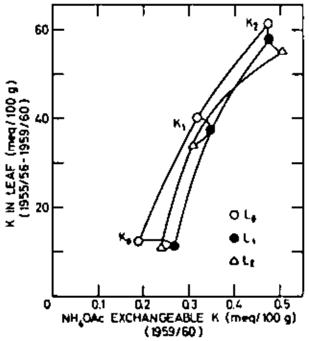

Fig. 98 The effect of exchangeable K in soil on the amount of K in the maize leaf in relation to different levels of K and lime application (each value represents the mean over all levels of N and P application). From data presented by *J. Marques [1961]*. (Nutrient balance in the soil in relation to fertilizer treatment and maize yield), and cited by *Koch et al. [1970]*. By courtesy of the Soil Science Society of America.

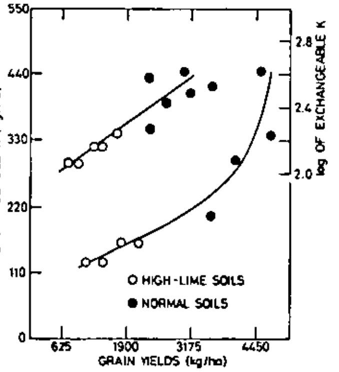

Fig. 99 Relationship between maize yields and exchangeable potassium content of the soils *(Stanford et al. [1941])*. In every field the normal soils contained more exchangeable potassium and were more productive than the high lime soils, the amounts ranging from 300 to 580 kg K/ha in the former group, and from 225 to 300 kg in the latter group. All fields responded to K fertilization with yield increases ranging from 19 to 80 per cent. By courtesy of the Soil Science Society of America.

successive level of liming; at the highest level, it was approximately twice that of plants growing on unlimed soil. Potassium fertilization also tended to increase the cation content of the plants *[ibid.]*.

10.4.4 Effects of potassium on phosphorus uptake

In contrast to nitrogen, the effect of adding potassium fertilizers to the soil on phosphorus utilisation by maize and on the phosphorus content of the plant has been found in most trials to be indeterminate or slight, *(Fine]1955])*.

For example, when *Borwell and Parks]1957]* studied the effects of four levels of K fertilization (0, 82, 192 and 302 kg K_2O/ha) applied to a loam soil low in exchangeable potassium, on the P content of maize leaf tissue, the phosphorus content of the leaves was found to be essentially unaffected by the potassium fertilizer treatments.

10.4.5 Interrelations between potassium and sodium

In experiments with excised roots and intact seedlings of maize grown in a solution containing 1 meq Na^+/l, it was found that the Na^+ accumulation in the roots is first rapid and then reaches a saturation level. Accumulation in the shoots is concurrent with that in the roots but at a much lower level. By contrast, the accumulation of K^+. is more rapid than that of Na^+ in both roots and shoots, and continues to rise after Na accumulation has become static.

The amounts of K accumulated are initially higher in the root than in the shoot, but the situation is reversed after about 16–17 hours **(Figure 100)**.

It was further found that the uptake from NaCl solution was reduced by the addition of equivalent amounts of KCl. Addition of $CaCl_2$ to the NaCl solutions drastically lowered Na^+ uptake by plants that had an initially high K^+ content. However, when the initial K^+ content was low, only a small reduction in Na^+ uptake was induced by adding $CaCl_2$. When K^+ and Na^+ were present in equal amounts in the outer solution, the addition of Ca^{++} increased K^+ accumulation and depressed that of Na^+. No

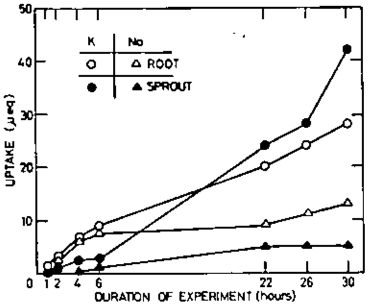

Fig. 100 Time course of uptake of Na^+ and K^+ by maize plants from a solution containing 1.0 meq NaCl+ 1.0 meq KCl/l *(Marschner and Schafarczyk [1967])*. The uptake is expressed as meq/g (root) and meq/1.5 g (shoot), fresh weight. By courtesy of Zeitschrift für Pflanzen- und Bodenkunde.

translocation of Na^+ into the shoots was detectable at low concentrations; it was only when the solution concentration was 10.0 meq/l or higher that detectable translocation of Na^+ occurred. The translocation of Na^+ to the shoots was increased by (a) increased concentration of Na^+ or other salts in the ambient solution, (b) increased transpiration, and (c) inhibition of the root metabolism *(Marschner and Schafarczyk [1967])*.

10.4.6 Potassium and zinc interactions

Potassium and zinc deficiencies cause similar stunting effects on maize; the leaf symptoms, however, are different (cf. p. 270, 271).

Stuckenholtz et al. [1966] have found that the depressive effects of phosphorus on the zinc content of maize were alleviated as the per cent potassium saturation or soil potassium increased.

In field experiments in Southern Rhodesia, with maize grown on a dark-brown clay (pH = 5.8) it was found that at low K levels an increase in K supply first raised the Zn level, but with increasing amounts of K the uptake of Zn was depressed (**Figure 101**). These results suggest that Zn deficiency can be aggravated by either a deficiency or an excess of K *(Thompson [1962])*.

Zinc and potassium appear to be related in action through the pyruvic lkinase enzyme system *(Miller and Evans [1957])*.

10.4.7 Effect of potassium supply on manganese uptake

In field experiments in Southern Rhodesia on dark-brown clay (pH = 5.8), increasing the potassium supply had a depressing effect on manganese and Al uptake (**Figure 102**). These results suggest that an increased K supply might induce or aggravate Mn deficiency, especially under conditions of low availability of Mn. Where the Mn level in the soil was adequate, the effect of K applications on Mn uptake was negligible *(Thompson [1962])*.

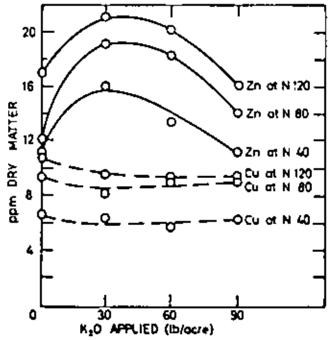

Fig. 101 Effect of increasing applications of potassium on the levels of Cu and Zn in maize leaves *(Thompson [1962])*. By courtesy of the State University, New Brunswick, N.J.

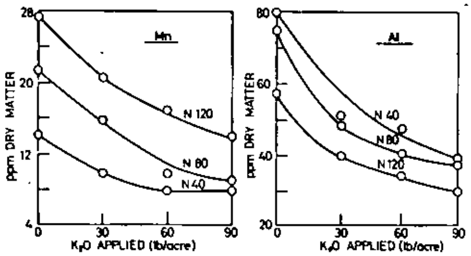

Fig. 102 Effect of increasing application of potassium on the levels of Mn (left) and Al (right) in the leaves of maize *(Thompson [1962])*. By courtesy of the State University, New Brunswick, N.J.

10.4.8 Potassium and molybdenum relationships

Jones [1965] was the first to report an inverse relation between potassium and molybdenum in the leaves of maize plants. It was found that maize plants showing marked symptoms of K deficiency contain considerable concentrations of molybdenum, about four times more than the leaves of normal plants. Applications of potassium fertilizer eliminated the deficiency symptoms and resulted in a concomitant significant reduction in the molybdenum content of the leaves.

As the potassium-deficient plants were somewhat stunted, part of the increase in molybdenum content can be attributed to a concentration effect. However, further investigations are required to determine the exact cause of high molybdenum content in potassium-deficient plants.

10.5 Cation – anion balance

Experiments with excised roots have shown that cations and anions from neutral salts are not necessarily taken up in equivalent amounts. Cation absorption will predominate when the salt consists of a preferentially absorbed cation such as K^+ and a slowly absorbed anion such as SO_4^{--}. Conversely, anion absorption will exceed cation absorption when the salt consists of a slowly absorbed cation such as Ca^{++}, combined with a rapidly absorbed anion such as NO_3^-.

10.5.1 Mechanism for maintaining cation-anion balance

Unequal uptake of cations and anions would inevitably upset electrical balance both inside and outside the cell, and set up large electrical fields, unless concurrent changes occur in ionic composition of cell and nutrient that are able to maintain electrical neutrality.

This is made possible by a flexible metabolic system, operating in the cells, which balances any differences between uptake of cations and of anions by an exchange of HCO_3^- or H^+. Because of the concurrent change in the organic anion content, the pH of the plant tissues remains fairly constant, at approximately 6 *(DeWit et al. [1963])*.

The total cation content consists of $K^+ + Na^+ + Ca^{++} + Mg^{++}$, and the total inorganic anion content consists of $NO_3^- + H_2PO_4^- + SO_4^- + Cl^-$. During reduction of ON_3^- and SO_4^-, the negative charge is released as HCO_3^-, which is either transformed into an organic anion, or exchanged with an inorganic anion from the medium, or neutralized by H^+ uptake. The ionic state of the phosphate is not changed by its utilization *(DeWit et al. [1963])*.

In the case of an excess uptake of cations, organic acids are produced, in the exact amounts required to balance the absorbed cations, while H^+ ions pass to the external medium where they compensate for the cations that have been removed.

In the opposite case of excess anion absorption, a sufficient amount of the organic acids in the cells disappears to compensate for the excess anion uptake and HCO_3^- ions pass to the external medium.

From the foregoing it follows that the total cation content minus the total inorganic anion content (phosphorus included as H_2PO_4) is numerically equal to the organic anion content. This value was found to remain remarkably constant under a wide set of cation ratios, provided the inorganic anion content of the nutrient solutions remained constant *(DeWit et al. [1963])*.

When cations are absorbed in excess of anions, the pH of the expressed root sap increases; the reverse occurs when anions are in excess of cations. Organic acid changes in the excised roots are proportional to expressed sap pH changes induced by unbalanced ion uptake *(Hiatt [1967])*.

10.5.2 The organic acids of the maize plants: effects of nutrient deficiencies

Mineral deficiencies in plants are usually associated with changes in organic acid compounds. Whilst citric and malic acids are the predominant organic acids in some plant species, aconitic acid is the dominant one in maize *(Clark [1968])*. In nutrition experiments on maize, one-third to one-half of the total acidity of the anion-charged fraction was found to be t-aconitate; malate was next highest in concentration and was approximately one-third that of t-aconitate. Citrate was approximately one-half of malate. Smaller amounts of succinate, fumarate and other unidentified acids were also present *[ibid.]*.

The total organic acid content was found to be increased by deficiencies of K, Ca, Mg and P; however, these deficiencies caused a decrease in t-aconitate and an increase in malate and citrate. Potassium deficiencies in particular, caused the most marked change in the relative amounts of organic acids: t-aconitate decreased fourfold with an associated fourfold increase of malate and citrate *[ibid.]*.

Clark relates the higher organic acid content of K-deficient, and other mineral deficient plants either to a reduced protein synthesis and a subsequent higher accumulation of amino acids, or a decreased use of carbon for amino acid synthesis. Alternately, if t-aconitate synthesis is an enzymatic process, the enzyme(s) may require potassium for activity.

10.5.3 Effects of fertilizer treatments

DeWit et al. [1963], after studying the growth rates and chemical composition of plants that had received high fertilizer rates, suggested that one of the factors regulating growth rate is the organic anion concentration of the tissue. In most plant tissues the total concentration of inorganic cations exceeds the total concentrations of inorganic anion. Because of electroneutrality, the difference between the two should be an estimate of the organic acid anions concentration, as explained above. The investigators found that the difference between inorganic cations and anions was constant until plants were stressed by nutrient deficiency. They further found that normal growth is possible under a wide range of total cation contents, of anion contents and of the contents of individual ionic species, provided the organic anion content is normal. This is an indication that the organic anions are essential for good growth.

The cations were found to be necessary in amounts above 250 meq/kg for potassium and 50 meq/kg for calcium and magnesium because they form neutral salts with the inorganic and organic anions. Potassium plays a dominant role among the cations as a positive charge because it is readily taken up by plants. Whilst other cations (Na, Ca, Mg) may replace K as a positive charge, potassium has a unique role in the downward transport of excess organic anions. The authors suggest that it is for these reasons that K deficiency may cause an excessive accumulation of organic acids *[ibid.]*. *DeWit et al. [1963]* suggest that the greater the difference between inorganic cations and anions, the greater will be the yield. This was confirmed by *Noggle [1966]*, who found that fertilizer treatments that increased the organic anion concentration increased yields; conversely, treatments that decreased this concentration also decreased yields.

At first sight, these various statements may appear contradictory, namely: (a) for plants grown without nutrient stress, the amount of organic acids is a constant; (b) the greater the amount of organic acids, the greater the yield; and (c) K deficiency causes an accumulation of organic acids. However, if placed in a proper context, what appears at first sight contradictory, may make sense.

In plants supplied with adequate and balanced amounts of nutrients, the balance between inorganic cations and anions tends to be constant. Deficiencies, or imbalance in nutrient supply, may cause either a decrease or an excess in the organic acid content, according to the physiological role of the nutrient(s) involved. If a deficiency has caused a reduction of organic acids below the normal level, appropriate fertilizer treatments will increase yields and at the same time increase the level of organic acids as compared with the deficiency treatment. In the case of K deficiency, the resultant dislocation of the downward transport of excess organic anions causes an accumulation of these anions above the normal level.

10.5.4 Effect of nitrogen fertilizers on cation-anion balance

The plant requirès large amounts of nitrogen and the cation-anion equilibrium is very much dependent on the form in which nitrogen is supplied to the plant. Since nitrate is rapidly absorbed and transformed to the reduction stage of ammonia prior to its assimilation into organic compounds, and ammonium is also readily absorbed, it follows that differences in response of the plant to the two different forms are related to their effects on the ionic balance of the plant and the growing medium *(DeWit et al. [1963])*.

The effects of an exclusive supply of either nitrate N or ammoniacal N on the metabolism of maize plants, grown in nutrient solution, were investigated by *Coïc et al. [1961])*. It was shown that the uptake of nitrogen is about equal both sources. When nitrogen is taken up as $(NH_4)^+$, this occurs in competition with other cations, together with an increase in uptake of anions. The reduction in cation uptake is less marked for divalent cations than for potassium. Conversely, the uptake of nitrogen as $(NO_3)^-$ is in competition with other anions, together with an increase in cation uptake.

This relationship is explained by the necessity of all plant tissues to maintain equilibrium. When $(NH_4)^+$ ions are taken up by the plant, higher amounts of inorganic anions are necessary to maintain ionic balance *(Kirkby and Mengel [1967])*. Excess cations are balanced by organic acids; when N is absorbed as an anion (NO_3)-, the associated cation must be neutralized by an organic acid, following the reduction of the nitrate to ammonium. These organic acids are then present as salts of the inorganic cations, and threfore contribute to inorganic equilibrium.

Therefore, an exclusive supply of ammonium N increases the uptake of phosphorus and sulphur and reduces the uptake of cations – the reduction in bivalent cations being greater than that of potassium. As a result of the excedent of cations over anions absorbed by the plants, the nutrient solution was found to become progressively acidified; the opposite effects occurred when nitrate-N was the sole source of N.

If the supply of nitrogen is in the form of nitrate-N, high amounts of anions will therefore be absorbed, whilst the opposite will occur with ammonium-N nutrition. The uptake of nitrate has to be accompanied by cations or by an exchange of anions in order to maintain electroneutrality. Conversely, the uptake of ammonium ions must be accompanied by anions or the exchange of other cations from the root.

Nitrate taken up by the plant does not remain in ionic form, but is reduced. During this reduction the negative charge shifts from NO_3^- to OH^-, which increases the pH of the system. This pH increase may lead to the accumulation of organic acid anions. Conversely, the assimilation of ammonium ions leads to the production of hydrogen ions: $NH_4^+ \longrightarrow NH_3 + H^+$, causing a lowering of the pH of the tissue, and in turn, a reduction in the accumulation of organic acid anions. This explains why with ammonium nutrition the content of organic anions is low and that of inorganic anions is high, whilst, with nitrate-N as the source of nitrogen supply, plants contain a higher concentration of cations and a greater quantity of organic acids is required to maintain electrostatic balance.

Hydrogen ions produced during ammonium assimilation will also diffuse out, lowering the pH of the nutrient medium, and also reduce cation uptake by competition effects. A balance between cations and anions in the plant infers that different cations compete for the bulk of the anions and vice-versa. This is probably the reason why an increase in the supply of a specific ion in the nutrient medium decreases the uptake of a similarly changed ion, where there is no specific competition for a carrier site *[ibid.]*.

10.6 Summary and conclusions

From the foregoing, it is clear that in agricultural practice it is not sufficient to apply large amounts of fertilizers, but that a proper balance between the nutrients supplied to the crop must be the aim. Although much work has been devoted to establishing the nutrient requirements of maize in relation to each other, the problem is extremely complex. The actual balance achieved by the plant growing in the field will depend on many factors that influence nutrient uptake, such as soil temperature, moisture regime, biological factors, etc., which cannot be forecast accurately at the time a decision must be made as to the amounts of fertilizers to apply. As an appreciable proportion of the nutrients required by the crop is supplied from the soil reserves, the actual amounts applied in the fertilizers need not be exactly according to the proportions which provide the optimum supply to the plant, though as a rule, these proportions are taken into consideration, when deciding on the fertilizer formula. Hence, in practice, it is necessary to distinguish between *nutrient balance* and the relative proportions of nutrients actually supplied in the fertilizers *(Mengel [1968])*. In agricultural practice, imbalance usually means that one or more nutrients are limiting. To achieve balance, it will usually suffice to ensure continuously an adequate level of phosphorus and potassium in the soil, and to adjust the rate of nitrogen applications according to each specific situation: expected yield level, residual nitrogen, etc. *[ibid.]*.

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11. Determining fertilizer requirements

Diagnostic methods, which would make it possible to advise the farmer on the kinds and amounts of fertilizers to apply to a crop grown under the specific conditions of involved the individual farm, are of considerable economic importance. The problems have been under study for many years, and a number of different approaches have been developed.

11.1 Soil tests

There is no difficulty in determining the soil content of essential elements by chemical methods. However, it is not the amounts of nutrients present in the soil that are of significance to crop production, but their availability in the proper proportions throughout the growth period of the plant. This is a function not only of the soil but also of the crop, its environment and management. It is therefore not surprising that no chemical tests have yet been devised that are able to provide an accurate assessment of the amounts of essential elements available to the plant in the soil, and hence the amounts that need to be added. In spite of these difficulties, by correlating the results of soil tests with the crop responses obtained in fertilizer experiments in the field, analytical methods have been developed which make it possible to predict approximate fertilizer needs, and the probability of obtaining a profitable response from fertilizer applications.

These tests are, however, empirical, and appropriate only to the specific soil types for which they were developed. Their interpretation requires calibration with fertilizer field experiments and their reliability depends on the practical experience of the interpreter. There also arise numerous practical problems of sampling, analysis and interpretation. Applying the results of soil tests is further complicated by the fact that availability of soil nutrients is not the same for all crops; different crops are also able to obtain their nutrients from different soil depths and hence the interpretation of the chemical tests will vary with the crop (and even varieties of the same crop) and according to their place in the crop rotation.

The big advantage of the soil test over plant analysis, is that the former can provide information in time, for the farmer to take advantage of it before he sows his crop.

11.1.1 Nitrogen availability

Nitrogen availability in particular is influenced by complex soil, climatic and biotic factors that frequently make a chemical soil test meaningless.

The amount of nitrogen that can be supplied to the maize crop from the soil is usually estimated from the organic matter content of the soil and the amount and kind of crop residues that are incorporated in the soil.

A rise in temperature of the soil may speed up nitrification and release relatively large amounts of nitrogen; leaching and denitrification, on the other hand, may cause rapid losses of nitrates. These continuous fluctuations reduce the value of any test developed for predicting nitrogen requirements.

Notwithstanding these limitations, a number of tests have been developed for predicting the N-supplying capacity of the soil, based on the organic matter of the soil, which provides the main supply of available nitrogen. Using standard procedures the rates of nitrogen released are measured or estimated **(Figure 103)** *(Richard et al. [1961])*.

11.1.2 Determination of phosphorus status of the soil

Much effort has been devoted to developing a chemical method for assessing the amounts of phosphorus that the soil can provide to the growing crop. However, no chemical method has yet been found that can accurately predict the yield response of a crop to phosphorus fertilization on different soils. Empirical methods which involve various kinds of extracting solution, have been developed for evaluating the so-called available phosphorus in the soil.

The levels of soil test P required for maximum yields, as well as the amounts of fertilizer P required to raise the level of soil P depend on soil texture. For example, a sandy soil will usually require a higher level of soil test P for maximum yields than does a clay soil **(Figure 104a)**, but the amounts of fertilizer P required to raise the level of soil P will be higher for a clay soil than for a sandy soil **(Figure 104b)**. For certain clay soils, really massive doses of phosphorus are required to make a significant change in their available P status *(Thomas [1969])*.

Soil pH has a considerable effect on the availability of phosphate ions released into the soil solution from the decomposition of organic residues or from the application

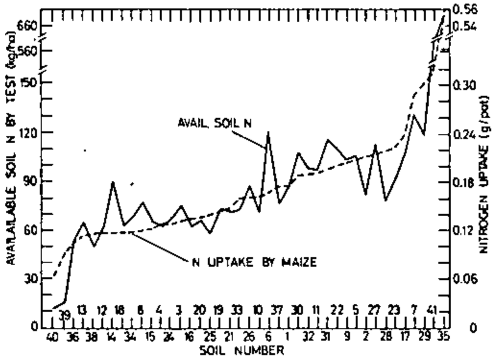

Fig. 103 Correlation between amounts of available nitrogen found in 41 soils and nitrogen uptake from these soils by maize grown in pots *(Richard et al. [1961])*. The soils are arranged in order of increasing nitrogen uptake. The test accounted for 67 per cent of the variations in nitrogen uptake. By courtesy of the Elsevier Publishing Co., Amsterdam.

of fertilizers. Below pH 5.5, relatively unavailable compounds with iron and aluminium are formed. Above pH 7.0, and in the presence of abundant calcium, a number of relatively unavailable calcium phosphate compounds are formed. Above pH 8.5, sodium phosphates are formed, so that above a certain pH level, solubility of the phosphorus increases *(Hanna and Hutcheson [1968])*.

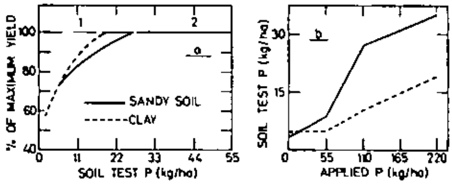

Fig. 104 (a) A sandy soil requires a higher level of soil test P for maximum yields than does a clay soil.

(b) The amounts of fertilizer P required to raise the level of soil P is higher for a clay soil than for a sandy soil *(Thompson [1969])*. By courtesy of the American Potash Institute.

When soils show very high levels of available P, it is difficult to estimate for how long they can be cropped without adding phosphorus fertilizer. It may take some years before yield responses to added phosphorus fertilizers are obtained *(Thomas [1969])*. In S. Rhodesia, a soil level of about 50–60 ppm of extractable phosphorus appears to be the minimum necessary for adequate growth of most field crops. Whilst the soil test is of value in indicating when a soil is poor or rich in available phosphates, the correlations obtained in the important intermediate ranges are of low accuracy *(Saunder [1954])*.

The critical soil level for a relatively immobile nutrient such as phosphorus is higher for a young plant than at later stages of its growth *(Bray [1954])*. This is because the root system that is not yet well developed, will not be highly efficient in nutrient uptake, and this will affect the uptake of relatively immobile nutrients more than it does that of nutrients with greater mobility.

11.1.3 Soil tests for potassium availability

A number of different approaches for determining the potassium-status of the soil have been developed.

– *Exchangeable potassium*

The most widely used tests are potassium extraction based on the removal of exchangeable potassium, which is a fairly good criterion of the potassium fertility status of the soil *(Peech [1948])*.

Bray [1944] developed a test for exchangeable potassium in soil which makes possible estimates of the potassium deficiency of a given soil, the yield increase that can be expected from an application of K-fertilizer, the amounts to be applied and the economics of fertilizer use **(see Figure 105)**.

However, exchangeable K as a soil test value has a number of limitations. The amount

– *Exchange capacity of the soil*

The speed with which potassium in the soil solution that is taken up by the plant will be renewed, is evidently dependent on the cation-exchange capacity of the soil. On soils with a low CEC, potassium will be early replaced, the opposite being true for soils with a high CEC **(Figure 107).**

Thomas [1969], working in Texas, found that the amounts of exchangeable potassium required for good crop growth were about two-and-a-half times as much for a soil with a high CEC as for one with a low CEC.

Loué [1963], in France, found that the exchangeable potassium content varies considerably (from 0.10 to 0.50 parts per thousand) on clay and calcareous soils containing 25–30 per cent clay, and with a very high Ca/K ratio – from 50 to 75. The exchange capacity of these soils, often ranging between 20 and 25 meq, must be taken into consideration in interpreting the results of soil analysis. For these soils, leaf content of K has been found to be a more reliable indicator of fertilizer needs of maize than the exchangeable K-content of the soil.

– *Saturation of the exchange capacity with exchangeable potassium*

Many soil scientists are of the opinion that a certain proportion of the cation-exchange capacity of the soil should involve potassium to ensure high yields of maize.

Investigations in South Rhodesia for example, indicate that for the heavier soils, it is desirable to evaluate the potassium status in terms of the saturation of the exchange complex with respect to potassium. The result of preliminary trials suggest that for maize the exchangeable potassium should be at least 1 per cent of the exchange capacity. The lower limit of exchangeable potassium necessary in soils of low exchange capacity appears to be about 0.12 meq per cent for maize, with its extensive root system *(Saunder [1954]).*

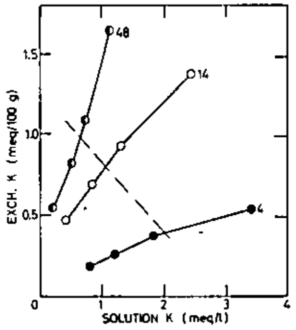

Fig. 107 Relation between cation exchange capacity (CEC) of the soil and the speed with which K is replaced in the soil solution *(Thomas [1969]).* In three soils, with CEC 's of 4, 14, and 48 meq per 100 g respectively, the soil with a high CEC required for good crop growth two-and-a-half times as much exchangeable potassium as the soil with low CEC. The dashed line indicates the amounts of exchangeable potassium needed for good crop growth. By courtesy of the American Potash Institute.

– *Potassium balance sheet*

Another approach to using potassium soil tests for determining fertilizer requirements, proposed by *Thomas [1969]*, involves maintaining a 'balance sheet' over the years, in which data on soil tests, fertilizer applications and potassium removal by the crop are logged annually. An example of such a balance sheet is given in Table 57.

Table 57. Sample balance sheet for potassium fertilization of maize (all data given in kg/ha) *(Thomas [1969])*

	1965	1966	1967	1968	1969
Soil test K	110	154	187	215	252
K added in fertilizer	110	110	110	110	110
Yield of maize	5100	6500	6800	7800	—
Removal of K in grain and cob	31	38	41	46	—
K unaccounted for	35	38	40	25	—

In the sample balance sheet shown in Table 57, potassium additions at the rate of 110 kg/ha have been made for a number of years. Yields of maize have risen steadily, the soil test values for potassium have become progressively higher and only a relatively small proportion of the potassium is unaccounted for. As long as yields and K soil test results continue to rise, this fertilizer programme should continue. When yields cease to go up, and soil test K is quite high, a change in fertilizer practice will probably be indicated.

– *Energy level or potassium potential*

A number of workers, e. g. *Schuffelen and Bolt [1958]*, have come to the conclusion that the amount of so-called available nutrient is not sufficient as a criterion of what is available to the plant. They proposed that the *degree of availability* or *intensity of supply* would also influence the amount at the disposal of the plants. Accordingly, information on three main points is required in order to assess nutrient status for a particular nutrient, soil and crop combination *(Nye [1963])*: (a) the critical intensity level or potential of a nutrient above which satisfactory uptake occurs; (b) the current intensity or energy level of the nutrient in the particular soil: and (c) the relation between the labile quantity of the nutrient in the soil and its intensity. With this information it should be possible to predict the amount of fertilizer required in order to bring the intensity of a particular nutrient to an adequate level. If the level is already adequate, it permits prediction of how much nutrient can be removed before it will be reduced below the critical level for optimum growth *(Koch et al. [1970])*.

On the basis of these concepts, various techniques have been developed, such as that of *Beckett [1964]*, which provide information on the intensity of potassium supply. Investigations by a number of authors have shown that the newer concepts, whilst important in research work, appear to be only a slight improvement over values for exchangeable K, especially in soils with a limited capacity for releasing non-labile K during the period of crop growth *(Barrow [1966]; Zandstra and MacKenzie [1968])*. For maize, in particular, they were found to be only slightly more reliable an index than available potassium values *(Zandstra and MacKenzie]1968])*.

11.1.4 Factors affecting reliability of soil tests

Predicting yield increases that can be expected from fertilizer applications on the basis of soil tests is complicated by a number of factors that influence the response of maize to fertilizers.

The subsoil may provide appreciable amounts of potassium, so that exchangeable K in the subsoil may have to be considered in addition to that from the surface soil layer.

Poor aeration, resulting from soil compaction or excess moisture, reduces the ability of the roots to absorb potassium, so that deficiency symptoms may be shown by plants though the level of exchangeable K may be quite adequate. Similarly – moisture stress and low temperatures restrict nutrient uptake by maize.

Braunschweig [1971] has shown that even at soil moisture tensions of p F 2.4 to p F 2.7, at which the water supply to the plant was still found to be adequate, the rate of K-supply to the roots by diffusion was markedly reduced. The author therefore concludes that when soil moisture tension increases, nutrient deficiencies reduce yields even before the actual water supply becomes limiting.

High concentrations of calcium, magnesium or ammonium in the soil solution are antagonistic to K uptake. The potassium in soils rich in organic matter is more readily available than in soils in which the potassium is absorbed on clays. The genetic characteristics of the hybrids sown, and planting density, will also affect the response of maize to fertilizers.

Therefore, many factors may affect predictions which relate the crop response to fertilizers and which are based on soil tests.

The testing procedures adopted may also have significant effects. Drying of the soil samples may cause a considerable increase in exchangeable K taken from surface layers in certain soils, but little change in others, and even cause small decreases in still other cases. Texture and the level of exchangeable K in the soil appear to the principal factors involved. In soil samples taken from subsoils, the increase in exchangeable K following drying is greater and far more consistent than in those taken from top soils. It is least in sandy soils, but up to tenfold increases were recorded on other soil types.

Summarizing the results of uniform field experiments in 51 locations in the Corn Belt, *Hanway [1964] et al. [1962]* concluded that exchangeable K determined in field-moist samples provided a more reliable estimate of the increases in grain yields of maize to be expected from K fertilizer applications than did determinations on air-dry or oven-dry samples **(Figure 108).**

11.1.5 Soil tests in agricultural practice

It is mainly for phosphorus and potassium that soil tests have been developed, which after correlation with crop response data and a great deal of practical experience, can be used for fertilizer recommendations. The basis for evaluating most soil test programmes for phosphorus and potassium, are calibration curves in which P and K content of the soil are related to the corresponding percentage of maximum yield *(Bray [1961])*. Two examples of such calibration curves, for P and K respectively, are shown in **Figure 109.** The probability of profitable response is greater the lower the nutrient level, as determined by analysis **(Figure 110)** *(Fitts [1955])*. Using the results of the soil test, and taking into account the nature of the crop, the physical conditions of the soil, the management of the preceding crops and their residues,

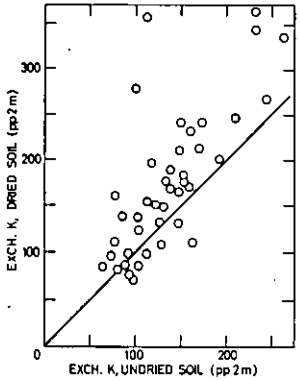

Fig. 108 Relation of exchangeable potassium, as determined on dried and on field-moist samples – and yields of grain *(Hanway [1964])*. By courtesy of the American Potash Institute.

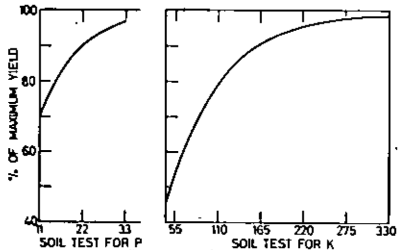

Fig. 109 Calibration curves in which P-content of the soil (left) and K-content (right) are related to the corresponding percentage of maximum yield *(Bray [1961])*. For example, with a 22 kg P test the percentage of the maximum yield is 90 per cent, and with 110 kg K-test it is 80 per cent. By courtesy of the American Potash Institute.

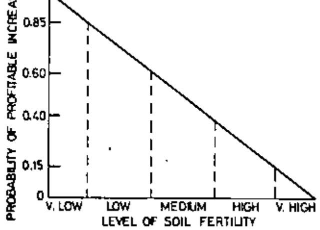

Fig. 110 There is a greater probability of obtaining a profitable response from fertilization on soils testing low in an element than from soils testing high in that element *(Fitts [1955])*. By courtesy of the American Potash Institute.

cultivation methods, moisture regime, etc., an experienced diagnostician may be able to predict the probability of profitable crop response to fertilizers and the approximate amounts to be applied.

On the basis of the soil tests, the soils are classified into three to five levels in relation to phosphorus and potassium availability (the accuracy of the tests generally not justifying more than three levels): *low*, at which an application of about double the amount of nutrients removed by the crop is recommended in order to allow for some build-up in the soil in addition to the immediate crop requirement; *medium*, at which the amount recommended is slightly higher than removal for phosphorus, and slightly less for potassium; and *high*, at which less than removal is recommended *(Nelson and Stanford [1958])*.

In an experiment on a loam soil in Tennessee, on areas testing from very low to high in available K, significant responses to K were obtained on soils that tested very low and low. A significant response to potassium was also obtained on the medium testing soil, but no significant differences were recorded between different rates of application of potassium. There was no response to potassium where the soil tested high in available K (Table 58) *(Parks et al. [1965])*.

Table 58. Average maize yields (kg/ha) for different rates of K at four soil test levels *(Parks et al. [1965])*

Fertilizer application K_2O/kg/ha	Soil test level				Average for all levels
	very low	low	medium	high	
av. K_2O/ha	77	132	185	317	
0	3746	7747	8736	9652	7445
33	6032	9080	10033	10032	8799
66	8128	9080	9715	9715	9159
99	7556	10096	10287	9778	9429

In general, it appears that where very high rates of fertilizers are continuously applied to maize, soil testing as a means of identifying deficiencies of the major nutrients will no longer be important. It will be used instead for the diagnosis of deficiencies of sulphur, magnesium and zinc, the excessive accumulation of nitrates and abrupt changes in pH *(Thomas and Hanway [1968])*.

The higher the soil test level, the lower the additional amounts of nutrients that it will be necessary to supply from fertilizers. The relative amounts taken up by the plant from soil and fertilizer at different soil test levels are shown graphically in **Figure 111** *(Reed and Nelson [1964])*.

In some regions of the U.S.A., recommendations on fertilizer applications are being made by computerised services, which take into account soil type, yield potential, cropping sequence, subsoil moisture, the amount and frequency of precipitation, managerial ability of the farmer, as well as the actual results of the soil test. Any results of new research are immediately included in the programming. One hundred soil samples can be processed per minute *(Walsh [1964])*.

11.2 Plant tissue tests

As the plant itself is an integrator of all the factors affecting nutrient availability, analysing the tissue of a metabolically active part of the plant, such as a fresh leaf, gives an accurate estimate of the nutrient status of the plant at the time of testing, provided it was not growing under conditions of acute deficiency. When there is a severe deficiency of one or more nutrients, growth is stunted and the plant tissues may show a higher concentration of the nutrient(s) than those of a plant growing under more favourable conditions.

Many studies have shown that the concentration of N, P and K in different tissues of the maize plant can serve as an indication of the nutrient status of the plant, and in particular can be used to diagnosis nutrient deficiencies. In certain cases, the *total* N, P and K contents of leaves at silking time have been used for this purpose *(Tyner [1946])*, while in others the tests are based on the *soluble* forms of the nutrients in the stalk or leaf *(Scarseth [1943])*.

11.2.1 Parts of the plant to be used in testing

Hanway [1962] found that differences in the total N, P and K of the leaves and sheaths of the maize plant reflected nutrient deficiencies better than those in any other part of the plant. These differences were at a maximum near silking time and were not much affected by sampling time or position of the leaf on the stalk.

Early in the growing season, the percentage of nitrate N in the leaves or stalks appears to provide a better estimate of the N status of the plant than does total N. Later in the season, nitrate-N in the leaves, whilst still indicating whether the supply of nitrogen to the plant is adequate or not, is less sensitive than total N for diagnosing the degree of N-deficiency *(Hanway [1962])*.

Hanway also found a high degree of correlation between total P and water-soluble P in all parts of the plant, thereby justifying the conclusion that the two are equally useful for diagnosing the P-status of the plant.

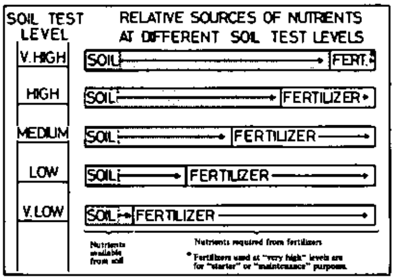

Fig. 111 Relative amounts of nutrients taken up from the soil or from applied fertilizer, in relation to soil test levels *(Reed and Nelson [1964])*. As the soil tests higher in a plant nutrient, the amount needed from fertilizers becomes less. But even at high levels, some nutrients come from fertilizers. By courtesy of the American Potash Institute.

11.2.2 Critical nutrient levels

Maize plants grow normally only within a narrow optimum range of concentrations of the substrate, with a corresponding effective range of concentrations within the plants. Below this range, the plants show pathological deficiency symptoms and above this range they show typical toxicity symptoms *(Marsh and Shive [1941]).*

The interpretation of leaf analysis data is based on the assumption that when the concentration of a certain element in the tissues of the plant is below a certain *critical level,* the uptake of that element from the soil was insufficient.

The critical nutrient level has been defined in a number of ways: as the transition from 'poverty adjustment' to the 'luxury consumption' region *(Macy [1936]);* as the narrow range of concentrations at which growth rate or yield first begins to decline in comparison with plants with a higher nutrient level *(Ulrich [1952]);* and as the concentration which is just adequate for maximum growth *(Tyner [1946]);* and as the concentration at 95 per cent of maximum yield *(Bennett et al. [1953]). Dumenil [1961]* introduces an economic concept by defining critical levels of nutrients as those levels in the plant associated with yields above which fertilization is not profitable. Thus, critical levels should be associated with the fertilizer combination that gives the maximum profit per unit area and not the maximum yield.

At N, P and K levels below the critical level, the need for a nutrient and the magnitude of the response varies – being greatest at low nutrient contents and decreasing as the critical level is approached. At nutrient concentrations in excess of the critical level, extraneous factors appear to have a greater influence on yields than do variations in nutrient concentration *(Tyner [1946]).*

The different definitions of critical nutrient levels actually lead to practically the same critical concentrations, because the critical level, in practice, is not a point but a narrow range of nutrient concentrations, above which the plant is amply supplied with nutrients and below which deficiencies occur *(Ulrich [1952]).*

In general, the results of plant analysis indicate which element is deficient, but not what caused the deficiency or how the deficiency can be corrected *[ibid.].*

– Dependence of critical levels on other factors

Macy [1936] was of the opinion that critical percentages are largely independent of the levels of other growth factors, including other nutrients. *Ulrich [1943]* found that although critical levels are influenced by other growth factors, including nutrients, these effects are not large enough to alter the interpretation of critical levels under field conditions. A number of authors have concluded that critical levels vary considerably with levels of other factors.

The response of plants to one nutrient is often markedly dependent upon the level of other nutrients *(Watanabe et al. [1965]). Lundegardh [1951]* uses an 'interference factor' in his yield response equations based on plant composition in order to compensate for the level of a second nutrient

Nitrogen, in particular, appears to control growth more than any other nutrient and thereby to determine the yield potentials that can be expected through the use of phosphorus and potassium fertilizers, *(Tyner [1946]). Hanway [1962]* found that a severe N-deficiency resulted in a low P and high K concentration in the leaves, sheaths and stalks, so that the interpretation of analyses for P and K, under conditions of N-deficiency, is difficult. *Clark [1968]* found that, in general, mineral-deficient leaves contain higher amounts of ions per gram of dry matter, except the ion of limited availability. It is therefore suggested that critical concentrations of P and K should be evaluated in terms of yield levels associated with the critical N concentration.

Because a deficiency of a single nutrient may affect the uptake of non deficient nutrients, the ratio between elements is frequently used instead of the critical level of a single nutrient.

The yields associated with the critical nutrient level in the leaves may also vary according to the supplying power of the soil. On soils of high supplying power of a certain nutrient, the yield at the critical level for that particular nutrient may be somewhat higher, whereas on soils of low supplying power it may be lower *(Tyner and Webb [1946])*.

Critical N percentages for maize were found to vary from year to year, and were apparently influenced by temperature. The lower critical levels were obtained in the years with higher yields, which may be an indication that temperature has a direct effect on the ability of the maize plant to utilise N efficiently for growth *(Reichman et al. [1959])*. The minimum level of N in the leaves, associated with maximum yields was found to be lower for dryland maize than for irrigated maize *(Ellis et al. [1956])*. Therefore, the critical level appears to include a wide range of values, depending on how it is defined and on the levels of all the other factors which have interactions with the specified nutrient.

11.2.3 Time of testing

The most desirable procedure would be, of course, to use very young maize plants for tissue testing, so that any nutrient deficiencies revealed could be corrected at an early stage. Unfortunately, this approach has a number of limitations which generally make it impractical. The rate of nutrient uptake and dry matter accumulation is very slow in the young plants so that nutrient requirements at this stage are still very low and do not reflect future requirements.

Very young plants may therefore have very high nutrient contents, and yet nutrient supply may not be sufficient to maintain adequate levels at later stages of growth, in particular at the critical stage **(Figure 112)** *(Wickstrom et al. [1964])*.

Temperature and soil moisture conditions during the early stages are usually very different from those to which the plant is subjected at later stages, again influencing nutrient uptake.

The composition of the maize plants is not static, but varies throughout the growing season. In the leaves, nitrogen content declines throughout the season; phosphorus content reaches a maximum about the middle of the season and then declines as the plant matures. Potassium shows a gradual decrease from a very high value at the beginning of summer to a low value at the end of the season. Calcium content decreases throughout the season and the magnesium content of the leaves first rises until the latter part of the season, when it decreases slightly.

In the stem, the concentration of all the elements increases until about the middle of the season and then decreases after the plant has reached maximum size, as the minerals -excepting potassium- are translocated to other parts of the plant, mostly to the grain. Only a small proportion of the potassium moves to the grain and another small amount may move back into the soil through the root system *(Sayre [1955])*. The most widely adopted stage for leaf analysis of maize is at 'silking'. When yields are related to critical concentrations of nutrients in an active leaf, at the silking stage, leaf analysis is actually a measure of the internal plant nutrient reserves during a period of heavy demands, which occurs about 40 to 50 days before maturity.

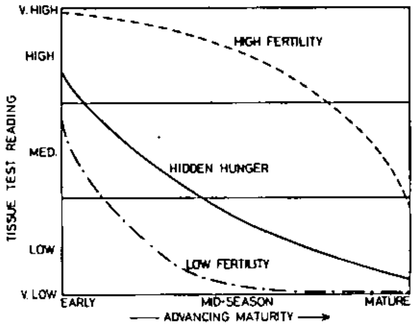

Fig. 112 Very young plants may have high nutrient contents, and yet these may not reflect adequate supplies from the soil for later stages of growth *(Wickström et al. [1964])*. By courtesy of the American Potash Institute.

Although leaf analysis at silking is too late to allow for corrective fertilizer treatments to the current crop, the analyses are useful for future cropping on the same field, and for research purposes.

The advantage of sampling at 'silking' are:

a) It is easy to recognise this stage of growth and the standard position of the leaf to be analysed is easily defined; the leaf opposite and just below the uppermost ear is the one usually used.

b) At this stage, nutrient uptake is rapid, so that any existing deficiencies in nutrient supply from the soil are brought into evidence.

c) Reliable relationships between leaf composition at this stage and yield response to fertilizers have been established *(Hanway [1962])*.

11.2.4 Predicting fertilizer requirements of maize from leaf analysis

– Nitrogen

Maize does not react to higher rates of nitrogen application by increased tillering, as is the case with most other cultivated cereals; the main effect of the additional increments of nitrogen is therefore to increase the number and weight of the kernels. As these take up relatively limited amounts of nitrogen, the overall result is an increase in the nitrogen content of all parts of the plant. This explains why leaf content of nitrogen is, in maize, such a sensitive indicator of the amount of nitrogen available to the plant on one part, and up to the critical level, corresponds so well with grain yields on the other *(Dulac [1955])*.

N-content of the maize leaf at silking usually ranges between 1.0 and 3.5 per cent on an oven-dry basis. When the N-content of the leaf of unfertilized maize exceeds 3.1 per cent*, little or no yield increase from N-fertilization is to be expected. When N-levels are below 3.1 per cent, the yield increase is usually inversely proportional to the N content of the leaf and proportional (within limits) to the amount of nitrogen applied.

Where other factors are fairly constant, yield increases from different levels of application of N-fertilizers are usually directly proportional to the increases in per cent – N in the leaf resulting from the fertilizer application **(Figure 113)** *(Hanway [1962])*.

Bennett et al. [1953] also found a nearly linear relationship between yield of grain and the nitrogen percentage of the leaf, as shown in **Figure 114**. However, when the nitrogen level in the leaf approximates 3 per cent, there is a tendency for changes in leaf nitrogen to be associated with smaller increases in yield than is the case at lower levels.

Whilst it may be questionable whether a definite critical level of nitrogen exists in the leaf, it does appear that the critical nitrogen percentage may occur within a relatively narrow range. Thus, in the series of experiments carried out by *Bennett et al. [1953]*, the range of nitrogen percentages encompassing the so-called critical values was found to be approximately 2.8–3.0 per cent. Above this range, little or no yield increase was to be expected from nitrogen fertilization. In investigations carried out on maize grown under irrigation, on a calcareous soil in Indiana, the application of nitrogen had a significant, positive, first-order effect on grain yield. The level of nitrate-N in the midrib of the leaf at the silking stage required to achieve high yield levels (up to 14.65 tons/ha of grain), was estimated to be about 1,000 ppm *(Fuehring [1966])*. Nitrate-N concentrations in the midribs gave a higher, although non-significant, correlation with grain yield than did total N concentrations in the leaf blades *[ibid.]*.

The increased nitrogen content of the leaves due to nitrogen fertilization is frequently closely paralleled by an increase of the nitrogen content of the grain *(Krantz and Chandler [1951])*.

– *Phosphorus*

P-content of the maize leaf at silking usually ranges from 0.1 to 0.5 per cent on an oven-dry basis. Little or no yield increases from P-fertilizer application can be expected when P-content of the leaf exceeds 0.33 per cent.

Between the levels of 0.10 and 0.33 per cent, the relationships between P-content of the leaf and yield increases from P-fertilization are fairly reliable *[Hanway [1962])*.

In experiments in N. Carolina, applications of 88 kg/ha P_2O_5 on a P-deficient soil had very little effect on the P-content of the leaves, whilst a significant increase was observed as a result of an application of 196 kg/ha P_2O_5. Although the P-content of the leaves was not markedly affected by P-applications it did reflect the level of soil phosphorus. On a low phosphorus soil (40 kg/ha P_2O_5) leaf P-content was only 60 per cent of that from a high phosphorus soil (510 kg/ha P_2O_5). This difference was also reflected in the

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* Under conditions of inadequate moisture supply the upper limit for response is about 2.5 per cent instead of 3.1 per cent.

P-content of the grain from the low – and high-phosphorus soils, which was 0.51 per cent and 0.71 per cent, respectively *(Krantz and Chandler [1951])*.
Tyner [1946] found a very high correlation between the percentage P in the sixth leaf of maize during the bloom stage and grain yields (see p. 265).

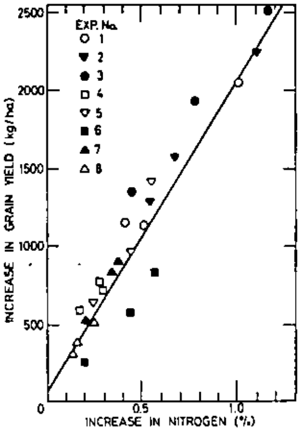

Fig. 113 Relation between increase in yield and in per cent N in the leaves of maize, resulting from nitrogen application *(Hanway [1962a])*. By courtesy of the American Potash Institute.

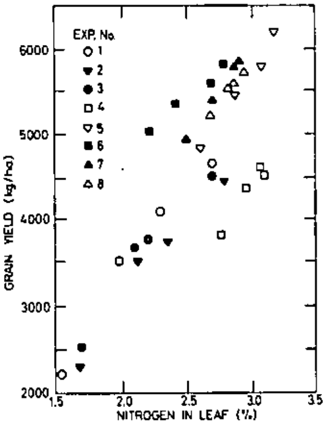

Fig. 114 Relationship between yield of grain and per cent nitrogen in the leaf *(Bennett et al. [1953])*. By courtesy of the Soil Science Society of America.

– *Potassium*

The per cent of potassium in the leaves at silking, which usually ranges from 0.5 to 2.0 per cent and above,* has been shown to provide a good estimate of the K status of the plants and the probable response that can be expected from applications of K fertilizer **(Figure 115)** *(Hanway et al. [1962])*.

Statistically significant yield increases were obtained only where the K content in leaves from maize grown on plots that received no K fertilizer was 1.7 per cent or less. It was found that no increase in yields is to be expected if the K leaf – content exceeds 2.0 per cent even slightly, whilst between 1.5 and 2.0 per cent, yield increases are usually small *[ibid.]*.

Increases in yield of grain from K-fertilized fields were found to be more highly correlated with the per cent K in maize leaves at silking time than with the exchangeable K content of the soil *[ibid.]*.

In trials carried out by *Hanway et al. [1962]* the following results were obtained: The K-content of the leaves at silking time, from maize grown on plots that had received no K fertilizer, varied from 0.60 to 3.14 per cent and averaged 1.73 per cent. K fertilization generally increased the K-content of the leaves, except for plants grown on soils with a high level of exchangeable K. The largest increase was recorded on a K—deficient, organic soil, in which every 110 kg/ha of K applied resulted in an increase of 1.25 per cent K in the leaves. The average increase in K-content resulting from K fertilization was 0.42 per cent per 110 kg/ha of K applied. The maximum recovery of applied K recorded in these trials was 56 per cent and the average for all locations was 23 per cent.

In trials carried out by *Barber [1959]*, a fairly good relationship was found between per cent potassium in the sixth maize leaf and the yields of maize, as shown in **Figure**

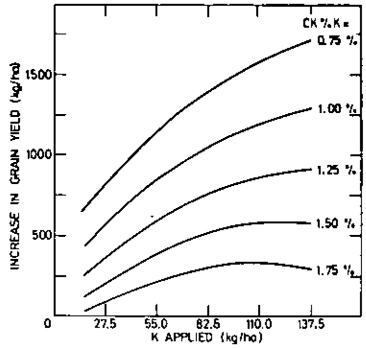

Fig. 115 Predicted yield increases of maize from potassium fertilization in relation to the K content of the leaves at silking time, of maize grown on plots that received no K fertilizer *(Hanway et al. [1962])*. By courtesy of Iowa State University.

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* On an oven-dry basis.

116. When the potassium content of the leaf was below 1 per cent, a large yield response was obtained from K-fertilizer application.

In experiments in N. Carolina, by *Krantz and Chandler [1951]* K-content of the leaves was increased by potassium applications of up to 350 kg/ha K_2O. At the high levels of K applications there was no effect on yield or lodging, so that the high K-content of the leaves was evidence of luxury consumption. The K-content of the leaves was also closely correlated with the K-content of the soil, especially on those plots which received no K fertilization. The range was from a high of 2.57 per cent K_2O to a low of 0.52 per cent K_2O in the leaves on soils with 0.23 and 0.10 meq K, respectively. The K-content of the leaves was also increased by nitrogen applications, the greatest difference being due to the first increment of nitrogen. K-content of the leaves decreased consistently throughout the growing season. Considerable differences in the K-content of the leaves *were not* reflected by differences in the K-content of the grain *[ibid.]*.

Loué [1963], working in France, found that a potassium content of less than 0.7 per cent indicated an acute deficiency. Yields under these conditions averaged less than 2500 kg/ha.

Plants from land fertilized at the rate of 80 kg K_2O/ha had a K content ranging from 1.3 to 2.0 per cent, with an average value of 1.65 per cent. At higher rates of fertilization – 120 to 160 kg K_2O/ha – K content of the leaves ranged from 1.80 to 2.75 per cent, with an average value of 2.05 per cent.

In these experiments the relationship between grain yield and potassium level in the leaf was generally found to be curvilinear **(Figure 117)**.

Values of 0.4 to 1.0 per cent K_2O in the leaves represent a zone of acute deficiency. Within this range, a clear correlation between K content and yield is found, an increase

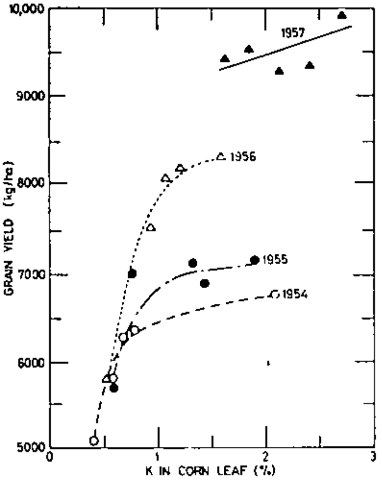

Fig. 116 Relation between per cent potassium in the sixth corn leaf and maize yield, 1954–57 *(Barber [1959])*. When the potassium content was below 1 per cent, a large yield response was obtained from the application of potassium fertilizer. By courtesy of the American Society of Agronomy.

of 0.1 per cent in K-content being reflected in a yield increase of approximately 500 kg/ha. In the range of 1–1.6 per cent K_2O, yields were still related to K-levels, but each increase of 0.10 per cent K_2O resulted in a yield increase of only 250 kg/ha. Above 1.7 per cent, which, according to *Loué*, could therefore be considered as the critical level, no clear relationship between K-levels and grain yield was apparent. *Loué* proposes 1.7 to 2.0 per cent as the critical zone for K_2O level in the leaves.

– *Nitrogen, phosphorus and potassium interrelationships*

A close correlation was observed between the increase of nitrogen and the phosphorus content of the leaves, with correlations of 0.945, 0.980 and 0.965 for three respective sampling dates **(Figure 118)**. There was a small but rather consistent decrease in leaf phosphorus content with K application *(Krantz and Chandler [1951])*.

Reichman et al. [1959] found that the per cent N and P in leaves of maize grown under irrigation on a loam soil in North Dakota, when sampled at pollination, was highly correlated with the yields and the total nutrient uptake at harvest. The N and P contents of the leaves were found to be positively correlated. Leaf N was the dominant indicator of yield, but leaf P was also important.

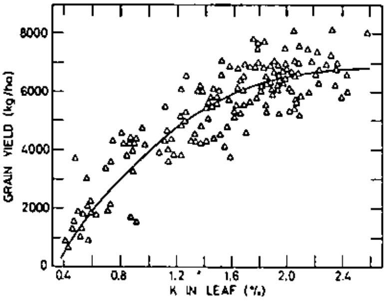

Fig. 117 Relation between grain yield (15 per cent humidity) and the K content of the flag leaf at the time of silking *(Loué [1965])*.

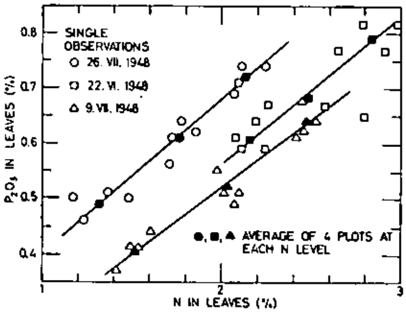

Fig. 118 The relationship between nitrogen and phosphorus content of maize leaves at three sampling dates on a fine sandy loam *(Krantz and Chandler [1951])*. By courtesy of the American Society of Agronomy.

Tyner [1946] studied the relation of maize yields to varying percentages of N, P and K in the sixth leaf at bloom stage in a number of location in West Virginia. Correlation and regression coefficients were calculated for the relation between yields and the concentration of a limiting unit (N, P or K) in the presence of adequate amounts of other nutrients. Highly significant correlation and regression coefficients were found to exist for the relation of yields to percentage N, P and K (see **Figures 119, 120** and **121**). The critical leaf nutrient concentrations of the sixth leaf at the bloom stage were tentatively set at 2.90 per cent N, 0.295 per cent P, and 1.30 per cent K.
For each change of 0.1% in leaf content of N, P and K, maize yields varied 281 ± 69.8 kg/ha for N, 1606 ± 42.5 kg/ha for P and 130 ± 59.0 kg/ha for K.

– *Zinc*
A close relationship between yields of grain and Zn-leaf content was established by *Pumphrey et al. [1963]*. Yields of grain within about 90 per cent of the maximum were obtained in western Nebraska when the Zn concentration in the index leaf was 15 ppm or more **(Figure 122)**.

– *Sulphur*
The relative constancy of the N/S ratio in plant tissues provides a useful means for assessing the sulphur status of the plant. When the total N to total S ratio is above 12–15, it may be assumed that lack of S is limiting protein formation. Still wider ratios indicate that S is severely deficient *(Stewart and Porter [1969])*.
The critical level of S in the maize leaves appears to be about 0.19 per cent. Sampling at an early stage is superior to late sampling for evaluating the S status of maize *(Fox et al. [1964])*.

11.2.5 Limitations and significance of leaf analysis as a diagnostic tool

Leaf analysis can give rapid and generally fairly accurate results, provided a number of inherent weaknesses of the method are taken into consideration.
When more than one nutrient is limiting, leaf analysis will pinpoint the *most limiting* nutrient, but will not be reliable in predicting the availability of the other nutrients. For example, N-deficient maize leaves always have low concentrations of P and K. Applying nitrogen under these conditions may increase the N-content of the leaves, and at the same time P and K contents may actually decrease although the amounts available from the soil have not changed *(Hanway [1962])*.
Critical plant composition values, such as those shown in Table 60, are not infallible but can serve as a guide in the interpretation of properly evaluated analytical results.

The main agricultural significance of leaf analysis is as a follow-up tool to the soil test, which makes it possible to determine how effectively the predicted soil supply and recommended fertilizer application are meeting the nutrient needs of the plant, and to uncover suspected deficiencies.
The main disadvantage of tissue tests is that the results are obtained at a time when it is too late to correct a deficiency of phosphorus or potassium for the current crop, although a top-dressing with nitrogen might still be advantageous.

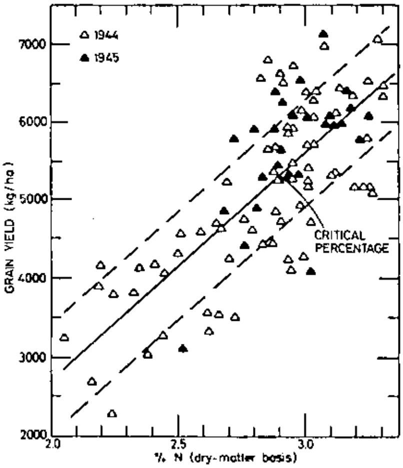

Fig. 119 Relation of maize yields (15.5 per cent moisture-basis) to the percentage N in the sixth leaf during the bloom stage *(Tyner [1946])*. The correlation coefficient for this relation is 0.7681. By courtesy of the Soil Science Society of America.

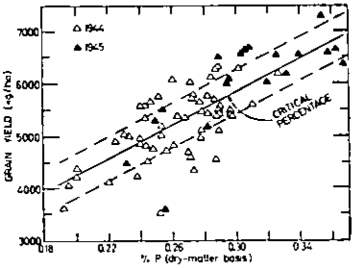

Fig. 120 Relation of maize yields (15.5 per cent moisture-basis) to the percentage P in the sixth leaf during the bloom stage *(Tyner [1946])*. The correlation coefficient for this relation is 0.8498. By courtesy of the Soil Science Society of America.

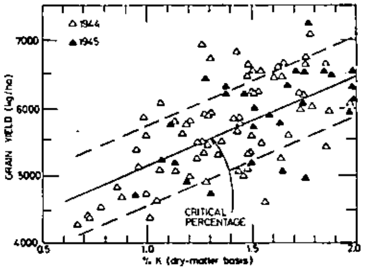

Fig. 121 Relation of maize yields (15.5 per cent moisture-basis) to the percentage K in the sixth leaf during the bloom stage *(Tyner [1946])*. The correlation coefficient for this relation is 0.5974. By courtesy of the Soil Science Society of America.

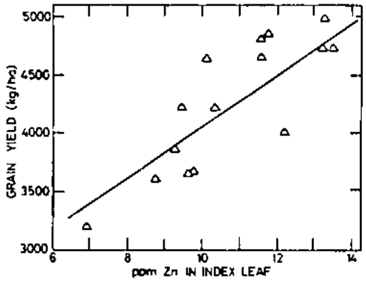

Fig. 122 Relationship between maize yields and Zn concentration in index leaves for concentration below 15 ppm *(Pumphrey et al. [1963])*. By courtesy of the American Society of Agronomy.

Table 60. Critical composition values for maize*

Nutrient	Critical level *(Melsted et al. [1969])*	Adequate levels *(Barber and Olson [1968])*
	in per cent	
Nitrogen	3.00	2.75–3.25
Phosphorus	0.25	0.25–0.35
Potassium	1.90	1.75–2.25
Calcium	0.40	0.25–0.40
Magnesium	0.25	0.25–0.40
Sulphur	—	0.10–0.20
	in ppm	
Manganese	15	20–150
Iron	25	20–250
Boron	10	4– 20
Copper	5	6– 20
Zinc	15	20– 70
Molybdenum	0.2	—

* in the ear leaf, at silking.

11.2.6 Effect of mineral deficiencies on enzymatic activity

In view of the shortcomings of tissue tests mentioned above, it has been thought that methods based on changes in the biochemical processes in the young plants as a result of nutrient deficiencies might provide a practical solution.

In a study by *Horovitz et al. [1968]* the following changes in the enzymatic systems of different organs of maize seedlings, due to deficiencies in the major nutrients, were recorded:

(a) Nitrogen deficiencies caused an increase in peroxidase and catalase activity and inhibition of pyruvic and glutamic decarboxylase.

(b) Phosphorus deficiencies caused an activation of peroxidase and catalase in leaves and an inhibition of acid phosphatase, invertase, pyruvic and glutamic decarboxylase in the roots.

(c) Potassium deficiencies, as compared to nitrogen and phosphorus deficiencies lead to the severest disturbances of the different enzymatic systems. They caused a strong increase in leaf invertase, catalase and peroxidase activity, a stimulus in respiration intensity in the roots, and an inhibition in pyruvic and glutamic decarboxylase in leaves and roots.

11.2.7 Agreement between soil and tissue tests

The level of nutrients in the plant is not always in accord with the predictions based on soil tests. In particular, adverse conditions affecting plant growth will generally be reflected in a reduced nutrient uptake, and hence in lower levels in the tissues. Mechanical injury to the roots, low soil temperatures, excessive dryness or water logging of the soil and lack of aeration in the soil, are examples of factors which reduce nutrient uptake below the potential supply of the soil, and will therefore cause lack of agreement between soil and plant tests *(Garrard [1966])*.

However, when growing conditions are normal, good agreement between soil and plant tests is generally recorded.

In tests carried out by *Ellis et al. [1956]*, a close relationship was found between the content of available K in the soil and the K levels in the leaves of maize. Plants growing on soils with less than 220 kg/ha exchangeable K had leaves with less than 1.3 per cent K, and showed severe K deficiency symptoms; they responded to K fertilization with increased yields.

Applications of N fertilizers to the soil were almost always reflected in the leaf analysis. P fertilization was mainly reflected in the early stages and any influence on leaf content had largely disappeared at the time of tasseling.

Applying K fertilizers to soils low in exchangeable K generally increased the K content of the leaves, and decreased their Mg content.

Experiments correlating maize yields with soil and tissue tests have been carried out in the Everglades (Florida, USA) on peat soils, which have up to 90 per cent organic matter content and may contain up to 3 per cent N, expressed on a dry weight basis *(Forsee et al. [1954])*.

Maize showed yield responses to increasing levels of potassium in the soil up to values as high as approximately 80 kg K/ha as determined by the soil tests. The yields ranged from 1650 kg/ha at the lowest K levels to 4000 kg/ha at the level of maximum response. K-deficient plants gave stem tissue tests as low as 2.72 per cent potassium, whilst at the level of maximum response the content was 5 per cent, on a moisture-free basis **(Figure 123)**.

Maize responded to applications of superphosphate up to levels of approximately 9 kg/ha soluble phosphorus as determined by soil tests. Plants that were not P-deficient showed above 0.10 per cent phosphorus (moisture-free basis) in stem tissue tests **(Figure 124)**.

The uptake of phosphorus was apparently reduced by higher levels of potassium in the soil, and that of potassium was slightly reduced by higher levels of phosphorus.

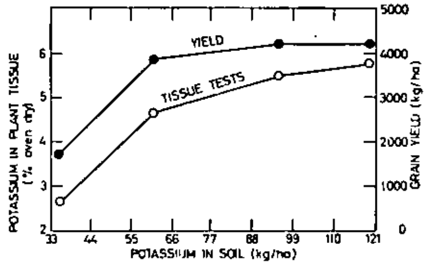

Fig. 123 Yields of maize in relation to tissue tests and soil tests for potassium on peat soils in Florida *(Forsee et al. [1954])*. By courtesy of the Soil Science Society of America.

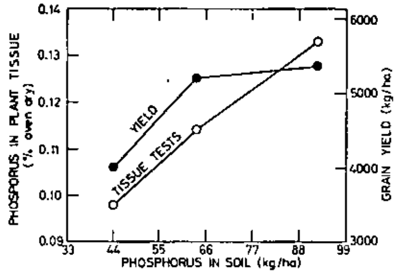

Fig. 124 Yields of maize in relation to tissue tests and soil tests for phosphorus on peat soils in Florida *(Forsee et al. [1954])*. By courtesy of the Soil Science Society of America.

11.2.8 Quick field tests

Tissue tests that can be carried out in the field have been developed as a diagnostic tool, using some conductive tissue of the maize plant for determining the amount of certain soluble portions of the nutrients in certain tissues instead of the total amount in the leaf, as discussed above. If these rapid tests are properly conducted and interpreted, and carried out a number of times during the growing period, they can provide useful information of a qualitative nature, by confirming or strengthening the deductions from visual observation of nutrient deficiencies. They cannot, for the time being, supply precise quantitative information.

– *Nitrogen*

Testing for nitrate-N is done on the midrib of a standard leaf, where easily detectable amounts of nitrate are usually to be found.

This test will indicate whether there is N-deficiency, without giving the degree of deficiency. An additional test of nitrate-N in the lower nodes of the stalk will give more information on the severity of the N-deficiency.

– *Phosphorus*

Visual symptoms for P-deficiency are not generally reliable. A nearly constant proportion of the total P in the tissues is water soluble, so that a test showing the amounts of soluble-P can provide information similar to that based on total P-content.

– *Potassium*
Practically all the potassium in the plant tissues is water soluble, so that water-soluble and total potassium in the tissues are essentially the same. The levels of potassium in the conducting tissues are very sensitive to environmental changes.

11.3 Deficiency symptoms

Certain nutrient deficiencies cause characteristic symptoms to appear in the plant, which enables visual diagnosis of the deficiency. The principal symptoms are severe stunting, leaf or stem discolouration, and delayed or advanced maturity.

– *Nitrogen* (Plate 17)
Slow initial growth, a yellowish-green colour of the leaves, and the premature senescence of the lower leaves are the principal symptoms of nitrogen deficiency in maize. The discolouration usually commences at the tip of the leaf and progresses along the midrib.

Under conditions of nitrogen deficiency, the proteins in the older leaves of the plant are hydrolysed, and the soluble nitrogenous compounds migrate to the actively growing centres. The yellowing of these leaves is due to the breakdown of the chloroplastic protein, causing the loss of the chloroplasts and the disappearence of the chlorophyll. The older leaves are therefore the first to show the symptoms, which spread progressively to the younger leaves of the plant, and the degree to which these are affected is a measure of N-deficiency. When the N-deficiency becomes extreme the leaf dies, turns brown and disintegrates.

An apparent deficiency of nitrogen may really be due to an irregular moisture supply. Most of the available nitrogen is in the upper soil layer, which is the first to dry out if intervals between irrigations or rains are excessive, so that the plant is unable to take up sufficient nitrogen for its requirements. In this case the hunger signs do not indicate a deficiency of nitrogen in the soil, but the inability of the plant to absorb nitrogen from the dry soil-layer.

- *Phosphorus* (Plate 18)
Phosphorus deficiencies are not always easy to diagnose. Slow growth of the seedlings, and a dark-green colour with a purplish tinge of stems and leaves, are fairly typical. The purple colouration is due to a decrease in protein synthesis as a result of P deficiency, with an attendant increase in sugar concentration in the plant tissues. Higher sugar concentrations promote the production of anthocyanin, the source of the purple colouration. However, the symptoms may be caused by factors other than P deficiency. For certain varieties, the purplish tinge of leaves and stems of the young plants, which is due to the formation of anthocyanin pigments, is a normal characteristic. Also, any factor that disturbs the metabolism of maize besides P-deficiency, such as low soil temperature or even insect damage to the roots, alters the metabolic pathways in such a way that large quantities of anthocyanin are produced **(Figure 125)** *(Knoll et al. [1964])*.

During pollination, the silks emerge slowly and defective ears are produced on P-deficient plants.

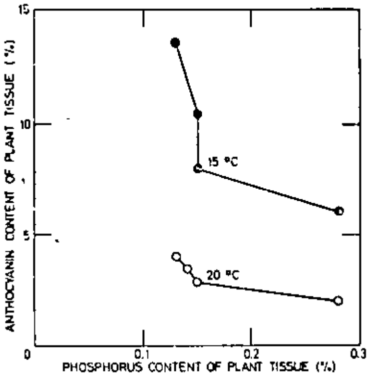

Fig. 125 Anthocyanin percentage versus phosphorus percentage in maize plants grown in sand cultures with different phosphorus concentrations at two soil temperatures *(Knoll et al. [1964])*. Air temperatures were the same for all treatments. By courtesy of the American Society of Agronomy.

– *Potassium* (Plate 19)

The characteristic symptoms of potassium deficiency in *young* maize plants are that they develop slowly; the leaves are light green or streaked with yellow; and the tips and margins of the leaves become necrotic. *Older plants* have similar symptoms, but the marginal browning of the leaves is more conspicuous. When the deficiency is prolonged, the plants become dwarfed and weak. Though stunted, the plants will tend to lodge because of the poorly developed root system and susceptibility to stalk rot. If ears are produced they are small, pointed and barren at the tips, and the grain is of poor quality *(Washko [1945])*.

– *Calcium*

In cases of calcium deficiency the growing tip of the plant becomes black and gelatinised, the leaves twist and stick together. The base of the stem becomes enlarged and there is a tendency to produce side-shoots *(Olson and Lucas [1966])*.

– *Magnesium* (Plate 20)

Symptoms of magnesium deficiency are a bronzing and reddening of the lower leaves with yellow or orange interveinal striping. The striping may be followed by white necrotic spots that give an appearance of a 'beaded' striping.

There is little published information concerning the relationship between magnesium deficiency symptoms and the yields of maize.

Foy and Barber [1958] report that in acid, sandy loam soils in northern Indiana, the occurrence of magnesium deficiency symptoms was not accompanied by a reduction in maize yields. Concurrently, additions of magnesium to the soil prevented the appearance of the symptoms and increased the levels of magnesium in the leaves but still had no effect on yields.

– *Sulphur* (Plate 21)

Sulphur-deficient plants are stunted and the leaves are pale-green to yellowish. The veins are lighter in colour than the rest of the leaf, giving a striped appearance to the plants. These symptoms appear mainly in the young leaves in the upper part of the plant. A reddish colour, due to anthocyanin accumulation, may be observed in the lower leaves and stalks. Maturity of the plant is retarded *(Olson and Lucas [1966])*.

– *Copper*
The first symptoms of copper deficiency are a yellowing of the young leaves as they emerge from the whorl. Later, the tips curl and show necrosis. The leaves are yellow and show striping similar to iron deficiency: their edges are necrotic. The stalk is soft and limp *(Olson and Lucas [1966[)*.

– *Iron*
Iron deficiency in maize is characterized by the chlorosis of the leaf tissue between the veins of the younger leaves, giving a typical striping of the leaves in the upper part of the plant. The plants may become severely stunted in growth *(Olson and Lucas [1966])*.

– *Manganese*
Moderate deficiency of manganese in maize is evidenced by a uniform streaking of all leaves, which are also lighter-coloured than normal leaves. With more severe deficiency, long white streaks appear and the tissue in the middle of the chlorotic area dies, and may fall out of the leaf. The stalks of affected plants are thinner than normal *(Olson and Lucas [1966])*.

– *Zinc*
Zinc deficiency symptoms may vary according to the degree of deficiency and the hybrid involved. *Pumphrey et al. [1963]* describe the following symptoms: During the early vegetative development of the maize plant, a pale yellowish-green stripe appears on each side of the midrib on the older leaves of moderately deficient plants. These stripes extend from the base of the leaf blade to the middle or tip of the leaf, and the midrib and leaf margins usually remain green. If the deficiency persists these stripes may become necrotic or may change to a reddish-bronze colour. The younger leaves of the plant usually remain normal. In cases of more extreme deficiency the whole plant becomes light green and growth diminishes. Plants exhibiting these extreme deficiencies may die before tasseling, may have barren ears, or ears which are abnormally shaped and improperly filled.
The new leaves may be nearly white in colour, hence the name of 'whitebud' given to the zinc-deficiency incurred disease. As plants grow older, and an increasingly larger soil volume is exploited by the roots, the plant tends to overcome zinc deficiency *(Olson and Lucas [1966])*.

11.3.1 Deficiency symptoms as a diagnostic tool

Using deficiency symptoms as a diagnostic tool is simple and frequently effective; however, it has a number of drawbacks:
The deficiency symptoms are an indication that the plant is already under severe stress, and yields may already be affected even if nutrients are applied subsequently.
Nutrient deficiencies may be insufficiently severe to cause visual symptoms whilst still

affecting yields adversely. This level of deficiency is called 'hidden hunger' *(Garrard [1958])* **(Figure 126)**.

Deficiencies are frequently relative, in that a deficiency of one element may be due to adequate or excessive quantities of another. For example, manganese deficiency may be due to an excess of iron, if the manganese supply is near to the critical level. A given level of phosphorus in the plant tissues may be quite adequate when the supply of nitrogen is low, but become totally inadequate with increasing applications of nitrogen *(Tisdale and Nelson [1966])*. This will be reflected in the appearance of deficiency symptoms.

The symptoms themselves may be misleading: different nutrient deficiencies may show similar symptoms; similar symptoms may be caused by waterlogging, low temperatures, disease or insect damage, etc. Much experience is needed for the correct assessment of nutrient needs based on visual symptoms.

11.4 Field experiments

Field experiments, which are carried out according to certain rules which ensure that a valid statistical analysis of the results can be made, are still the most satisfactory method for ascertaining crop response to fertilizers in a given environment, and are also essential for calibrating the soil and plant tests mentioned above.

The main drawback of field experiments is that since the nutrient level in the soil is not constant, the results obtained reflect a one-time situation, not likely to be repeated in time or space. In order to enable generalised conclusions to be drawn from field experiments, they have to be carried out on sites that are representative of a large area. They have to be repeated on the same locations over a period of years, whilst climatic data, build-up or depletion of nutrients, and changes in the physical characteristic of the soil are determined and recorded.

The cultural practices and the varieties chosen should be in accord with accepted use in the region. Changes in agricultural practices and new varieties may make previously determined correlations obsolete *(Thomas and Hanway [1968])*.

11.4.1 Correlating soil tests with the results of field experiments

Field fertilizer experiments that are not designed for correlation with soil tests can only give information on what was the response of the crop to a particular set of circumstances, which is generally unique. They cannot explain why the response occurred or when it will occur again.

Fertilizer experiments can be designed to measure the efficiency of the native soil forms of P and K as well as the fertilizer forms ('c' values). A simple replicated experiment of varying rates of application of a given nutrient, when an adequate supply of the other nutrients is provided, will give the data required for soil test correlations, provided the soil test is a reliable measure of the available soil form. The most reliable results are obtained on fields which have not been fertilized in the past and which are

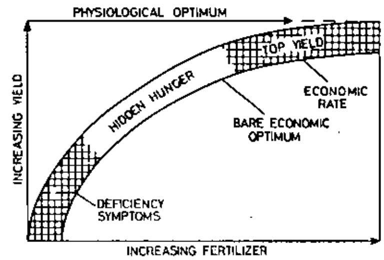

Fig. 126 Physiological optimum and economic optimum rates of fertilizer application *(Garrard [1958])*. By courtesy of the American Potash Institute.

highly deficient in one or more nutrients. The values A, Y, b or x[*] are calculable if three out of the four values are known. The percentage yield values can also be calculated and are used more extensively than actual yield values.

If the experiment is repeated for a second year on the same site, it is possible to measure the residual value of the added fertilizer *(Bray [1961])*.

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[*] A is the yield possibility: the 100 per cent yield.
Y is the percentage value obtained when b amounts of the nutrients are present and x amounts of fertilizers are added.

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Plate 17
Nitrogen deficiency symptoms in maize leaves. Note yellowish colour extending from the tip and progressing down the mid-rib.

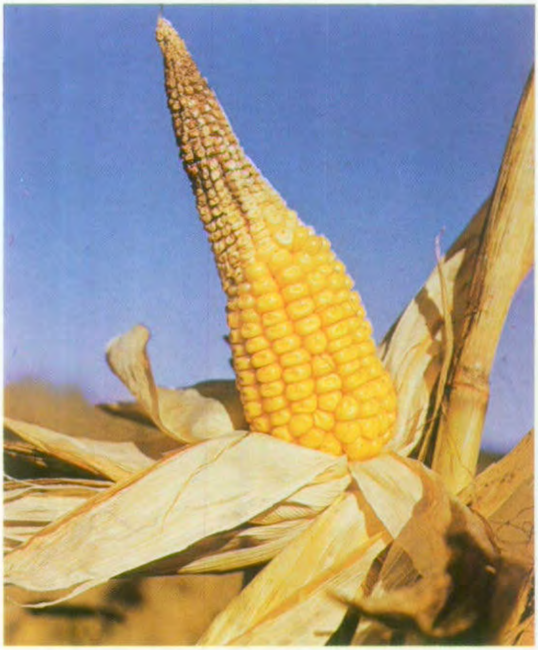
Plate 18
Phosphorus deficiency symptoms in maize leaves. Note the purple coloration due to anthocyanin pigments.

Plate 17 △

▽ Plate 18

Plate 19
Potassium deficiency symptoms in maize.

(a) leaves showing typical necrotic margins of leaves and discolouration of ear sheaths;



(b) typical ear of K-deficient plant: small, pointed and barren at the tip.

Plate 20
Magnesium deficiency symptoms in maize leaves. Note ,beaded' interveinal yellow striping.

Plate 21
Sulphur deficiency symptoms in maize plants. Note typical yellowish colour of the leaves, and purplish colour of lower leaves and stalks.

12. The choice of fertilizer carriers

The various commercial fertilizers available to farmers have been fully described in the literature, and the reader is referred to such recent textbooks as *Cooke [1967], Kilmer and Webb [1968], Tisdale and Nelson [1966]*. Only the specific effects of certain fertilizer carriers on maize will be discussed here.

12.1 Relative value of various fertilizer carriers of nitrogen

Most studies comparing different nitrogen carriers have, as a rule, shown no consistent differences in their effects on the yields or composition of maize.

Whatever nitrogen carrier is applied to the soil, within a relatively short time the nitrogen will be present in only two forms: $(NH_4)^+$, which is rapidly attracted to and absorbed by the negatively charged colloids of the soil; and NO_3^-, which is not held by the soil colloids. The ammonium ion may also 'be fixed' by being held in the lattice structure of certain soil minerals.

The choice of the commercial fertilizer will therefore depend first on the effective cost, *in the field*, per unit of nitrogen; on the physical characteristics of the fertilizer affecting ease of application (hygroscopicity, granulation, liquid or gaseous forms); and specific effects on soil properties. A priori, for the arid region soils, preference will generally be given to acid-forming fertilizers, whilst those adding sodium are best avoided. In humid regions, the tendency is to avoid fertilizers that lower soil pH. In the warm and moist soils of irrigation farming, there is practically no difference in the relative rapidity with which the nitrate and the ammoniacal forms of N become available to plants. On the other hand, the ammoniacal form is less subjet to leaching, although the importance of this aspect should not be exaggerated, in view of the rapid nitrification that is characteristic of irrigated conditions. High temperatures as well as drying of the soil favour losses of NH_3 from ammonium fertilizers and urea applied to alkaline and calcareous soils with a low cation-exchange capacity.

With overhead irrigation, which makes it possible to confine added water to the root zone only, losses of nitrogen by leaching are practically eliminated, whatever the forms of nitrogen used *(Nielson and Banko [1960])*.

When the long-term effects of various types of fertilizers on the physical and chemical properties of an irrigated soil are investigated, far-reaching differences may be observed. *Aldrich and Martin [1954]*, when comparing different nitrogen carriers, found marked physical and chemical changes in the soil after 16 years of differential treatment. In particular, the rate of water percolation was greatly affected. The use of sodium nitrate and ammonium sulphate brought about structural breakdown resulting in reduced macrospore space. In the sodium nitrate plots, the poor physical conditions appeared to be due to an unfavourable calcium-sodium ratio. In the ammonium sulphate plots the cause was apparently the dispersing action of the ammonium ion. The low pH, caused by the continuous use of ammonium sulphate due to the accumulation of hydrogen in the exchangeable complex, inhibits the ability of soil organisms to nitrify the ammonium. No such unfavorable effects were found to result from the use of urea or calcium nitrate.

Where continuous use of large rates of certain types of fertilizer is apt to cause difficulties, the answer is not to reduce or abandon fertilizer application, but to change the type of fertilizer used or to apply appropriate soil amendments.

12.2 Relative value of various carriers of phosphorus

The effectiveness of phosphorus supplied in fertilizers is determined largely by their chemical and physical characteristics, the rate and method of application and certain soil properties.

12.2.1 Chemical characteristics

Of these, the solubility of the phosphorus compounds receives most attention. Phosphorus fertilizers can be grouped according to whether the phosphorus is (a) mostly soluble in water; (b) not readily soluble in water, but soluble in ammonium citrate; and (c) insoluble in ammonium citrate. For fertilizer control purposes, no distinction is generally made between water-soluble and citrate-soluble phosphorus which together are considered as the available phosphorus content of the fertilizer *(Kilmer and Webb [1968])*.

Webb and Pesek [1958, 1959] found that maize yields tended to be consistently higher with increasing phosphorus water solubility, when the fertilizers were applied in the hill or row, whilst water solubility had little effect on yields when the same fertilizers were broadcast. However, this was not the case for broadcast applications on calcareous soils, in which a highly soluble phosphorus fertilizer, such as concentrated superphosphate, appeared likely to be most effective for maize *(Webb et al. [1961])*. Field experiments indicated that phosphorus carriers differed in effectiveness when broadcast on calcareous soil, as measured both by the concentration of P in the leaves and in grain yields, and could be ranked into three groups:

(a) The most effective sources were concentrated superphosphate and dicalcium phosphate dihydrate, with the former slightly superior.

(b) Anhydrous dicalcium phosphate, calcium metaphosphate and a chemical blend of mono- and dicalcium phosphate were of intermediate effectiveness, producing yield increases of 70 to 80 per cent of that obtained by applying concentrated superphosphate.

(c) Granular calcium metaphosphate was the least effective source, producing yield increases of 60 per cent in comparison with concentrated superphosphate.

The investigators came to the conclusion that for broadcast applications on calcareous soils, a highly soluble P-carrier, such as concentrated superphosphate, is likely to be most effective for maize *(Webb et al. [1961])*.

In investigations in North Carolina, using the tracer technique, it was shown that maize plants that received phosphorus as superphosphate and as calcium metaphosphate were consistently higher in the percentage of phosphate derived from the fertilizer than those receiving alpha tricalcium phosphate. There was an appreciable difference in the utilization of phosphorus from superphosphate and calcium metaphosphate (**Figure 127**) *(Hall et al. [1949])*.

12.3 Relative value of various carriers of potassium

Generally, wherever potassium is applied to crops, nearly equivalent quantities of Cl or SO_4 are added, depending on the K-carrier used. With the large quantities of potassium applied under many conditions to maize, appreciable amounts of Cl and SO_4 are also added, and it is important to know whether these have some influence on maize, either directly or by affecting the absorption and accumulation of other ions by the crop.

According to the theory of cation-and-anion-equivalent constancy, as a plant absorbs greater quantities of a particular ion, a corresponding chemical equivalent decrease occurs in the absorption of other ions of the same charge.

Since chloride is a very mobile ion, and its absorption is closely related to the quantity present in the soil, it is possible that the plant may not obtain sufficient quantities of other necessary anions if these are present in limited supply and chloride is present in large supply *(Seatz et al. [1958])*.

Eaton [1942] found that yield depression curves for maize were about the same for chloride as for sulphate ions. However, *Seatz et al. [1958]* found that when chlorides were applied at rates of up to 990 kg of Cl (corresponding to 1320 kg of K_2O, supplied as potassium chloride), yields of maize were lower than when sulphate or carbonate

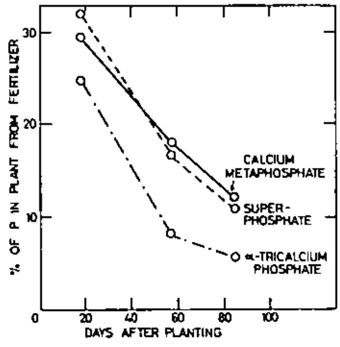


Fig. 127 Phosphorus content of the plant as influenced by the type of P-carrier applied to a sandy loam soil, containing 351 kg P_2O_5/ha *(Hall et al. [1949])*. By courtesy of the State University, New Brunswick, N.J.

was the major anion present. As no specific deleterious effect on the maize could be observed, the investigators ascribed the depressive effect of Cl to the much higher electrical conductivity values of saturation extracts from the soils in which chlorides dominated.

The highest rates of fertilizers used in these experiments are far above those used in normal practice. Under field conditions even these high fertilization rates would probably have less effect on plant growth because of salt movement in the soil away from the point of application. The investigators therefore concluded that there is no need for undue caution in using potassium chloride for normal field use.

In these experiments, a large increase of Cl content in the plants as a result of increasing chloride rates, did not cause a corresponding decrease in the content of P or S of the plants. Other anion constituents of the plants were not determined, and possibly the increased Cl content resulted in a decrease in these constituents */ibid./*. This is confirmed by the investigations of *Nielson et al. [1963]*, who found no effect on maize yields due to increasing amounts of Cl or SO_4.

Similar conclusions were drawn from investigations carried out in a number of states in the Corn Belt during the period from 1953 to 1960. It was found that the chloride form of potassium fertilizer is both safe and economical for use on maize. No consistent or practical differences between the chloride, sulphate and carbonate forms were observed.

However, maize yields may be depressed by chloride rates between 50 and 100 kg/ha, when the fertilizer is applied in the row. *Younts and Musgrave [1958]* found that broadcasting tended to alleviate these effects. When the KCl was applied at lower rates, the Cl ion was beneficial and increased yields.

Under certain circumstances, such as high leachability of and excessive K-uptake from coarse-textured soils, it might be assumed that certain slowly soluble K fertilizers would be more effective than the conventional K-carriers. Potassium phosphate materials, such as KPO_3 and $K_2CaP_2O_7$, can be manufactured with variable water-soluble properties.

DeMent et al. [1963] found that finely ground particles of fused potassium phosphates were equal to KCl and concentrated superphosphate as sources of potassium and phosphorus to maize grown in a greenhouse. With increasing particle size, the relative effectiveness of the fused potassium phosphates decreased.

In an investigation on maize in Minnesota, in which KPO_3 (99 per cent water solubility), $K_2CaP_2O_7$ (24.8 per cent water solubility) and KCl were compared on a K deficient soil at the same nutrient rates and particle sizes, all three carriers were approximately equivalent with respect to yield. The slowly soluble potassium fertilizers did not appear to have any advantage over the more soluble ones; nor did they restrict luxury consumption when applied at practical rates *(Caldwell and Kline [1963])*.

In general, it can be concluded that there is no evidence that slowly soluble potassium fertilizers have an appreciable agronomic advantage over completely soluble fertilizers for maize. In any case, leaching losses of potassium are generally not serious and do not, as a rule, exceed 6 to 20 kg/ha. On silt loam and fine-textured soils, they may be still less *(Kilmer and Webb [1968])*.

The fixation rates of slowly soluble K may be slightly reduced, but positive effects therefrom on yields have not yet been demonstrated */ibid./*.

12.4 Secondary nutrient carriers

12.4.1 Magnesium

Magnesium can be applied to plants either from liming materials with a high content of Mg, or from Mg fertilizers.

In trials on a fine sandy loam the response of young maize plants to the following Mg carriers was investigated: magnesium sulphate (9.9 per cent Mg), coarse dolomitic limestone (12.0 per cent Mg; 24 per cent through a 100-mesh sieve), fine dolomitic limestone (12.4 per cent Mg; 80 per cent through a 100-mesh sieve), hydrated lime (18.7 per cent Mg) and burnt lime (21.0 per cent Mg).

With the exception of the coarse dolomitic limestone, all the carriers were equally effective and gave significant increases in the dry matter yield of 30-day-old maize plants, when applied at rates of 7.5 to 15 ppm Mg. Higher Mg rates caused no further significant increases.

An increase in soil pH from 5.3 to 6.7 significantly decreased the uptake of Mg from soil treated with dolomitic limestone, but had no significant effect on Mg uptake from magnesium sulphate *(Usherwood and Miller [1967])*.

12.5 Micronutrient carriers

12.5.1 Iron

Iron is supplied mainly as a foliar spray with a soluble ferrous salt such as a 1 per cent ferrous sulphate solution. Iron chelates can be used as foliar sprays or for soil application.

Utilisation of chelated forms of iron by single-cross maize was studied by *Chesnin [1963]*, in a solutions culture medium. Iron was supplied in the form of EDTA, DPTA, HEDTA, and EDDHA. The maximum production of dry matter by the maize plants was obtained at the 2.5 ppm of iron concentration in the HEDTA form. All other forms were less effective. At higher concentrations there was a marked decrease in dry matter production per milligram of iron in the form of HEDTA in the solution. This was apparently due to the increased concentration of the iron in the tops of the plants, which had adverse physiological effects on dry matter production *[ibid.]*.

12.5.2 Zinc

In a comparison of zinc sulphate, zinc oxide and zinc sulphide as sources of Zn at rates of 1.2 and 4 ppm Zn, for two successive crops of maize, on a sandy clay loam in Alabama (pH = 7.3), the sulphate and the oxide were found to be markedly superior to the sulphide *(Giordano and Mortvedt [1966])*.

Shaw et al. [1954] found that the rate of utilisation of zinc fertilizers was inversely related to the rate of application, but was very low in all cases. Very little difference in utilisation was observed between two inorganic zinc carriers $ZnSO_4$ and $ZnCO_3$, the latter being the less soluble of the two. There was also little difference in response to $ZnSO_4$ applied directly to the crop and to the residual effects of $ZnSO_4$ applications during five preceding years.

The seed of maize supplied an appreciable part of the crops' zinc requirements.

Investigations on the relative efficiency of organic and inorganic zinc carriers have given conflicting results. In some cases, organic or chelate forms of Zn were found to be superior to the inorganic forms *(Boawn et al. [1957]; Chesnin [1963])*.

On sandy soils in Florida, the soluble inorganic sources of Zn, such as $ZnSO_4$, were superior for maize to insoluble sources such as ZnO *(Barnette [1936])*.

In research on two soil types in Georgia – a sandy loam and a loamy sand, a differential response to different zinc carriers was observed *(Shukla and Morris [1967])*. On the sandy loam, maize showed no visual symptoms of Zn-deficiency, but still responded by improved growth to Zn-fertilization. Under these circumstances, there were no significant differences among the Zn sources in their effect on plant growth. Apparently, any of the Zn carriers was able to correct the relatively slight Zn-deficiency on this soil. By contrast, maize grown on the loamy sand, showed visual symptoms of marked Zn-deficiency. Under these conditions, higher yields of maize were produced by $ZnSO_4$ than by any of the other carriers.

It should be pointed out that in these investigations, the chelate and organic Zn sources were applied at lower rates than were $ZnSO_4$ and ZnO. If equivalent amounts of all carriers had been applied there would probably have been no difference in effectiveness among the carriers. However, the high cost of the organic and chelate forms would make it economically unfeasible to use these sources for supplying Zn to maize, at the high levels required.

The relative efficiency as fertilizers for maize of two zinc carriers: Zn-EDTA and $ZnSO_4$ was also investigated on two zinc-deficient soils in Virginia: a silt loam and a loamy fine sand *(Schnappinger et al. [1969])*. The deficiency was greater on the silt loam, on which zinc-deficient plants remained stunted throughout the growing season, whilst the plants on the loamy fine sand recovered at a later stage of growth. Both soils had relatively normal levels of Zn as compared with other soils which did not give rise to Zn deficiencies. The Zn deficiency of the maize plants grown on these two soils was therefore attributed to liberal applications of limestone and phosphorus, causing low plant availability of Zn.

In general, in order to correct the Zn deficiency of the maize plants, less zinc was required in the form of Zn-EDTA than of $ZnSO_4$, confirming results which had been obtained by other authors. The greater zinc-supplying power of Zn-EDTA is attributed to its ability to support higher amounts of Zn in solution and to its greater mobility in the soil *(Brown and Krantz [1966])*.

Banded Zn-EDTA was more efficient than broadcast (equivalent amounts) in supplying Zn to the maize plants *(Schnappinger et al. [1969])*.

12.6 References

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13. Methods and timing of fertilizer application

In order to ensure maximum yields it is not sufficient to determine the amounts of nutrients required by the crop. The methods employed in applying the fertilizers and the time they are applied, have a considerable bearing on their effectiveness. The young plants must be able to obtain a ready supply of nutrients, so that they can get a fast start; however, the fertilizers must not damage the seedlings. The growing plant must find a continuous supply of nutrients commensurate with its needs at different stages of growth. Fertilizers should remain available even when the top soil layer dries out. For nutrients such as phosphorus, which become less available following reactions with the soil, this reduction in effectiveness should be minimized as far as possible. These objectives can be more or less achieved by chosing appropriate methods and proper timing of fertilizer application.

13.1 Techniques of application

Formerly, when the open-pollinated varieties of maize with their relatively low productive potential were the only ones grown, the most common and efficient method of applying the moderate amounts of fertilizers used at the time was by localised placement or banding near the seed.

With the advent of high-yielding hybrids, higher rates of fertilizers are commonly used and the types of carriers have also changed. Solid, liquid and gaseous fertilizers are applied to maize in a number of ways.

The principal methods of applying fertilizers are *directly to the soil,* by broadcasting or by localised placement (in bands, or by mixing with the seed); *indirectly,* through irrigation water; and *directly to the plant,* by spraying on the foliage. The choice of method depends on a number of factors, such as characteristics of the fertilizer, the amounts required, the stage of plant development, the fixing power of the soil, the size of the area to be fertilized and the season of the year (whether fields are accessible to ground machinery or not).

13.1.1 Broadcasting

Broadcasting may be carried out before ploughing the land, before sowing or on the growing crop. Broadcasting followed by ploughing makes possible an even distribution of the fertilizer throughout the ploughed layer, in which plant roots are most active. This method is of particular importance for incorporating phosphorus and potassium in soils deficient in these elements, as the first step in a build-up of sufficient reserves.

Due to the rapid fixation of phosphorus there is very little downward movement of this element in the soil. With irrigation, the downward movement of phosphorus is increased, the depth of penetration being proportional to the amount of water applied *(Jordan et al. [1952])*. However, even with irrigation, the downward movement is limited. It has been found that after 28 years, 80 per cent of the P fertilizer applied to an irrigated soil remained in the top 30 cm of the soil and very little penetrated beyond 60 cm. It is therefore frequently recommended to incorporate phosphoric fertilizer into the soil by ploughing. This method is also indicated when there is a need for heavy rates of application which might harm the crop if applied in localised placement.

Broadcast application ensures greater contact between the fertilizer and the feeder roots of the plant, and therefore ensures more efficient uptake as the plant develops and its root system expands.

Water-insoluble fertilizers benefit most from thorough mixing with the soil.

It has been found that in alkaline soils, thorough incorporation of the phosphorus fertilizer is of particular importance *(Stanberry [1959])*. In practice, however, the mixing of fertilizer with the soil is never very thorough and the fertilizer granules chiefly enrich the soil particles lying close to them. In this way, manuring creates zones of enhanced nutrient richness in the soil and the roots seem to be capable of feeding preferentially from these. Little by little the diffusion of nutrient ions will tend to make the medium uniform again, but this diffusion is quite slow, and 'placement effects' may be perceptible for as long as several months.

When the broadcast fertilizer is superficially mixed with the soil, for example by first ploughing, then broadcasting and disking, or harrowing, the fertilizer will remain in the surface 5–7 cm and will be 'positionally' unavailable during dry periods. Hence the importance of incorporating the fertilizer in soil layers that remain continuously moist. This is particularly important for relatively immobile nutrients such as phosphorus or potassium.

Broadcast applications of phosphorus prior to listing has given unsatisfactory results. The lister moldboards push the fertilizer high up into the middle ridges where the young plants cannot utilize it. When grown on P-deficient soil, lister-sown maize may be stunted in growth and show the typical purplish colour of P-deficient plants, notwithstanding the application of adequate amounts of phosphorus fertilizer, simply because it has become positionally unavailable *(Shubeck [1963])*.

Broadcasting before sowing is used mainly for easily leached nitrogenous fertilizers, or in cases in which a light levelling of the soil follows the ploughing. The fertilizer is then disked or harrowed in. However, for a summer-growing crop such as maize it may be advisable to incorporate the nitrogen fertilizers at a greater depth, in a more continuously moist zone, so that the nitrogen remains available during the period between rains or irrigations when the upper level dries out.

13.1.2 Localized or band placement (Plate 22)

In some countries, in particular the United States, localising fertilizers in bands close to the seed rows of maize, has been common practice for many years, but has not been generally adopted elsewhere.

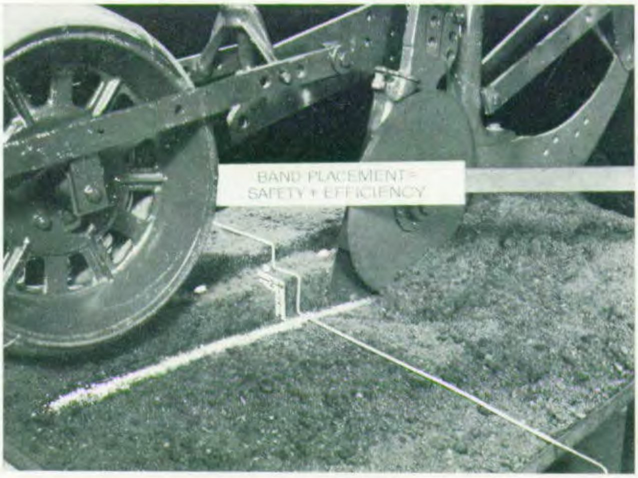

Plate 22
Fertilizer placement.
By courtesy of ,Better Crops with Plant Food' of the Potash Institute of North America.

Cooke [1954] is of the opinion that placement is of particular value for rapidly growing crops with a limited root system, whilst crops with an extensive root system utilize nutrients more efficiently between the rows and therefore show smaller benefits from a localised placement of fertilizers.

However, maize appears to be an exception to this general rule *(Prummel [1957])*. This crop has an extensive root system capable of taking up nutrients from a large soil volume, and yet placement has frequently been shown to have marked advantages over broadcast applications. This is probably due to the high requirements of the very young maize plant for nutrients, at a time when the root system is still undeveloped. *Barber et al. [1963]* have calculated that the roots and root hairs of maize are able to contact a maximum of 3 per cent of the available nutrients in the soil (cf. 134). This indicates the importance of localized fertilizer placement for those nutrients with low mobility, such as phosphorus.

Band application concentrates the fertilizer in a relatively small volume of soil. The effective volume of the fertilizer band is no more than one hundredth to one thousandth of the total root volume, depending on the stage of development of the crop *(Ohlrogge [1957])*.

Because of the higher concentration of nutrients per unit soil mass, the nutrient-supplying power of the fertilizer band is greater than that of broadcast fertilizer. The band will therefore be more effective in maintaining the concentration of nutrients in the soil solution *(Grunes [1959])*.

As a consequence, the roots that penetrate the fertilizer band are in a zone of higher nutrient concentration than roots growing in soil on which an equal amount of broadcast fertilizer per hectare has been incorporated.

The most extensive root system develops in soil in which the plant nutrients are most abundant *(Wilkinson and Ohlrogge [1962])*. Only a small fraction of the root surface is in contact with the banded fertilizers; however, the rapid proliferation of the roots in the fertilizer band enables a high recovery rate of the nutrients in the band.

Although the concentration of salts in the band may exceed the accepted limits beyond which damage is normally caused to plants, no harmful effects are generally experienced. This is probably due to the fact that only a very small part of the root system is involved *(Duncan abd Ohlrogge [1958])*.

Maize seedlings respond more readily to a high nutrient concentration than do older plants, hence the effectiveness of banded fertilizer placed near the seed at the time of sowing.

De Wit [1953] has developed an equation expressing the relation between plant uptake of fertilizer from bands and from broadcast applications. The smaller volume of fertilized soil involved in the band application is compensated for by the higher concentration of the nutrient(s), so that fertilizer uptake per unit volume of fertilized soil is greater. *Singh and Black [1964]* tested *de Wit's* theory and their results confirm his view that the 'compensation function' represents the results to a first approximation.

However, *Prummel [1957]*, in exhaustive trials in the Netherlands, found that his results did not corroborate the conclusions of *de Wit* on the effects of fertilizer placement.

– *Phosphorus*

Broadcasting phosphorus fertilizers and then incorporating them into the soil by ploughing has several disadvantages. The phosphate applied in this way is exposed to a great surface of contact between soil and fertilizer and fixation is rapid and complete. Therefore, the emerging seedling does not find sufficient available phosphorus and is hindered in its development; by the time its root system has developed sufficiently to exploit the soil efficiently, the phosphorus is no longer readily available. It has been repeatedly shown, under conditions of ample soil moisture, that placing water-soluble phosphates, such as superphosphate, in bands in the vicinity of the seed row, considerably reduces fixation and the seedlings are able to derive their phosphorus requirements from the fertilizer and develop rapidly. In soils low in available phosphorus, banding may stimulate early root growth and thereby enable the plant to resist drought conditions later in the season *(Kafkafi [1963])*.

In extensive trials in the Netherlands, band placement of superphosphate was found to give spectacular results with maize, on soils deficient in phosphorus. The crop grew more quickly, earlier ripening was promoted and higher yields were obtained than with broadcast applications **(Figure 128** *Prummel [1957])*.

The relative efficiency of banded as compared with broadcast phosphorus depends on a number of factors such as soil moisture, temperature, characteristics of the fertilizer, rate of application, P-status of the soil and associated fertilizers.

– *Soil moisture*

This subject will be discussed in chapter 14.

– *Soil temperature*

Routchenko and Delmas [1963] warn against the dangers of placing P, in particular in conjunction with NH_4, too near to the seed row in cold soils with a low nitrification rate. Replacing NH_4 by NO_3 under these conditions, entirely eliminates the toxic effects and increases the growth of the young plants considerably.

However, cool spring temperatures considerably enhance the favourable effect of row applications, if the fertilizer is placed at an appropriate distance from the seeds, in order to avoid harming the seedlings *(Barber [1969])*.

– *Characteristics of the fertilizer*

Webb and Pesek [1958], in a large number of field experiments, have shown that increasing the water solubility of phosphorus fertilizer applied in the row for maize, resulted in increased early plant growth, fertilizer-P uptake and yield responses. For satisfactory yield responses the P-fertilizers should contain at least 60 per cent of their P in water-soluble form.

Mixing broadcast P-fertilizer with the soil tends to reduce water solubility compared with localized placements which concentrate the fertilizer. In the localized placements, the P is applied at the time of sowing, a minimum amount of mixing with the soil occurs, and the P is rapidly taken up by the plants. Under these conditions, the effectiveness of the fertilizer depends mainly on its own characteristics rather than on those of the soil. By contrast, broadcast applications are generally made several weeks before sowing, the fertilizer is well mixed with a large volume of soil and conditions are favourable for close reactions between them.

Because of its dilution in the soil, the broadcast phosphorus is not taken up by the very young plants, but at the time of maximum crop requirement later in the season. For these reasons, the water-soluble P reverts to water-insoluble forms, so that the initial amounts of water-soluble P in the fertilizer become largely irrelevant.

These effects will probably be less marked on calcareous soils, because of the slower rate of dissolution under these conditions *[ibid.]*.

– *P-status of the soil*

Welch et al. [1966] working on three soils with different levels of native available phosphorus, found three kinds of response to broadcast *versus* banded fertilizer when all the superphosphate was applied by one *or* the other method. They distinguish three cases:

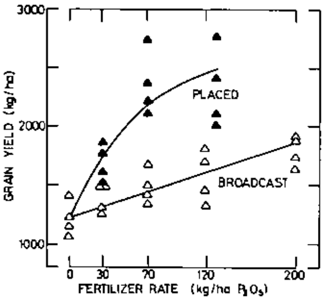

Fig. 128 Comparison between placement (▲) and broadcasting (△) with phosphate for maize on sandy soil *(Prummel [1957])*. By courtesy of the Koninklijk Genootschap voor Landbouwwetenschap.

Case 1 **(Figure 129a):** Less banded P than broadcast P was required to obtain a specified yield of maize. The highest yield that was obtained with banded P was also obtained with broadcast P, but a higher rate was required when the fertilizer was broadcast.

Case 2 **(Figure 129b):** As with case 1, less banded P than broadcast P was required to obtain a specific yield of maize. However, the highest yield obtained with banded P could not be achieved with broadcast application even when the latter was applied at a higher rate.

Case 3 **(Figure 129c):** There was little difference in effectiveness between banded and broadcast P.

The investigators concluded that the relative efficiency of broadcast versus banded P appears to be related to the initial P status of the soil to which the fertilizer is applied. The higher the level of available P, the smaller the response to the applied fertilizer, and the lesser the advantage of banded over broadcast fertilizer. However, the advantage of band application is not expected to disappear entirely until the initial available P level is so high that only a small yield response to added fertilizer can be obtained during the year in which the fertilizer is added.

Similar results were obtained by *Prummel [1957]* (cf. p. 290), who carried out a trial with maize comparing placement with broadcasting in relation to the phosphate content of the soil*. He found that even a small quantity of phosphorus fertilizer (30 kg P_2O_5/ha) increased the yield of maize as much as a difference of 6 units P citr.** on non-fertilized soil **(Figure 130).** At all levels of soil P at which P fertilization increased yields, banded fertilizer was more effective than broadcasting; the advantage of the former over the latter decreased with increasing levels of P citr. in the soil.

The results described above pertain to either banded or broadcast application of the total quantity of fertilizer applied. On soils that are very deficient in phosphorus, band

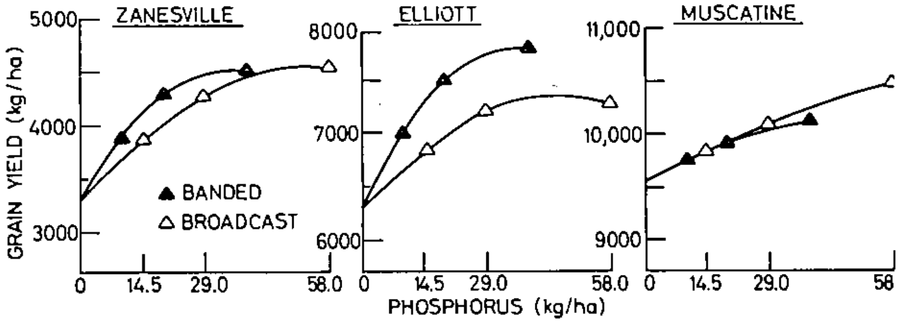

Fig. 129 Maize yields as affected by different rates of phosphorus, with all the P either banded or broadcast, on three soil types *(Welch et al. [1966])*. By courtesy of the American Society of Agronomy.

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* Expressed as P-citr. value: phosphoric acid soluble in 1 per cent citric acid.

** 6 unit P citr. correspond to approximately 260 kg P_2O_5/ha.

fertilization alone will not produce maximum yields. *Welch et al. [1966]* have shown that a combination of banded and broadcast placement gave higher maize yields than either method alone when the rate of application was 38 kg P/ha (Table 61).

Table 61. Relative efficiency of different methods of application of superphosphate (38 kg P/ha) *(Welch et al. [1966])*

Amounts in per cent of total Broadcast	Banded	Yield (kg/ha
0	100	3750
25	75	4000
50	50	4087
75	25	4018
100	0	3795

At lower application rates (9.7 and 19.4 kg/ha) higher yields were obtained on soils with relatively good yield responses to P if all the P was banded. On a soil with little response to P, banded and broadcast P produced about the same yield **(Figure 131)**. In Indiana, band applications of phosphorus were found to help increase yields on soils with low fertility, but were not able to produce maximum yields, unless supplemented by broadcast application **(Figure 132)** *(Nelson [1965])*.

From these experiments it is possible to conclude that as a rule, the general level of phosphorus in the soil should first be built up by broadcast applications and incorporation in the top level of the soil. Subsequent row applications will then usually be effective.

– *Rate of application*

Barber [1958] found that phosphorus, applied at rates of 12 to 48 kg P/ha, did not increase the P content of the leaves or increase yields significantly when applied as a band near the row, while broadcast applications at the same rates had significant effects on leaf composition and yield. The same investigator, summarizing a 16-year study at the Purdue Agronomy Farm in Indiana, reports that broadcast applications of phosphorus were more effective in producing high yields of maize than were row applications alone. Phosphorus, at the rate of 12 kg P/ha, applied by the row, increased

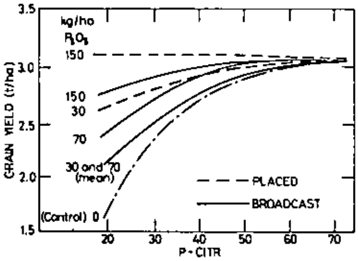

Fig. 130 Comparison between placement and broadcasting with phosphate for maize in dependence on P-CITR, on sandy soil *(Prummel [1957])*. By courtesy of the Koninkljik Genootschap voor Landbouwwetenschap.

maize yields by 635 kg/ha, while the same amount broadcast and ploughed under gave 50 per cent higher than the best yields from row application (**Figure 133**).

These results are at variance with these of other investigators who have shown that band placement of P is more effective than broadcasting *(Nelson and Stanford [1958]; Widdowson and Cooke [1958])*. These differences may be ascribed to the rates of P used in the different experiments, as fixation can vary with application rate. *De Wit*

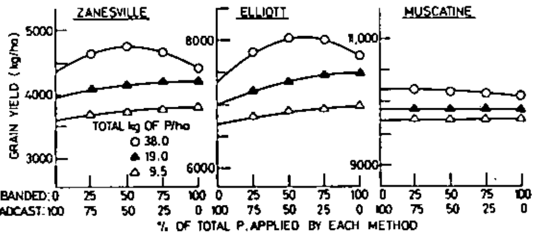

Fig. 131 Maize yields, as affected by different rates of phosphorus, with various percentages of the P banded and broadcast *(Welch et al. [1966])*. The numbers on the curves are total kg of P/ha. By courtesy of the American Society of Agronomy.

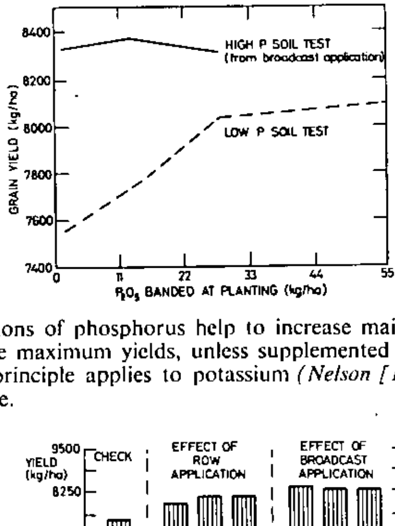

Fig. 132 Band applications of phosphorus help to increase maize yields on low fertility-soils, but cannot produce maximum yields, unless supplemented by appropriate broadcast applications. The same principle applies to potassium *(Nelson [1965])*. By courtesy of the American Potash Institute.

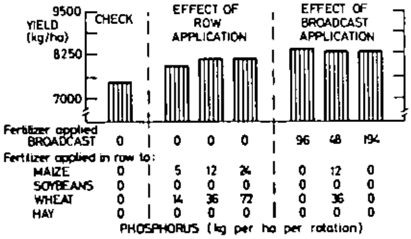

Fig. 133 Effect of method of application of phosphorus fertilizer on the yields of maize *(Barber [1969])*. In these trials, no advantage of banding over broadcast applications was evident. By courtesy of the American Society of Agronomy.

[1953] has shown that at high rates, relatively more fertilizer may be taken up from broadcast than from band placement.

In trials carried out by *Prummel [1957]* (cf. p. 290 and (**Figure 128**), banded fertilizer was more effective than broadcast fertilizer at both the lowest (30 kg/ha P_2O_5) and the highest (150 kg/ha P_2O_5) rates tested.

– *Associated fertilizers*

A number of investigators have established that applying phosphorus in the band in association with certain other fertilizers, greatly enhances the efficiency of the phosphorus *(Caldwell [1960])*.

A mixture of ammonium sulphate, muriate of potash and 20 per cent superphosphate applied in a single band near the side of the seed row, was found to be more effective in promoting early phosphorus utilization than was applying the nitrogen and potassium salts in one band, and the phosphate in another band on the opposite side of the seed row *(Robertson et al. [1958])*.

This effect was ascribed mainly to the ammonium sulphate. Potassium added to the superphosphate in the starter fertilizer had little effect on vegetative growth or phosphorus utilization. Addition of potassium to the nitrogen-phosphorus mixture even tended to decrease the concentration of phosphorus (in the young plant) derived from the fertilizer *[ibid.]*.

Investigations on the interaction of nitrogen and phosphorus, when applied together, showed that the effects of N on P uptake are dependent on the volume of fertilized soil and the proximity of the P and N fertilizers. When the P-fertilizer was broadcast and incorporated into the soil, the presence of nitrogen had no effect on the uptake of phosphorus by the maize plants *(Duncan and Ohlrogge [1958])*. When the nitrogen and phosphorus were mixed in the same band, the uptake of P per plant was increased 100 per cent at all levels of soil phosphate, ranging from zero to over 200 kg/ha of added P_2O_5. When the bands of P and N were separated by 7–10 cm of soil, N increased the uptake of P by 50 per cent at low soil phosphate levels and by 25 to 30 per cent at the higher levels (**Figure 134**) *(Miller and Ohlrogge [1955])*.

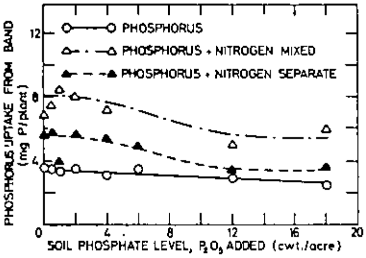

Fig. 134 The influence of soil phosphate level and nitrogen additions on the phosphorus absorption by maize from band-applied phosphorus fertilizer *(Miller and Ohlrogge [1958])*. Note that when the bands of N and P were separated by 7–10 cm of soil, the effect of N on P uptake was considerably reduced, as compared to N and P mixed in the band. By courtesy of the American Society of Agronomy.

Grunes et al. [1958] have also shown that nitrogen does not increase the effectiveness of P fertilizer when the latter is broadcast in the soil. As a result of the rapid fixation of the fertilizer P, placing a limited amount of fertilizer particles in intimate contact with a large volume of soil reduces the concentration gradients of the P-fertilizers and their capacity to renew the supply of solution P to the plants. At such low rates of renewal, N fertilizer has little effect. It is expected that there will be no great difference in this respect between fertilizer P and soil P.

An interesting phenomenon observed in many field trials is that not only must the nitrogen be intimately mixed with a soluble P form, that is applied to the soil in a restricted band, but that the nitrogen must be in the ammonium form **(Figure 135)** *(Ohlrogge [1957]). Rennie and Soper [1958],* for example, who carried out field and greenhouse studies in Saskatchewan, Canada, report that while considerable increases in fertilizer phosphorus uptake were recorded when ammonium fertilizer was mixed with the phosphorus carrier, nitrate sources of nitrogen were relatively ineffective in this respect. Any increase in P uptake that was observed in the nitrate-phosphorus mixtures, could be attributed to the nutritional effect of the nitrogen, causing increased growth. Similar results are reported by *Leonce and Miller [1966]).*

The reasons for the synergistic effects of phosphorus and nitrogen applied in the band have been discussed in chapter 10.

– *Potassium*

The placement of potassium has been shown to be more critical than that of phosphorus, because relatively large amounts of potassium, when placed too close to

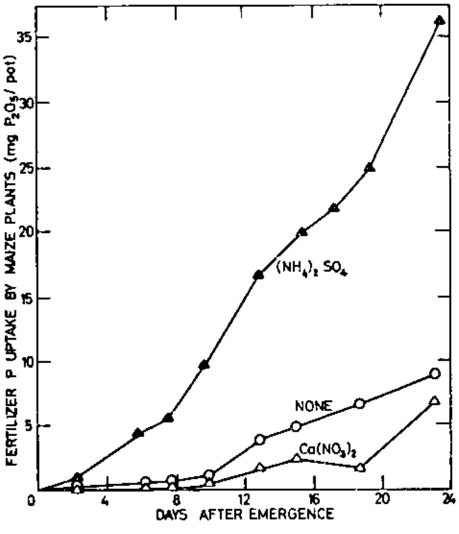

Fig. 135 The effect of source of nitrogen on the uptake of phosphorus from a fertilizer band. The nitrogen containing compound is mixed into the fertilizer band *(Ohlrogge [1957])*. By courtesy of the American Potash Institute.

maize seed, may reduce germination markedly more than does phosphorus *(Cummings and Parks [1961]; Lutz et al. [1963])*.

Although both K and P are 'fixed' in the soil after application and both are considered immobile nutrients because of their limited and slow movement in the soil, potassium appears to be more mobile than phosphorus, as shown by *Vasey and Barber [1963]* who found that Rb^{86} diffused at a faster rate than P*.

Since K is more dangerous than P when placed in proximity to the seed, and is more mobile, it might be expected that banding of K would be less effective than banding of P.

In trials in which yield response to K was not large, no differences in maize yields between row application and broadcasting were found *(Barber [1959]; Wittels and Seatz [1953])*. Naturally, if there is little response to K, it would be difficult to demonstrate any yield differences due to method of application.

Investigations on the relative merits of banded *versus* broadcast potassium were carried out on a loam soil in Tennessee, on areas testing from very low to high in available K. On soils that tested very low or low in available K, banded application of K was found to be more effective than broadcast. Banded and broadcast fertilizers gave approximately the same yields on soils with medium levels of available K. On soils testing high in available K, neither method had any significant effect on yields (Table 62) *(Parks et al. [1965])*.

Table 62. Average maize yields (kg/ha) for different methods of K-application at four soil test levels *(Parks et al. [1965])*

Fertilizer application K_2O		Soil test level: Very low	Low	Medium	High
	Av. K_2O:	77	132	185	317
Broadcast		5 650	8 700	9 780	10 032
Banded		7 112	9 270	9 525	9 590

Experiments were conducted in Illinois on three soil types to determine the relative efficiency of banded *versus* broadcast potassium for maize *(Welch et al. [1966])*. The amount of banded K required to obtain a specific grain yield was divided by the amount of broadcast K required to obtain the same yield. This ratio represents the efficiency of broadcast K, in relation to banded K, with respect to maize production.

Less K was required in all these soils to obtain a given yield when the potassium was banded than when it was broadcast. On one soil type, rates of 11 and 55 kg/ha of banded potassium produced the same yields as 33 and 116 kg/ha, respectively, when broadcast **(Figure 136)**. The broadcast K was only 33 and 47 per cent, respectively, as efficient as banded K. On the soil on which maize showed the least response to potassium, the differences in efficiency between banded and broadcast K were smaller. The highest maize yields were obtained in all cases by banding all or most of the potassium

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* Because of the lack of a convenient radioactive K isotope, Rb^{86}, which is very similar to K, is used.

(Figure 137). These results do not confirm the assumption that banding would be less efficient for K than for P.

In an other investigation by *Barber [1959]* on the relative merits of row placement and broadcast application of potassium (at equivalent rates), the two methods of application gave about the same increases in the percentage of potassium in the leaf and in their effects on maize yields (see table 63).

Table 63. Relative effectiveness of equivalent row and broadcast applications of potassium on maize *(Barber [1959])*

K_2O applied	% K in leaf		Yield (kg/ha)	
(kg/ha)	Row	Broadcast	Row	Broadcast
0	1.61		7190	
33	1.61	1.63	7600	7820
66	1.72	1.71	7750	7650
132	1.83	1.87	7950	8040
264	1.95	2.04	7750	7860
LSD, 5%	0.07		457	

In an experiment at Rothamsted comparing placing* and broadcasting of potassium fertilizers for maize, in association with nitrogen, it was found that early growth was improved by placed dressings of potassium and by the lower level of placed nitrogen

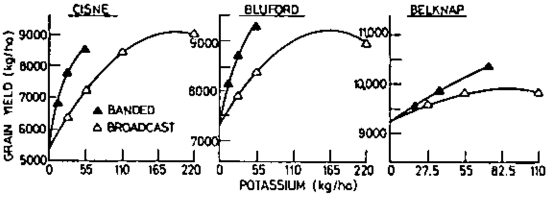

Fig. 136 Predicted maize yields, as affected by different rates of potassium, with all the K either banded or broadcast, on three soil types *(Welch et al. [1966])*. By courtesy of the American Society of Agronomy.

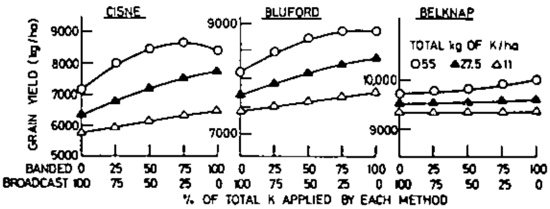

Fig. 137 Predicted maize yields, as affected by different rates of potassium, with various percentages of the K banded and broadcast *(Welch et al. [1966])*. The numbers on the curves are total kg of K/ha. By courtesy of the American Society of Agronomy.

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* In bands placed 5 cm to the side of the seed and 7.5 cm below the soil surface.

in the presence of placed potassium. Since the weather was cold and wet, the crop did not ripen: all nitrogen dressings delayed maturity; placement of the single dose of nitrogen, whether alone or together with potassium, depressed yields significantly in comparison with broadcasting. Potassium fertilizer increased yields slightly in the absence of nitrogen; the increase in yield obtained from placing the potassium was significant *(Widdowson and Cooke [1958])*.

Table 64. Unmanured yields and the increases from broadcast and placed* dressings of fertilizer on maize *(Widdowson and Cooke [1955])*

	Increases in yields (kg/ha) from:			
	N_1	K	N_1K	N_2K
Broadcasting	495	787	1900× ×	–279
Placing	–1905× ×	1346×	318	–1524×
Placing minus broadcasting	–2400× ×	559	–1588	–1204

Significant effects: × for P=0.05 to 0.01
× × for P>0.01

* In bands placed 5 cm to the side of the seed and 7.5 cm below the soil surface.

In brief, in this experiment placement increased the efficiency of fertilizer application. With nitrogen this resulted in reduced yields because the placed nitrogen was more effective in delaying maturity, whilst with potassium, yields were increased on this K-deficient soil.

In recent trials with maize grown on a loam soil, with varying K test levels, the effect of broadcastng and low application of potassium was investigated. The results are shown in **Figure 138.**

A comparison of the curves in this figure shows that the effects of placement become less important as the level of soil K increases, also as the total K available to the plant (from soil and fertilizer) increases. Thus, the importance of placement diminishes as the fertilizer technology goes towards higher rate of application *(Parks and Walker [1969])*.

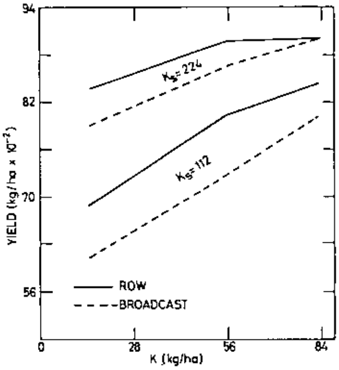

Fig. 138 The relative effects of row applied or broadcast potassium upon maize yield at two K soil test levels *(Parks and Walker [1969])*. By courtesy of the Soil Science Society of America.

Mederski [1962] summarizes the results of investigations on the relative advantages of band application and broadcasting of potassium fertilizer for maize as follows:

1. On soils relatively deficient in potassium, both band and broadcast potassium increase yields; the greatest return per unit of K is obtained from row application.

2. As the soil K level increases, less band fertilizer is needed in order to produce maximum economic returns. An increase in the rate of fertilizer applied by one method enables a parallel decrease in the rate applied by the other method, without affecting yield, so that different combinations of row and broadcast K produce similar results.

3. At least some potassium should be applied in the band, even where K level in the soil is relatively high. This band application helps to ensure an adequate supply of potassium when growing conditions are unfavourable and also hastens early development.

– *Nitrogen*

A study was made of NO_3^--and NH_4^+-N nitrogen movement on a fine sandy loam soil on which maize was grown under irrigation. Nitrogen was applied at the rate of 660 kg/ha, in the form of ammonium nitrate fertilizer. Broadcasting the fertilizer and ploughing under was compared with banding midway between furrows 85 cm apart. The movement of the nitrogen with the irrigation water is illustrated in **Figure 139.** Band application resulted in a greater concentration by capillary water of NO_3^--N above the band, near the surface. Downward movement resulted in moderate concentrations at the 26 cm depth and some NO_3^--N at the 52 cm depth. The broadcast method gave a more extensive distribution. High concentrations occurred near the surface between the furrows.

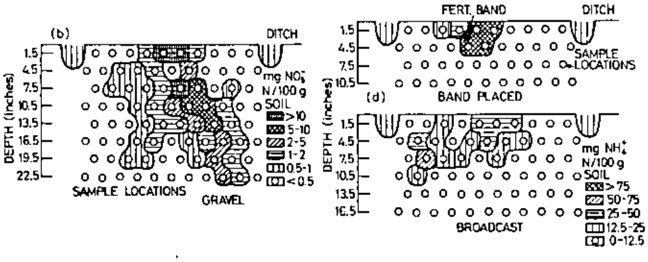

Fig. 139 The movement of nitrogen with irrigation water *(Nelson [1953])*. (a) Movement of NO_3^--N from a fertilizer band; (b) movement of NO_3^--N broadcast and ploughed under; (c) movement of indigenous NO_3^--N; (d) movement of NH_3^+-N. By courtesy of the American Society of Agronomy.

NH_4^+ – N did not move more than 7–10 cm with the irrigation water. No significant effects on maize yields due to the differences in application methods were observed in this case *(Nelson [1953])*.

In experiments with labelled N (^{15}N isotope) it was shown that the fraction of nitrogen derived from fertilizer increased with time. When maize was only ten days old, no nitrogen was taken up by the plant from fertilizer placed 25 cm or further away from the seed row. As the plants grew, more and more of the fertilizer which was placed away from the plant began to be taken up. On the average, it took 10–20 days after emergence for the plants to take up nitrogen from fertilizer placed 25 cm away from the seed row, and approximately 40–50 days to obtain N from fertilizer which was placed 50 cm away. The different placements of N had no effect on the final yields of maize *(Cho et al. [1967])*.

– *Zinc*

Zinc sulphate as well as other sources of Zn have been effective in correcting Zn-deficiency. The effectiveness of $ZnSO_4$ has been found to vary with the rate and method of application. On zinc-deficient soils in western Nebraska, 5.5 kg Zn/ha, broadcast and ploughed under before sowing was found to be the most effective method of application for increasing early growth and grain yield *(Pumphrey et al. [1963])*.

Since the amount of Zn fertilizer required for the correction of a deficiency is very small per unit area of surface, it is difficult to achieve uniform distribution of this nutrient. Hence, the interest in either banding or incorporating with a macronutrient carrier.

Brown and Krantz [1966] studied the effects of placement of a number of zinc carriers on a Zn- and P-deficient soil. When Zn fertilizers were well mixed with the soil, $ZnSO_4$ and organic sources such as Zn EDTA and Rayplex-N were equivalent in their effectiveness. Banding the fertilizers under the seed did not increase their effectiveness. With the relatively immobile $ZnSO_4$, banding actually reduced the effectiveness of the fertilizer.

Mortvedt and Giordano [1969] found that incorporating and mixing Zn fertilizers with the soil is generally more effective than band application; apparently uniform distribution of the applied Zn is essential for maximum effectiveness. However, the effectiveness of granular $ZnSO_4$ was not reduced when it was band-applied with granular macronutrient fertilizers *[ibid.]*.

– *Starter fertilizers*

Any fertilizer that is placed near the seed row will affect the early growth of the plant more than would the same amount evenly broadcasted and incorporated in a large soils volume. The term 'starter fertilizer' is used, when only a small proportion of the total amount applied is localized near the seed row, with the specific intention of giving the young seedlings a rapid start; hence the name. This starter fertilizer may provide adequate amounts of nutrients for the seedlings, but may be entirely inadequate at a later stage *(Hanway [1962 d])*.

The effects of starter fertilizer mixtures comprising N, P and K on maize, have been studied on a typical loam soil in the Perche region in France *(Gautier and Langlet*

[1970]). The amounts of N, P and K applied as starter fertilizer were very small in relation to the total amounts of nutrients incorporated into the soil before sowing and yet they had marked effects on the composition of the leaves and on grain yields. In the case of both K and P, high levels of nutrient supply which caused yield reductions when applied broadcast, were still capable of giving yield increases when part of the fertilizer was supplied as a starter (Table 65).

Table 65. Effects of broadcast and starter applications of fertilizers on yields (kg/ha) *(Gautier and Langlet [1970])*

Treatment	No starter	With starter
NP	2660	2610
NPK	5350	5780
NPK + K	4520	5970
NK	2660	3500
NPK + P	4990	6010

– *Appraisal of band application*

Dumenil et al. [1965] summarized the advantages and disadvantages of band application of fertilizers.

The advantages of banding are:

1. Starter effect: Band application usually gives an early growth response, and increases leaf area and root development, thereby increasing the yield potential. The starter effect is often visible seven to ten days after emergence.
2. Band application generally gives the largest growth responses on slowly draining to imperfectly drained soils, particularly when the weather in late May, June and early July is cool and wet.
3. The accelerated early growth of the plants due to band application often permits inter-row cultivation to start earlier. The work is also easier and faster.
4. Maturity may be hastened by up to 10 days by banding the fertilizer. This may be very important in certain regions. Occasionally it may be a disadvantage, if silking is thereby moved into a hot dry period. There are also cases when the nitrogen in the band causes delayed maturity.
5. Banding is usually the most efficient method for soils testing medium to high in P and K, for the minimum rates recommended. It is also practical for higher rates in continuous maize production, as most of the residual fertilizer in the band will be ploughed under for the next maize crop.

The disadvantages of banding are:

1. If rainfall after sowing is low, the availability of nutrients in the band for early growth may be limited and the starter effect almost nil. Nutrient uptake may be improved by deeper placement of the fertilizer, but the early starter effect will be delayed thereby.
2. Nutrient uptake from the bands may be impeded in later growth stages as the fertilizer may remain in dry soil for much of the time.

3. Banding may stimulate weed growth in the row, since weeds also benefit from the fertilizer. This effect will be negligible if herbicides have been used effectively.
4. Banding may increase first-brood borer infestation and thereby nullify the potential yield increase.
5. Banding fertilizer slows planting. This is less marked with planters equipped with large-capacity fertilizer hoppers or tanks.
6. Yield responses from banded fertilizers are often low to nil in dry years.
7. Profitability of amounts above 14 kg P/ha and 27 kg K/ha usually decreases sharply. Rates in the band should be limited to 5–10 kg/ha of both P and K, if high rates of these fertilizers are also ploughed under.

In brief, banding is not a technique that can be applied indiscriminately. It has its advantages and disadvantages; there are circumstances under which the former outweigh the latter and vice-versa. An understanding of the processes involved, and ad hoc experimentation, should provide the answer as to the method to be chosen, for particular cases.

– *Placement techniques*
Field experiments in Iowa, using superphosphate that contains P^{32}, showed that placing the fertilizer at seed depth, in bands on one or both sides of the seed, generally increased uptake of P by maize plants as compared with placement in a single band 7.5 cm below the seed *(Stanford and Nelson [1949])*.

However, placing fertilizers in too-close proximity to the seeds may cause a delay in germination or even reduced emergence markedly. This danger is enhanced under conditions of soil moisture stress.

Robertson et al. [1954] found that early utilization of phosphorus was greatest when the fertilizer bands were placed at seed level. Fertilizer placed 20 cm below seed level was not used as early as seed-level placement. One band of fertilizer was as effective as two bands per seed row.

Numerous field experiments have shown that the most satisfactory results in farm practice are generally obtained when the fertilizer band is 5–7 cm from the seed row and 5 cm beneath it; this placement ensures efficient utilization of the fertilizer and minimises the risk of damage to the germinating seed and the seedling.

– *Equipment* (Plate 23)
Special equipment has been devised that can place the fertilizer band at the sides and slightly below the seed row.

Modern disk side-applicators have replaced the old split-boot applicator. The new applicators place the fertilizer about 5 cm to one side of the seed and scatter it in a vertical band over a depth of 3 to 12 cm.

– *Pop-up fertilizer*
In recent years, another system of fertilizer placement has been investigated, namely, placing a small quantity of fertilizer directly in the row with the seed. This technique is popularly called 'pop-up' fertilizer. It is employed of course, in addition to the normal rates of application.

Placing fertilizer in contact with maize seed has not been adapted in the past in farming practice because of the damage caused to the germinating seed and the young plants. This damage does not appear to be due to any particular sensitivity of maize, as compared with wheat, for example, to which fertilizer is normally applied with the seed without apparent adverse effects. The difference in the effect of fertilizer placed in the row in contact with the seed, between maize and wheat, appears to be related to the concentrations normally used for each crop; they are two to ten times as high for maize as for wheat. In trials in Canada, it was shown that small amounts of fertilizer* applied with the seed (60 kg/ha of 6–10–6) in addition to the recommended amounts of banded fertilizer markedly increased early uptake of nutrients, improved growth, produced earlier silking and earlier maturity as compared with conventional banding. Yields were increased on various soil types by an average 440 kg/ha *(Bates et al. [1966])*. *Ohlrogge [1966]* also found that pop-up fertilizer increased the yields of early planted maize in 70 cm rows (Table 66).

Table 66. Effect of pop-up fertilizer on maize yields *(Ohlrogge [1966])* (all figures are in kg/ha)

Pop-up	Rate	Date of planting May 5	June 3
5–20–20	49	10 350	6600
0–53– 0	33	10 035	8130
18–46– 0	38	9 780	7870
6–22–22+3% Zn	66	9 780	7170
6–24–24	60	9 700	7620
13–29–11+2% Zn	88	9 640	6980
33– 0– 0	49	9 600	7850
0– 0– 0	—	8 760	7430

In greenhouse studies in Illinois, mixing small amounts of phosphorus with the seed had no adverse effect on per cent seed emergence, and increased the rate of dry matter production *(Garg and Welch [1968])*.

The individual and combined effects of varying rates and ratios of fertilizers placed in contact with the seed, on the stand, growth, maturity and yield of maize, were studied in a series of field trials carried out in various parts of Virginia *(Lutz et al. [1963])*. These investigations showed that the amount of fertilizer that can safely be applied in contact with the seed depends on the rainfall just prior to and immediately after sowing maize.

Nitrogen and potassium in particular, unless applied at very low rates, were found to reduce the stand and the yield of maize when placed in contact with the seed, if the amount of soil moisture was low during the germination period. Large amounts of nitrogen and/or potash, in contact with the seed, not only reduced the stand and caused slow emergence and growth, but also, in certain cases, delayed silking and

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* In order to minimize harmful effects a special low-salt fertilizer was used for mixing with the seed: ammonium potassium phosphate, made from ammonium phosphate and potassium hydroxide.

maturity. Nitrogen, under these conditions, caused a greater reduction in stand than did potassium, whilst phosphate usually had only a small or no detrimental effect on germination or yields. Therefore, when moisture was limited during the germination period, the best results were generally obtained when none of the fertilizer, or only the phosphorus, was applied in contact with the seed. When rainfall was abundant immediately after sowing, even the highest rates of nitrogen, potassium and phosphorus used in these trials did not reduce the stand. Hence, it may be assumed that for irrigated maize, the hazards attending the placing of fertilizers in the row, in contact with the seed, are minimal.

– *'Dollop' placement*

'Dollop' placement is a method used in African agriculture, and consists of making a hole with a stick, about 10 cm from the plant and 10 cm deep, when the plants are 3–4 weeks old, into which a measured cup-full of fertilizer is poured and covered with soil *(Brown [1966])*.

– *Seed-treatments with fertilizers*

Pre-sowing treatment of hybrid maize with $(NH_4)_2MoO_4$ (18 g in 5 l water per 100 kg seeds) increased grain yields by 370 kg/ha in trials in Rumania. The Mo-treatment also increased Mo-content, 10 000-grain weight and per cent germination of the resulting grain *(Gaevoi [1968])*.

– *General comment*

The effects of certain fertilizer techniques in promoting early growth of maize have been pointed out. It is however necessary to stress that the promotion of early growth is not always beneficial.

In an investigation on the effects of shade on maize production, *Earley et al. [1967]* came to the conclusion that extensive vegetative growth during the first 54 days was not a prerequisite for a high yield of grain per plant. They therefore suggest that the frequent failure of starter fertilizers to increase grain production on fertile soils, even though early growth is stimulated, may be due to increased mutual shading during the critical reproductive stage, which is detrimental to grain production.

They conclude that management practices that restrict early growth, and high rates of sowing combined with favourable environmental conditions during the reproduction and maturation phases, could lead to increased grain yields.

The practical conclusion is that whilst a good early start for the seedlings and vigourous growth of the young plants are essential if good yields are to be achieved, fertilization that promotes excessive vegetative growth should be avoided.

13.1.3 Side-dressing

Side-dressing is used mainly for applying nitrogen to the crop during the period of peak requirements, or after heavy rains have leached the soil nitrogen beyond the root system (Plate 23).

13.1.4 Applying fertilizers in irrigation water

Applying fertilizers in irrigation water is very attractive to the farmer as it makes for economy in labour, savings in equipment and faster crop responses. The method is

Plate 23
Side-dressing maize with anhydrous ammonia. By courtesy of John Deere Co.; photo by Broghill Co., Nebraska.

becoming increasingly popular in many countries. The application of phosphoric acid and nitrogen in irrigation water is being used quite extensively.

Special metering devices are available for applying the desired rate of fertilizesr. Where water distribution is not uniform, fertilizer application in solution will further aggravate the negative results of faulty irrigation techniques.

For use with overhead irrigation fertilizer concentrations of 1 to 3 per cent are normally recommended. It is also recommended to irrigate first without fertilizers in order to moisten the soil thoroughly, then to irrigate for about one hour with the fertilizer in solution, and finally to irrigate with clear water in order to flush the irrigation system and rinse off the foliage *(Kopetz [1965])*.

The application of fertilizers with irrigation water is not intended to replace the traditional methods of applying fertilizers before sowing the crop, but rather to supplement them.

From the point of view of the nutrition of the crop, the main advantages of supplying the fertilizers with the irrigation water are: (a) the nutrients can be supplied at critical periods, and are immediately available to the plants because of the favourable soil moisture regime provided at the same time; (b) the low concentrations of fertilizer which can be used without limiting the amounts applied, as well as the possibility of washing off the foliage after the fertilizer application, completely eliminate any harmful effects.

13.1.5 Liquid or solid fertilizers

There appears to be little reason to expect differences from potassium applied as a liquid or a solid, since the chief source of potassium in fertilizers is water soluble. Since phosphorus undergoes many reactions in the soil, most of which reduce its availability to plants, the problem of relative efficiency of liquid and solid phosphorus fertilizers appears to be more complex than for nitrogen or potassium. In fertilizer experiments using concentrated superphosphate, diammonium phosphate and ammoniated superphosphoric acid, it was found that the response of maize to phosphorus applied from the same material in liquid or solid forms, was similar *(Lathwell et al. [1960])*.

In general, under a wide range of conditions, liquid fertilizers have been found to be as satisfactory for maize as equivalent solid fertilizers. Therefore, in most situations, the price per unit of plant nutrient and the relative convenience of use will be the deciding factors in choosing between liquid and solid fertilizers. An additional factor that must be taken into account is whether the solid fertilizer contains secondary elements which may be beneficial or detrimental, according to circumstances, such as sulphur or acid forming radicals.

In trials in Italy, with maize grown without irrigation, N as urea was applied 15–21 days before the flowering of maize (a) in solution by injecting it into the soil at a depth of 15–20 cm between the rows, or (b) as granules broadcast over the whole area. The average yields of maize were higher from injection as a solution than from broadcasting granules for similar rates of applied nitrogen *(Covarelli [1968])*.

13.1.6 Foliar application

Experiments have shown that phosphorus, nitrogen and potassium in solution, when sprayed on the foliage, are easily absorbed and spread rapidly to all parts of the plant. Spraying fertilizer solution directly on the foliage of a crop has the advantages of avoiding the problems of fixation, loss of availability and losses by leaching which occur when fertilizers are applied to the soil.

The main drawback of this method is that in order to apply a major nutrient in a quantity that can have a significant effect on the crop, a large amount of dilute solution is needed, more than the foliage is capable of absorbing; increasing the concentration of the solution causes scorching of the foliage and damages the crop. The other alternative is to spray a dilute solution frequently, but this will make fertilizing labour-consuming and costly.

However, once the basic requirements for fertilizers have been supplied through soil application, foliar application might fulfill a secondary role, by supplying nutrients during critical stress periods, when absorption from the soil is not adequate.

The successful use of urea foliar sprays for the application of nitrogen to horticultural crops has stimulated interest for their use on field crops, in particular maize. In investigations in Indiana, it was shown that the yield response of maize to nitrogen applied before tasselling by foliar sprays was no greater than to the same amount of nitrogen applied at the same time as a side-dressing. All foliar spray applications caused leaf injury; a dilute spray containing 6 kg of urea per 100 liters of water, caused only light injury, whilst more concentrated sprays caused necrosis of part of the leaf area. The injury appeared to be due to a product of ammonia metabolism *(Foy et al. [1953])*.

In another experiment, hybrid maize was sprayed at the end of August with a 2.5 per cent urea solution or an equivalent amount of 5 per cent urea solution. Both treatments had practically the same effect on leaf N content, which rose considerably during the first 24 h after spraying. Sampling 19–21 days later showed that N contents were similar for all leaves, indicating that translocation of foliar-applied N had taken place. Leaf scorch occurred in maize sprayed with the more concentrated solution *(Van Maercke [1965])*.

In trials in Hungary spraying leaves with 1% ammonium nitrate decreased the yield by 25 per cent in 1965, the leaf blades being injured *(I'so and Hussien [1968])*.

Using a labelled phosphatic fertilizer, *Oliver [1952]* demonstrated that when a soluble phosphate solution is sprayed on the leaves of maize, phosphorus can be absorbed and translocated to all parts of the plant. The most effective time for spraying would be shortly after a rain or irrigation, when the plant would be growing rapidly. Whether spraying with a phosphate fertilizer would be an economical proposition was not tested.

Of the macronutrient elements, phosphorus is possibly the most promising for foliar application. The quantitative needs are much lower for phosphorus than for nitrogen or potassium, movement in the soil is more limited, and a larger proportion becomes unavailable when applied to the soil than is the case for the other major nutrients.

Maize plants grown at low P levels responded to foliar applications of P at a concentration of 25–50 millimoles of P per liter, by increased height and higher fresh weights. Tracer studies have demonstrated that foliar applied radioactive o-phosphoric acid is rapidly absorbed by the leaves of maize and translocated to the root tips and other regions of high metabolic activity *(Silberstein and Wittwer [1951])*.

In trials in India, it was found that when phosphorus fertilizers were sprayed on maize plants at a volume sufficient to wet the foliage without causing runoff, the percentage uptake of P fertilizer from spraying during the early stages of growth was eight times as efficient as soil applications of equivalent doses.

Percentage uptake of phosphorus from the sprayed fertilizer declined as the plants grew older. The experiments showed that where higher doses of P fertilizer through soil application cannot be given economically, a small quantity (5.5 kg P/ha) applied as a spray on young plants, can be more efficiently used. For spraying, ammonium phosphate appeared to be the most suitable P-fertilizer *(Datta and Vyas [1967])*.

In trials during 1959–62 at Voronezh (USSR), foliar dressings with N, P and K raised the yields of maize grain by 90–660 kg/ha while corresponding gains from soil dressings were 50–340 kg/ha. Crude protein yields were raised correspondingly by 11–52 per cent and 1–35 per cent, depending on the amount and type of fertilizers applied *(Pronin and Mostovich [1964])*.

– *Micronutrients*

The limitations outlined above do not apply to micronutrients. Deficiencies of iron, manganese and zinc are frequent in alkaline soils, and are not necessarily due to an absence of these elements in the soil, but rather to the chemical reactions in the soil which make them unavailable to the plant. Applying these minor nutrients to the soil therefore does not usually relieve the deficiency, whereas spraying directly on the foliage is usually highly effective.

Summing up: it appears that the potential value of foliar application of fertilizers to maize has not been fully explored, and the method might be useful for the application of phosphorus at critical periods and in particular for alleviating deficiencies of micronutrients.

13.1.7 Depth of fertilizer placement

The data obtained in investigations by *Hall et al. [1953]* indicate that at 11 weeks, 39 per cent of the total nutrient uptake by maize occurs from the surface soil (0 to 10 cm), 32 per cent from the subsurface (10 to 20 cm), and the remaining 29 per cent from the lower depths. There is therefore, *a priori*, a case for deep placement of at least part of the fertilizers applied to the crop.

In irrigation farming the upper 15–20 cm of the soil are periodically dried out during the intervals between irrigation. This layer also frequently dries out between rains, in unirrigated maize. It is evident that nutrients, applied in the upper soil layer, will pass through similar cycles of unavailability. Thus, water applications not only improve the moisture status of the soil layer in which the most active and abundant roots are usually found, but also make available nutrients that had become positionally unavailable to plants. Deeper placement of fertilizers has the advantage of avoiding these periodical cycles of availability and unavailability of nutrients due to dryness of the upper soil layer.

In a series of trials extending over a period of years in the south of France, it was found that urea placed at a depth of 15–20 cm produced an average 520 kg/ha more grain than the same amount of urea applied to the soil surface. The greater the response to nitrogen, the greater was the advantage of deep placement *(Soubiès and Lenain [1967])*. In field trials in Florida, on a loamy fine sand and a fine sandy loam, tagged phosphorus was placed at depths of 5, 20, 35 and 50 cm. In dry years, the deeper placement gave significantly higher yields of maize than the shallow treatments, provided the surface soil had residual fertilizer phosphorus and the fertilizer was not placed in a soil layer too compact for proper root development. When the surface soil had no residual P, there was not enough P to promote growth of roots to the fertilizer band and deeper placements were not effective. In wet years, the maize was able to obtain sufficient phosphorus from residual fertilizer to promote root penetration, and subsoiling alone was as effective as the application of phosphorus in increasing maize yields *(Robertson et al. [1957])*.

13.1.8 Fertilizing the subsoil

Subsoil moisture plays an important role in maize production by serving as a steady source of water supply, thereby offsetting the moisture fluctuations of the topsoil. It is good irrigation practice to wet the whole soil-horizon which will eventually be penetrated by the root systems to its full depth, even prior to sowing. This practice will, however, be ineffective if conditions are not favourable for the penetration of roots into the subsoil. Experience has shown that simply improving the physical conditions of the subsoil, even the breaking up of impervious layers between soil and subsoil, is not sufficient. There is even evidence that adequate soil fertility may enable plants to overcome compact layers.

Fertility levels are, on the whole, lower in subsoils than in surface soils, especially as regards readily available nutrients *(Winters and Simonson [1951])*. *Gliemeroth [1953]* has shown that the fertility of the subsoil may greatly affect the utilization of subsoil water. He found that subsoil fertilization doubled the proportion of roots in the soil layer at a depth of 36–54 cm as compared with more shallow fertilization.

These results have been confirmed by other workers. *Kohnke and Bertrand [1956]* found that maize roots did not penetrate deeply into a compacted silty clay loam, mainly because of lack of oxygen. Subsoiling alone improved root development under these conditions, but fertilization of the subsoil gave even more striking results.

The adage that the livelihood of farmers is derived from the 18–20 cm of topsoil is certainly not justified, and yet the full possibilities of subsoil fertilization have not yet been developed in practice, or even thoroughly investigated. However, it can be safely concluded that whilst keeping the entire soil profile moist is good farming practice, this will not be fully effective unless a proper moisture – fertility balance is maintained in the entire root zone.

The interactions between subsoil tillage and fertilization are treated in more detail in chapter 15.

A special case is when the subsoil becomes exposed, as a result of the removal of the topsoil through erosion or when land is levelled for irrigation. The effects of removing the topsoil of a silt loam, on the yields of maize, and means of improving the fertility of exposed subsoils, are discussed in chapter 15.

13.2 Timing of fertilizer applications

The proper timing of fertilizer application aims at obtaining the maximum response of the crop, by minimizing losses of nutrients and by making them available at the time and rate they are most needed.

In chapter 7 it has been shown that nitrogen requirements are minimal in the early stages of growth and reach a peak during the period between the onset of flowering and early grain formation. The maximum uptake of phosphorus occurs between the third and sixth weeks of growth. The rate of accumulation of potassium during the first 30 days of growth exceeds that of both nitrogen and phosphorus.

Other factors to be considered are the convenience of application, and the need to avoid field operations that may delay or extend the sowing period. Heavy rates of fertilization applied during sowing may slow sowing by 40 per cent *(Barber and Olson [1968])*. Spreading most of the fertilizer required by maize in the preceding autumn or winter months, will save precious time in the spring, and make possible sowing at the optimum date. Heavy fertilizer applications during wet springs, ahead of sowing, will cause compacted soils and poor seed beds. Another advantage of autumn application of fertilizers is that the decomposition of the residues of the previous crop will be considerably speeded up.

The dangers of nutrient losses by leaching need not be exaggerated. Phosphorus and potassium are in any case well held by most soils. Nitrogen losses need not be important in temperate regions if applied in the ammoniacal form and if a large proportion of the nitrogen is tied up by the microorganisms active in the breakdown of the crop residues.

13.2.1 Nitrogen

The most effective time to apply nitrogen depends on the soil, the climate and the fertilizer carrier used.

In regions with low winter temperatures, ammonium nitrogen may be applied in the autumn preceding sowing, as leaching and volatilisation losses under these conditions will generally be minimal. At temperatures higher than 5–10 °C, nitrification may increase leaching losses *(Barber and Olson [1968])*.

In tests conducted in a number of locations in Alabama, Georgia and Mississippi, on widely different soil types, it was found that nitrogen fertilizer broadcast in November or December was only 49 per cent as effective in increasing maize yields as were the same amounts applied in spring. No consistent differences between fertilizer carriers were recorded, although nitrogen recovery from urea tended to be lower than that from the other nitrogen carriers *(Pearson et al. [1961])*.

Losses of nitrogen may also occur because of denitrification. Field investigations in Ontario (Canada) on clay and silt loam soils, have shown that autumn applications of nitrogenous fertilizers always produced lower yields of maize than spring applications, at all the rates tested and irrespective of the kind of nitrogen carrier used. The disadvantage of autumn application was more marked on clay soils than on loam soils. The investigators *(Stevenson and Baldwin [1969])* ascribe the poorer results from autumn-applied nitrogen to denitrification. In the clay soils denitrification would be due mainly to poor aeration of the soil; in the well-aerated loams, into which large amounts of crop residues were incorporated and underwent rapid decomposition, it may have been the microenvironment of the bacteria which was anaerobic.

Nitrogen can be applied in spring before sowing, either ploughed under or knifed into the soil, on all except very sandy soils. Part of the nitrogen can also be applied as a side-dressing to the growing crop.

The amount of loss of nitrogen due to leaching, and hence the potential benefits of late versus early applications, will also depend on soil texture. In sandy soils with a permeable B horizon (Norfolk), *Nelson [1953]* found that side-dressing most of the nitrogen at the knee-high stage was superior to early application. On these soils, some of the nitrogen applied before sowing was apparently leached out by rain, even when applied in the ammoniacal form, as it nitrified rapidly. By contrast, on other soil types with heavier B horizons, application before sowing was fully as effective as side-dressed applications during growth **(Figure 140)**.

If nitrogen is applied too late in the life of the plant, much of its effectiveness is lost. Field experiments in Nebraska with irrigated maize grown on a fine sandy loam indicated that, in general, nitrogen fertilizer was more efficiently used during the year of application when it was applied prior to ploughing, at planting time or as a side-dressing when the plants were 15 to 30 cm high, than when applied as a side-dressing when the plants were 75 to 90 cm high *(Pumphrey and Harris [1956])*.

13.2.2 Phosphorus and potassium

In a greenhouse experiment that studied the effects of the rate and time of phosphorus fertilizer applications on the growth of maize and its P uptake, it was found that the same treatment did not give both maximum dry matter production and maximum P

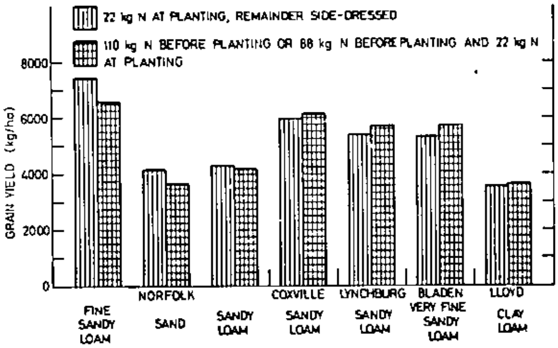

Fig. 140 The effect of time of application of nitrogen on the yield of maize in relation to soil texture *(Nelson [1953])*. (Only the sandy Norfolk soil had a permeable B horizon.)

uptake values. The investigations showed that a critical period exists in the physiological development of the maize plant during which time phosphorus must be available to the plants if it is to be effective in producing higher yields of dry matter. If additional phosphorus is applied or becomes available only after this critical period, it will be taken up by the plant, but will not increase yield. Hence the extreme importance of applying P fertilizer at the latest soon after planting, when the initial rates of P are low, in order to obtain maximum yields of dry matter. In most cases it was found that yields were reduced if the phosphorus was not applied within 4 weeks after sowing *(Seatz and Sterges [1963])*.

By using radioactive P injections into a silty clay loam soil, at depths of 15, 30 and 60 cm, it was possible to establish that when the plants were 23 days old, most of the ^{32}P taken up by roots of maize was derived from the upper 15 cm soil layer. When the plants were 59 days old, uptake of ^{32}P was very limited, an indication of the importance of early P application for efficient use of the fertilizer. By injecting ^{32}P in the top 15 cm of soil, within 20 cm of the plants, maximum ^{32}P deposition in the grain was obtained *(Lavy and Eastin [1969])*.

In Hungarian trials with hybrid maize grown in pots, the plants were supplied with labelled phosphorus fertilizer. It was found that whilst the proportion of phosphorus in the plant derived from the fertilizer was insignificant just after emergence, within two weeks the proportion was over 50 per cent *(Latkovics and Maté [1966])*.

Barber [1969], summarizing the results of a 16-year study at Purdue, found that a great degree of flexibility was possible in the timing of application of phosphorus and potassium, provided the rates used are sufficiently high. Phosphorus was found to be about equally effective four years after application as when it was applied directly to the maize crop, whilst a potassium application may remain effective for up to two years **(Figure 141)**.

In brief, phosphorus and potassium fertilizers for maize can be applied either in the autumn – a few months before sowing or in spring – shortly before sowing. If one timing is more effective than the other, this should not be ascribed to changes in the availability of phosphorus and potassium because of increased fixation.

Results from tests carried out in Iowa indicate that autumn applications give higher yield increases of maize than do spring applications. In autumn the fertilizer is normally ploughed under, whilst in spring it is superficially incorporated into the soil by disking. The advantage of the autumn application can therefore be ascribed to the deeper placement of the fertilizer rather than to a direct effect of time of application. Disking of spring-applied fertilizer results in the fertilizer being placed in a surface layer that generally dries out rapidly, so that the P and K are even less available than they are after fixation *(Dumenil et al. [1954])*. Similar results have been obtained elsewhere.

A comparison between ploughing down applied phosphorus and potassium fertilizers and disking them into the surface layer, has been made in Iowa. The results are shown in Table 67.

Table 67. Plough-down as compared with disked-in fertilizers *[Nelson [1965])*

Fertilizer applied	Treatment yields (kg/ha) Ploughed-down	Disked in
Phosphorus	1270	1016
Potassium	2730	2476

– *Side-dressing*

Applying potassium fertilizer 14 to 40 days before sowing on a potassium-deficient soil in Tennessee, gave a greater response than applying the fertilizer as a side-dressing during the growing period. Side-dressings made 60 days after planting still gave a small response. When the side-dressing was delayed until 73 days after planting, potassium deficiency was somewhat alleviated, even at this late date, but the yield response was too low to justify the fertilizer application *(Washko [1945])*.

Side-dressing potassium fertilizer to maize that is stunted because of K-deficiency may be justified as an emergency measure, but will never be as effective as an equal amount

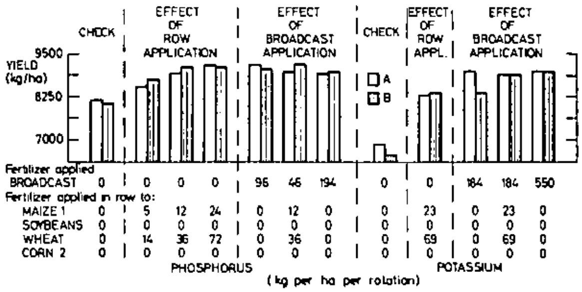

Fig. 141 Effect of time of application on efficacity of phosphorus (left) and potassium (right) fertilizer applied to maize *(Barber [1969])*. Note that maize grown the year of phosphorus application (A) yields no better than maize grown 4 years after application (B). By contrast, broadcasting potassium once every 4 years does not maintain corn yields unless very large amounts are used. By courtesy of the American Society of Agronomy.

of potassium applied before sowing *(Johnson [1952])*. When side-dressing is resorted to, it should be done as soon as possible after the plants have emerged. For these reasons, phosphorus and potassium fertilizers are generally applied before sowing, at any time that is convenient to the farmer. That part of the fertilizer which is banded (usually not more than a small proportion) is of course applied at the time of sowing.

13.2.3 Split-applications

The practice of applying fertilizers in split-applications – one part at the time of sowing and the rest at different growth periods – has become accepted agricultural practice.

– *Nitrogen*

For nitrogen in particular, which can be rapidly taken up by the plant and is easily lost by leaching from the soil, the practice of split-applications appears to be based on sound theoretical considerations.

In Delhi (India) the provision of nitrogen in two and three split-applications, gave on an average increases of 11,5 and 22,7 per cent, respectively, in grain yield of irrigated, pre-monsoon sown hybrid maize. This occurred under conditions of heavy rainfall, resulting in considerable leaching of nitrogen. High levels of nitrogen applied before sowing were found to favour heavy weed growth. In seasons with well-distributed rainfall, the advantages of split application were less evident *(Gautam et al. [1964])*.

In West Africa, fertilizers are usually applied at the time of planting, which follows the onset of the rains. However, nitrate content of the tropical soils is highest at the beginning of the rainy season, and is rapidly reduced following frequent rainfalls and the growth of the crop. Applying all the nitrogen at the time of sowing is therefore conducive to heavy losses by leaching. Under these conditions, split applications in two equal doses applied to maize one and two months after sowing, significantly increased grain yield by 35 per cent. There was no advantage to more than two split applications. Yields were significantly reduced when nitrogen application was delayed two months after sowing *(Fayemi [1966])*.

However, even for nitrogen, there are limitations in the use of split-applications. The additional expense incurred is justified only when there is danger of the nitrogen applied at the time of sowing being leached beyond the root zone. This is the case when heavy rainfall occurs in spring and also with most irrigation methods, especially when excess water is applied to prevent salt-accumulation. However, with overhead irrigation, when water is given in accordance with the water deficit within the root-zone area, there is no advantage to split-applications over a single application prior to sowing *(Arnon [1972])*. This is probably due to the more complete control of water supply made possible by overhead irrigation, as compared with furrow irrigation of flooding. Downward movement of the fertilizers, as far as it occurs, corresponds in this case to the development of the root system – and should be more beneficial than detrimental, as long as the fertilizers are not leached beyond the reach of the roots. Another possible reason for the lack of effect of split-applications could be the high rates of nitrogen applied to maize grown under intensive irrigation practice. In research carried out in Nebraska on irrigated maize, it was found that the time of nitrogen application, and hence split applications, was extremely important when low rates were used, but had little effect when the rates were in excess of 90 kg N/ha **(Figure 142)** *(Olson et al. [1960])*.

Similar results were obtained by *Nelson [1953]* who found that with applications of 140 kg N/ha, there was no advantage to split applications of ammonium nitrate applied to irrigated maize on a fine sandy loam soil.

In Rhodesia, it was common practice in the past to apply a large proportion of the nitrogen as a side-dressing, when the maize was approximately knee-high. However, experimental results have shown that in general, on heavy soils, it is immaterial whether all the nitrogen is applied at planting or partly at planting and the remainder as a side-dressing. It is now becoming common practice, on heavier-textured soils, to plough all the nitrogen fertilizer under, together with the stover and other fertilizers. On sandy soils, on which serious leaching is likely to occur, part of the nitrogen is applied as a top-dressing *(Burkersroda [1965])*.

– *Phosphorus and potassium*

Phosphorus and potassium have too low mobility in the soil for it to be practical to apply them in split-applications in accordance with their respective rates of uptake. For potassium, losses by leaching are minimal and even the potassium immobilised in the clay lattices is gradually released to the crop.

Phosphorus is fixed very shortly after application, and is then gradually released to the crop. Split-applications are therefore hardly more effective than single, relatively heavy dressings before sowing.

In the Krasnodar Province (USSR), trials during several years with maize grown on chernozem soil showed that the application of NPK fertilizers in a single dose before sowing gave increases in grain yields similar to those given by split applications *(Simakin et al. [1967])*.

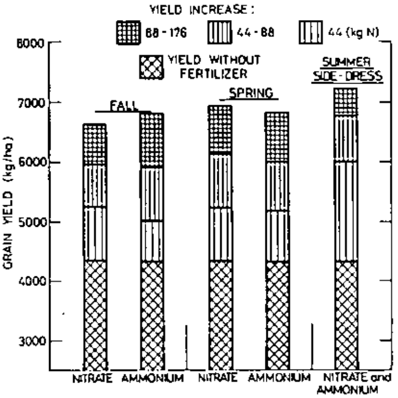

Fig. 142 Influence of time of application of nitrogen on maize in relation to the rates applied *(Olson et al. [1960])*. Averages of 12 irrigated maize experiments in Nebraska. Note that side-dressing is more effective than pre-sowing applications only when low rates of N are used. By courtesy of the Nebraska Agricultural Experiment Station.

The only practical solution for phosphorus and potassium is therefore to apply sufficient fertilizer before sowing so that at all times the rate of renewal of the nutrient content of the soil solution is adequate.

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14. Response to fertilizers in relation to environment

The effect of climate can be considered from two entirely different aspects:

(a) Maximum yields can be obtained only under favourable climatic conditions, and commensurate heavy rates of fertilization must be applied in order to utilize the full potential available.

(b) Under unfavourable conditions, liberal fertilization may mitigate to some degree the undesirable effects of low temperatures, cloudiness, etc. In particular, potassium has been effective in this respect. It is frequently under unfavourable conditions that the biggest relative responses to fertilizers are recorded, although overall yield levels are low.

14.1 Aerial environment

The relationship between yield and climatic factors is extremely complex; this causes variations in yields which affect crop response to fertilizers and therefore make average figures of little value. As a result, generalizations for different seasons and locations are very difficult.

For example, in a season of well-distributed rainfall and warm temperatures, with moderate drying of the soil between rains, decomposition of organic matter will be very active, and relatively high amounts of nitrogen and phosphorus will be released to the crop. Conversely, a cool spring will result in a slow release of these nutrients, and this effect will be compounded by low availability *(Thomas and Hanway [1968])*.

Little work has been published on the relationship between the response of maize to fertilizer applications and climatic variables. This relationship is of particular importance for assessing and predicting the economic returns from fertilizer applications.

Plants do not react to a single climatic factor but rather to the total environment in which they grow. It is only when a given factor approaches the maximum or minimum toleration limits of a plant, that it dominates the system sufficiently to obscure the influence of other factors *(Ragland et al. [1965])*.

There is a pressing need for a quantitative characterization of environmental factors that have a modifying effect on crop response to fertilizer applications. Such information could serve as a basis for constructive changes in cultural practices and permit maximum efficiency in the use of plant nutrients *(Ragland et al. [1965])*.

14.1.1 Light

Light is not known to play a direct and indispensable role in the absorption, translocation and metabolism of the mineral nutrients. The effect of light on mineral nutrition must therefore be an indirect one, resulting from temperature effects and the supply of photochemically synthesized ATP needed for active ion uptake and translocation *(Mengel [1968])*.

In many cases, mineral elements are involved in the photochemical processes either as an essential constituent of an enzyme system or of a pigment or other substance involved in these processes. Hence, the rate of the photochemical process will influence the mobilization and utilization of these mineral elements.

The main photochemical process affecting mineral metabolism is photosynthesis. The carbohydrates produced by photosynthesis are the essential source of energy for the uptake of minerals by the roots. The mineral elements enter into photosynthesis with carbohydrate – derived materials forming the various components of the plants. Therefore, the mineral nutrient requirements of plants are directly dependent on carbohydrate supply and, hence, on photosynthesis *[ibid.]*.

The effect of light on yield levels and hence on nutrient requirements, as well as the need to adjust plant population, moisture regime and nutrient supply to the levels of radiant energy available to the plant throughout its life, have been discussed in detail in chapter 4.

14.1.2 Air humidity

Working in sand cultures under glasshouse conditions, *Mederski and Wilson [1960]* found that under conditions of low atmospheric humidity, the P content of maize plants increased linearly with increasing soil moisture. Under conditions of high atmospheric humidity, the differences in P content were not significant. Potassium and magnesium contents of the plants increased with increasing soil moisture, under conditions of both low and high atmospheric humidity; the increase was linear with low humidity, but not with high humidity.

14.1.3 Winds

In the Altai steppes (S.W. Siberia) the response of crops to fertilizers was found to be increased in fields protected by tree windbreaks, compared with open fields. In the Priob' steppe (annual rainfall 470 mm), yield increases from the application of fertilizers at sites protected by windbreaks were 10 800 kg fresh matter/ha for maize; on an adjacent unprotected site, the corresponding increases were 6000 kg/ha *(Adrianov [1966])*.

14.2 Interactions of fertilizers with edaphic factors

The efficiency with which fertilizers are used by the crop to which they are applied and their residual effects are closely related to the characteristics of the soil.

Many soil properties cause changes in the fertilizers after their incorporation in the soil and their availability to plants. Conversely, fertilizers may have a marked influence on soil characteristics.

The principle soil properties involved in these interactions with fertilizers are: the chemical constituents of the soil, soil reaction, buffering capacity, soil texture, the levels of nutrients in the soil, soil salinity, biotic factors, soil temperature and aeration, the moisture regime in the soil, and certain management practices.

Many of the soil factors influencing uptake of nutrients are interrelated. For example, the moisture status of the soil will influence air supply, soil temperature and the decomposition of organic matter, with its resultant release of nutrients.

14.2.1 Fixation

In soils in which 'fixation' of phosphorus occurs, only a small proportion of the fertilizer phosphate (usually not more than 5–15 per cent) may be taken up by the crop to which it is applied. However, the remaining phosphate is not lost. A distinction must be made between non-solubility and non-availability of the phosphorus, as the rapid fixation does not prevent the fertilizer phosphorus from contributing gradually to the replacement of phosphorus in the soil solution.

The fertilizer phosphorus not taken up by the crop to which it is applied should be considered as a capital investment. Remaining as it does in the 'labile ionic pool', its presence will enable the next addition of phosphate to increase the potential to a greater extent than would have been the case otherwise *(Russell et al. [1961])*.

Fixation is not generally so acute a problem for potassium as for phosphorus; it helps to reduce leaching losses and luxury consumption; fixed potassium can be considered as a reserve supply whose availability to plants is intermediate between that of exchangeable and naturally non-exchangeable forms, which is partly recoverable after a few weeks and probably completely so in a longer time. Potassium fixation therefore has merits for maize production, which counterbalance its disadvantages *(De Turk [1943])*.

About half the fertilizer nitrogen applied to maize is recovered by the growing crop, under normal field conditions. Part of the nitrogen is immobilized in the soil through microbial activity or fixed as ammonium in the lattices of certain clay materials. This immobilized nitrogen may become available to the following crop. Another part of the nitrogen is lost by leaching, by volatilization or by erosion *(Kilmer and Webb [1968])*.

Ammonium-N can be fixed by clays in a manner very similar to the fixation of potassium. The addition of ammonium fertilizers to the soil can therefore affect the fixation of added potassium and can block the release of fixed potassium. This is illustrated by the results obtained by *Welch and Scott [1961]*, who studied the effects of additions of ammonium to the soil on the availability of nonexchangeable soil potassium. In one soil type, when ammonium sulphate was added at the rates of 0, 10, 25, 50 and 100 mq of NH_4 per 100 g of soil, the maize plants absorbed 21.8, 16.4, 11.6, 4.96 and 0.12 mq of nonexchangeable K from the soil, respectively. This reduction in the uptake of nonexchangeable potassium was due to the blocking effect of NH_4 on the release of K, and not an effect of NH_4 on the absorption of available K **(Figure 143)**. It is, however, probable that in field practice, the effect of NH_4 will be short-lived, because of its rapid nitrification.

14.2.2 Soil reaction

– Nitrogen and phosphorus

A study of the relationship between soil pH and the response of maize to nitrogen and phosphorus fertilizers was made in East Africa *(Robinson [1969])*. No relationship of practical significance was observed between topsoil pH in the neutral to acid range and maize yield responses to nitrogen fertilizers, applied at the rates of 45 and 90 N/ha. By contrast, maize yields responded to phosphorus fertilizer, applied at the rates of 45 and 90 kg P_2O_5/ha, in relation to changes in the pH range from acid to neutral. The yield responses to phosphorus fertilizer decreased as the topsoil pH value approached neutrality *[ibid.]*.

The reasons for reduced response of maize to phosphorus fertilizer with increasing pH in the acid to neutral range are assumed to be related to the increased availability of native phosphorus. *Birch [1952]* has shown that the lower the base saturation and hence pH value in the soil, the higher is the response to fertilizer phosphorus.

In the pH range of 4.0–6.0 or higher, exchangeable calcium has the effect of holding appreciable amounts of phosphorus in a readily accessible form for plant use *(Allison [1943])*.

In East African soils, a high proportion of the total soil phosphorus is present in the organic form *(Friend and Birch [1960])*. Higher soil pH values favour mineralisation of the organic phosphorus and thereby increase the amount of phosphorus that the plant can derive from the organic complex in the soil *(Thompson et al. [1954])*.

– Potassium

Many investigators have reported a general lack of response to potassium by plants grown on acid soils. Potassium when applied without limestone to maize grown in rotation with other crops was even found to cause a decrease in yields *(Williams et al. [1942])*.

Many conflicting reports on the effect of pH on the availability of potassium have been published. When the soil is limed before potassium fertilizer is applied, the

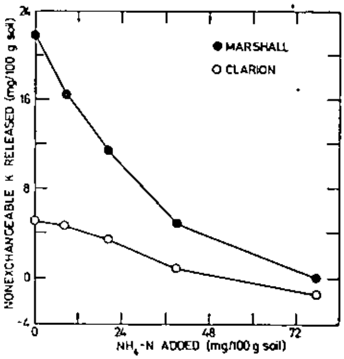

Fig. 143 Nonexchangeable potassium released by two soil types during a 10-day cropping period as influenced by the amount of added NH_4^+ *(Welch and Scott [1961])*. By courtesy of the Soil Science Society of America.

availability of the potassium to the crop may be greater than when the liming occurs after fertilizing. According to *Hanna and Hutcheson [1968]),* in the former cases calcium ions enter the exchange complex, from which they are more easily displaced by potassium than would be the case with the original H^+ and Al_3 ions. The potassium absorbed by the exchange complex remains available to the crop.

– *Secondary nutrients*

The availability of calcium and magnesium in slightly acid to alkaline soils is generally satisfactory. With pH above 8.5, sodium alkalinity reduces the solubility of calcium and magnesium compounds.

The influence of applied sulphur on soil properties and on the availability of soil nutrients for maize was investigated in the greenhouse in soils ranging from acid to calcareous. Increasing rates of sulphur application resulted in sharp reductions of soil pH in the neutral and acid soils. On the calcareous soil, sulphate production was rather limited and consequently the reduction in pH was small. Residual soil nitrate was decreased by increased S applications, probably because the greater resulting acidity inhibited nitrification *(Hassan and Olson [1966]).*

– *Micronutrients*

In investigations in New Jersey on the capacity of ten important soil types to provide micronutrients to maize, it was found that whilst the total supply of micronutrients in the soil has a definite bearing on the amounts taken up by the maize plant, factors which influence the available state, such as pH and solubility, were more important in regulating absorption. For example, the lowest uptake of molybdenum occurred on a soil which had the highest total supply of this element, but had a very low pH, causing low availability of Mo *(Prince [1957]).* However, molybdenum is the only micronutrient that decreases in solubility with decreasing pH.

Iron, copper, manganese, zinc, boron and chlorine become more available with increasing acidity. The most frequent alkalinity-induced deficiencies are of zinc and iron. When large amounts of phosphorus fertilizers are applied, these deficiencies may become severe (c. f. pp. 225—7) *(Hanna and Hutcheson [1968]).*

On acid soils, Fe and Al_3 react with phosphorus to form relatively insoluble compounds; on calcareous soils, calcium may have a similar effect.

Different nitrogen carriers influence the response of maize to Zn, primarily by altering the soil pH. Thus, applying Zn together with anhydrous NH_3, which causes an alkaline reaction, reduces the efficacity of the Zn fertilizer in correcting Zn deficiency. Similarly, band application of Zn together with certain macronutrient fertilizers, that increase soil pH in the band, may result in reduced Zn effectiveness *(Giordano et al. [1966]).*

14.2.3 Soil texture

Because of differences in their inherent physical, chemical and biological characteristics, each soil responds differently to fertilization, and is generally characterized by its potential yield level. Even when an adequate supply of plant nutrients is added, inherent differences in soil characteristics will affect plant response to climatic and edaphic factors.

In an investigation in Tennessee on the productivity of four selected soils in terms of maize yields, it was shown that the plant population and fertilizer combination resulting in the highest yield was different for each soil *(Russ and Bell [1962])*.

The soil colloids play a central role both in the exchange capacity of the soil and in determining its physical characteristics. Hence the many interactions between soil texture and the availability of plant nutrients. The need to adjust K fertilizer rates to the clay and silt contents of the soil has been discussed on p. 119.

The K–content of maize leaves is highly correlated with the exchangeable K-content of samples taken from the 0–15 cm soil layer. However, this relationship is very different for fine-textured soils and for coarse-textured soils. The leaf K contents of plants grown on loams and sands are much higher than those from plants grown on silty loams and silty clay loams, indicating a higher level of K availability in the coarse – textured soils *(Hanway et al. [1962])*.

The effect of soil texture on losses by leaching, and hence on the need to adjust the time of application of fertilizers, in particular nitrogen carriers, has already been discussed in chapter 13.

14.2.4 Nutrient levels in the soil

Maize absorbs a relatively high proportion of its phosphorus requirements from fertilizer in the early stages of growth and only small amounts in the later part of the growing period. The percentage of fertilizer P absorbed by the plants increases with rate of application, but the shape of the absorption curves is not changed appreciably **(Figure 144)**. The more native soil P is present, the lower the percentage of uptake of fertilizer P *(Nelson et al. [1947])*.

14.2.5 Soil salinity

Salinity affects plant nutrition by increasing the osmotic pressure of the soil solution and by altering nutrient uptake. Both these effects have relevance to the response of maize to fertilizers applied under saline conditions.

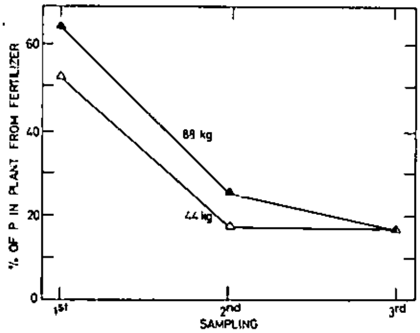

Fig. 144 Effect of rate of P fertilizer application on the percentage of fertilizer P absorbed by the plants *(Nelson et al. [1947])*. Note that the shape of the absorption curves is not changed appreciably. By courtesy of the Soil Science Society of America.

Many experiments have shown that the concentration of the soil solution is more important than its composition in its effect on water uptake and plant growth. Solutions of sucrose, mannitol, sodium sulphate, sodium chloride, and calcium chloride of the same osmotic potential, reduced water absorption by maize roots to the same extent *(Hayward and Spurr [1943])*.

In greenhouse trials, increasing soil salinity, in the range of EC values from 0 to 16 mmhos/cm of the soil solution at field capacity, was found to cause a significant decrease in the production of dry matter by the leaves, stems and tassels of maize **(Figure 145)**. The uptake of P, K, Ca, Fe and Mn was significantly reduced by increasing salinity; that of Na was increased *(Hassan et al [1970])*. Soil salinity therefore has a depressing effect on nutrient utilization in addition to causing toxicity and reducing water availability.

In humid regions, fertilizers will rarely have a markedly adverse effect on crop growth as a result of an increase in the osmotic pressure of the soil solution. The situation is different in dry regions; as the soil dries, the osmotic pressure of the soil increases, and will eventually reach a level that adversely affects plant growth. This effect is felt sooner, the higher the concentration of salts in the solution. Soluble salts from fertilizers may accumulate, especially in semi-arid climates in which low rainfall and high evapotranspiration are the rule. Even under irrigation, moisture levels fluctuate from high to low between irrigations, and an increase in osmotic pressure of the soil, resulting from the heavy applications of fertilizers characteristic of irrigation agriculture, may have a detrimental effect on crop production.

The foregoing is no reason for renouncing the benefits of fertilizer application, but further underlines the need for adjusting fertilizer supplies to the moisture regime of the soil and vice-versa.

Fertilizers differ considerably in their effect on the salt concentration of the soil solution. High-analysis fertilizers generally have a lower salt-index* per unit of plant nutrients than do lower-analysis fertilizers. For example, the salt index per unit of plant nutrients for three representative nitrogen carriers are shown in Table 68 *(Rader et al. [1943])*.

Table 68. Salt index of three nitrogen carriers

	Salt index	in %
Sodium nitrate	6.060	100
Ammonium sulphate	3.253	53.6
Anhydrous ammonia	0.572	9.4

In brief, low-analysis potassium and inorganic nitrogen carriers will generally cause the greatest increase in osmotic pressure of the soil solution, whilst phosphate carriers, urea and ammonia will have relatively little effect in this respect *[ibid.]*.

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* Salt index: ratio of increase in osmotic pressure produced by a fertilizer, in relation to that produced by the same weight of sodium nitrate, based on a relative value of 100.

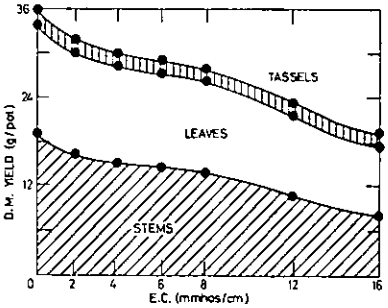

Fig. 145 Effect of soil salinity on dry matter production by maize *(Hassan et al. [1970])*. By courtesy of the American Society of Agronomy.

– *Effect of fertilizers under saline conditions*

In general, salinity causes decreased yields of crops, but for a given level of salinity there is usually an increase in yield as a result of fertilizer application.

In a study by *Khalil et al. [1967]* on the effect of fertilizers on yield and on the nutrient content of maize grown under different soil salinity levels, it was found that salinity (a) did not have a marked effect on N uptake, (b) caused a reduction in P uptake proportional to the reduction in root growth, and (c) reduced K uptake to a greater extent than plant growth. A plant grown on a saline soil may therefore have a higher N content, a similar P content and a lower K content than when grown on a non-saline soil. This situation leads to nutrient imbalance in addition to a reduction in the total amount of nutrients absorbed because of osmotic stress. As a result, utilization of absorbed nutrients will probably be inefficient and a poor response to fertilizer application will be obtained under saline conditions. For example, maize response to N applications was reduced to 79, 71 and 67 per cent of the nonsaline soil for increasing levels of soil salinity of 5, 7 and 9 mmhos/cm respectively. However, in spite of salinity, marked yield increases can be obtained by the application of fertilizers **(Figure 146)**.

The total nitrogen requirement for a crop on a saline soil may be similar to that of a nonsaline soil, but it may be advisable to apply the N in a number or dressings in order to avoid sudden excessive increases in the osmotic pressure of the soil solution. Rates of phosphorus application may have to be increased with salinity, in order to compensate for the decrease in P availability associated with the reduced root system, and rates of potassium applications be increased in order to increase the ratio of K to competing ions at the root absorption sites.

The response of maize grown in lysimeters on calcareous loam to irrigation with saline water at 1, 2 or 3 atm. osmotic pressure and sodium-adsorption ratios *(SAR)* of 2.7, 19.3 or 51.2, was investigated. When compared with the unfertilized control at the lowest salinity and SAR, fresh-weight yields were increased by up to 18% by ammonium nitrate at 2.7 SAR, irrespective of salinity; at the other SARs, nitrogen raised yields by up to 18% at 3 atm. and by greater proportions at lower salinities *(Abdel Salem and El Nour [1965])*.

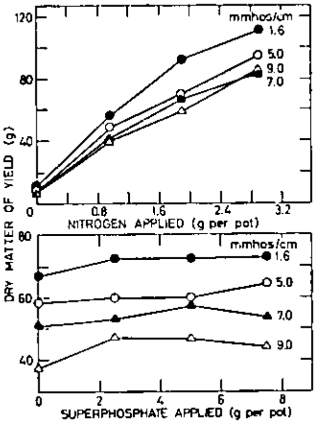

Fig. 146 Effect of fertilizers on dry matter yield of maize at different salinity levels *(Khalil et al. [1967])*. Top: Effect of N applications. Bottom: Effect of P applications. Note that even under saline conditions, marked yield increases can be obtained by fertilizers. By courtesy of the Soil Science Society of America.

14.2.6 Biotic factors

Mycorrhizal fungi grow in association with the roots of certain plants and help them to dissolve and absorb mineral nutrients from the soil. There are not many cases in which such a symbiotic relationship with crop plants has been proven *(Hanna and Hutcheson [1968])*.

In experiments with phosphorus sources of different availability, *Murdoch et al. [1967]* found that maize plants infected with a mycorrhizal fungus grew as well as non-mycorrhizal maize when an available source of phosphorus was supplied. When the phosphorus source was only slowly available, mycorrhizal maize had a much higher P content and grew much better than non-mycorrhizal maize.

14.2.7 Soil temperature

Crops that are indigenous to warm climates, such as maize, are particularly sensitive to low soil temperatures.

The interactions among air temperature, soil temperature and starter fertilizer effects was studied by *Ketcheson [1968]*. A significant interaction was found among these three factors. The highest yield of grain was obtained from the combination of low* air temperature (22–16 °C) and high soil temperature (21 °C). Fertilizer increased yields in all temperature treatments except high air temperature (26–16 °C) and high soil temperature. While the most pronounced response to fertilizer was in the high air temperature – low soil temperature treatment, this was the temperature combina-

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* Low in the sense that it was the lower treatment tested.

tion that gave the lowest yields. The yield with this combination when fertilizers were added was still below that for other temperature treatments.

There is reason to assume that the growth depressions observed under conditions of low soil temperatures are the result of a restricted uptake, translocation and/or assimilation of plant nutrients. Restricted uptake of nutrients may reflect changes in availability of the nutrients in the soil or it may be due to differences in the absorption ability of plants grown at different soil temperatures.

Cold spells in early spring cause a retardation of growth of maize and a purpling of the leaves. The latter is generally considered to be an indication of P-deficiency, hence the assumption that low root-zone temperatures may affect the growth of the young plants indirectly by reducing the supply of phosphorus to the plant. The reduced supply of phosphorus may be due either to inadequate mineralisation of organic phosphorus in the soil, or to restricted uptake and translocation of phosphorus by the plant itself.

In a greenhouse experiment, the interrelationship between soil temperature (15, 20 and 25 °C) and phosphorus uptake by maize was investigated. On two soils, one acid and the other neutral, it was found that P uptake by the plants increased with increasing soil temperature.

Although there was a marked yield response to P, the addition of fertilizer P did not completely alleviate the harmful effects of low soil temperature, as measured by growth, P uptake or P-content of the plants. It was therefore assumed that the reduced P-uptake was due mainly to a depression in root growth, induced by the low root zone temperature *(Knoll et al. [1964])*.

It has been established that there is a general relationship between soil temperature and nitrification rates. The latter decrease with diminishing soil temperatures; however, the relationship is not linear over the entire temperature range. Complete inhibition is not attained until soil temperatures approach the freezing point *(Sabey et al. [1956])*.

The response of maize to potassium fertilization was found to be very different in two soils, although they had very similar levels of available potassium, as indicated by soil tests. On the one soil, yields were increased by 3300 kg/ha by an application of 165 kg/ha K_2O in conjunction with 88 kg/ha N and 132 kg/ha P_2O_5, whilst on the other soil the increase was only 1710 kg/ha. The higher response was obtained under cold, wet growing conditions and the lower response on a warm soil with a favourable moisture regime. These results confirm that low soil temperatures and excessive moisture reduce the availability of potassium to plants *(Caldwell and Hovland [1961])*.

Other investigations confirm these findings:

In young plants of maize grown in sand and solution cultures, the maximum uptake of NH_4^+, K^+, NO_3^- and PO_4^- was observed at temperatures ranging from 27 to 30 °C, 25 to 28 °C, 29 to 32 °C and 23 to 27 °C, respectively *(Gvozdikovskaya and Parshikov [1969])*.

In field experiments with maize grown on a silt loam, it was found that the uptake of nitrogen, phosphorus, potassium, calcium and magnesium usually increases with increases in soil temperature to at least 19 °C *(Nielsen et al. [1961])*.

Grobbelaar [1963] also found that root temperatures affected the uptake of nitrate, phosphorus, potassium, calcium and magnesium **(Figure 147)**. Low temperatures

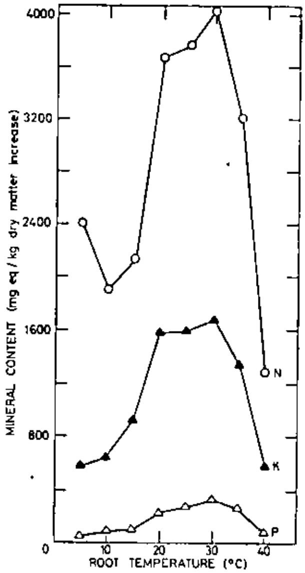

Fig. 147 Uptake of N, P, and K per unit increase in total dry weight (shoots + roots) during an exposure period of 14 days to a range of root temperatures *(Grobbelaar [1963])*. Note that both excessively low and high temperatures reduce the uptake of N, P, and K. By courtesy of the University of Wageningen.

(5–15 °C) and excessively high temperatures (40 °C) reduced the uptake of nitrogen, phosphorus and potassium. At temperatures of 20–35 °C, there were indications of a luxury accumulation of nutrients by the root. The retarded rate of uptake of mineral nutrients both at low temperatures and too high temperatures did not appear to be the primary cause of the retarded growth rates recorded at these temperatures. The basic reason appeared to be a decrease in absorption of water by the roots, with a concomitant increase in the internal pressure deficit of the plants *(Grobbelaar [1963])*. Relative fertilizer effects are generally greatest with temperature conditions giving the lowest yields. This was demonstrated by *Ketcheson [1968]* in his working under controlled conditions of soil and air temperatures.

The increased growth of tops and roots of maize with rising temperatures undoubtedly favours a greater uptake of nutrients. High nutrient uptake at favourable soil temperatures is, however, greatly dependent on the addition of adequate amounts of nutrients. For example, the total uptake of phosphorus at 27 °C, by maize supplied only with nitrogen and potassium, was found to be only 10 per cent of that obtained when phosphorus was also added. Conversely, P uptake decreased considerably at lower soil temperatures even when adequate amounts of phosphorus were supplied. Consequently, a favourable soil temperature does not adequately compensate for a low level of nutrients, nor does the addition of nutrients entirely offset the adverse effects of low temperatures *(Nielsen et al. [1961])*.

14.2.8 Soil aeration

An expenditure of energy is required for the plant to take up ions from the external medium against a concentration gradient. This energy is provided by root respiration which, in turn, requires oxygen. Therefore, factors that impair the aeration of the soil, such as water-logging, soil compaction, etc., will have an adverse effect on the uptake of nutrient from the soil, particularly clay soils.

In poorly aerated soils, reductions in yield and absorption of nutrients may be due to a deficiency in oxygen, or to toxicity of carbon dioxide, or to a combination of both factors. Other factors may be involved when poor aeration is due to soil compaction or to water logging, and all nutrients have been supplied in amounts adequate for maximum growth. These may be: restricted aerobic biological activities, limited root growth, the presence of toxic substances, and retardation of physiological processes other than root respiration in the plant, etc. *(Lawton [1945])*.

Not only is the activity of the roots impaired by soil conditions that limit air supplies to the plant, but the structure of the root system and its extension are also affected, as are the weight, number and orientation of its component roots.

– *Supply of oxygen and carbon dioxide*

The composition of soil air is not markedly different from that of the atmosphere, the only important difference being that the former is normally richer in carbon dioxide. However, the carbon dioxide content of the soil air is far from constant. Additions of organic matter to the soil usually result in a rapid increase of carbon dioxide and a parallel decrease of soil oxygen; root respiration has similar effects. Oxygen deficiencies and excessive CO_2 in the root atmosphere have a depressive effect on the growth of most crop plants and their associated microorganisms *(Grable and Danielson [1965 b])*.

When the oxygen content of the soil air falls to below 10 per cent, the root system is usually damaged.

On young maize plants, lack of oxygen in the root medium reduces the growth of the aerial parts by 66 per cent and of the roots by 75 per cent. With more developed plants, the aerial parts and the root system are equally affected by a lack of oxygen *(Périgraud [1967])*.

When the level of oxygen falls to 3 per cent, the roots of most cultivated plant species die *(Grable and Danielson [1965 b])*. Soil air usually contains sufficient oxygen for the vital processes of the plant and soil microorganisms, but air as a whole may be in short supply in compacted soils or in those which are excessively wet.

Investigations in Ohio on the effect of soil aeration on the growth and yields of maize growing on a silt loam, showed that poor aeration reduced the tissue contents of K, Mg, N and P in the tops and increased the contents of these elements in the roots *(Shapiro et al. [1956])*. The investigators therefore concluded that reduced oxygen in the soil air was affecting translocation of ions from the roots to the tops, more than absorption of the ions into the roots themselves.

The effect of an improved oxygen supply on potassium uptake as soil moisture increases, is shown in **Figure 148** *(Danielson and Russell [1957])*.

The best growth of maize was obtained at oxygen diffusion rates of approximately 10 to 12 $g \times 10^{-8}$ per cm^2 per minute *(Bertrand and Kohnke [1957])*.

Similar results were obtained by *Williamson [1964]* who also found that at an oxygen diffusion rate of approximately 30 × 10^{-9} per cm^2 per minute, which indicates conditions of very poor aeration, yields were reduced by about 75 per cent **(Figure 149).** *Grable and Danielson [1965 a]*, who investigated the effect of various concentrations of CO_2 on the germination of maize, reached the conclusion that the danger of injury during germination of maize due to excessive CO_2 concentrations in the soil, has probably been overestimated. They found that maize during germination tolerated, and sometimes was even stimulated, by CO_2 concentrations higher than those normally found in soils. Adverse effects on germination of excessive soil moisture were ascribed to reduced O_2 diffusion rates, rather than to excess CO_2 concentration.

Growing maize plants were also tolerant of high CO_2 concentrations, and grew satisfactorily for several days when tops, roots or both received 20 per cent or more

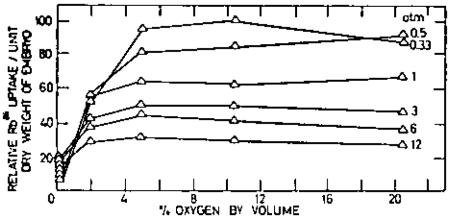

Fig. 148 The effect of oxygen level and soil moisture tension on Rb^{86} uptake by maize seedlings *(Danielson and Russell [1957])*. Rb^{86} is used for convenience, because of the great similarity in its activity to that of K. By courtesy of the Soil Science Society of America.

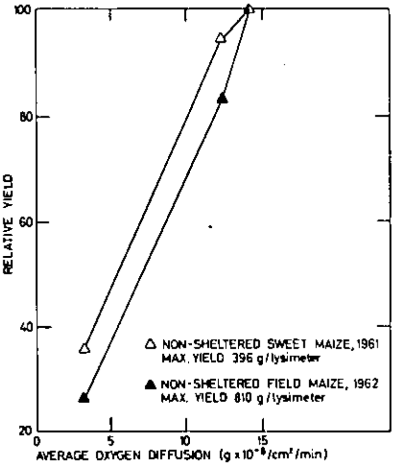

Fig. 149 Relative yield of maize as a function of the average oxygen diffusion rate in the soil above the water table *(Williamsan [1964])*. By courtesy of the Soil Science Society of America.

of CO_2; lesser concentrations of ten stimulated top and root growth as compared with the normal CO_2 concentrations in the air *(Grable and Danielson [1965 b])*.

Nonphotosynthetic uptake of CO_2 by maize root tips has been shown to occur, and the presence of CO_2 is apparently necessary for optimum root growth *(Danner and Ting [1967])*.

14.2.9 Effects of soil compaction

In investigations by *Phillips and Kirkham [1962]* on the effects of compaction of a clay soil on the growth of maize, it was shown that compaction reduces stands of maize, and also causes reductions in yield, even after the stands have been equalized. Yields were higher if the maize was fertilized, but no interaction between fertility level and compaction was observed in the trials. In other words, compaction reduced yields about equally on fertilized and unfertilized soils. The yield reductions were ascribed to mechanical impedance to root growth, causing a reduction in the amount of roots produced **(Figure 150)** *(Phillips and Kirkham [1962])*.

However, in many other cases, interactions between soil fertility and soil compaction were recorded.

In Uttar Pradesh (India), for example, a progressive decrease in grain and stover yields, in grain protein content and in root weight (per unit area) were noted as soil bulk density increased from 1.28 to 1.59 g/cc. Application of 133 kg N/ha increased grain yield, the increases being higher on normal than on compacted soil *(Modgal and Bhatnagar [1968])*.

In a study carried out by *Bertrand and Kohnke [1957]*, it was shown that dense subsoils may act as effective barriers to normal root penetration of young maize plants. This is not entirely due to mechanical impedance, as penetration was not better in wet, pliable soil than in dry soil. Maize roots grew profusely in a subsoil with a bulk

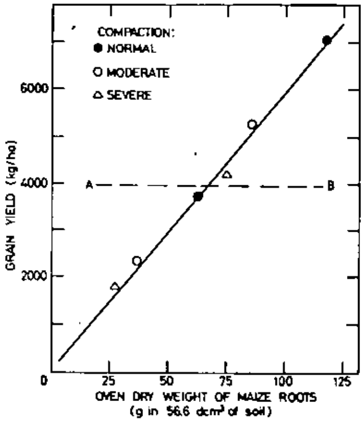

Fig. 150 Effect of compaction of a clay soil on the grain yields of maize *(Phillips and Kirkham [1962])*. The points above the line AB are for added-fertility, below AB for existing fertility. By courtesy of the American Society of Agronomy.

density of 1.2 gm/cc, but did not penetrate the subsoil when it was compacted to 1.5 gm/cc.

Ohlrogge [1962] showed that an extensive root system develops in a fertile soil which has a good physical structure throughout the profile. On soils low in fertility, with a tough impervious subsoil, the root system is shallow and restricted **(Figure 151).**

A significant interaction was found to exist between compaction and fertilization, indicating that greater utilization of the fertilizer was possible only from the less dense soil. The effect of compaction was greater in moist soil than in relatively dry soil. A combination of loose subsoil, high moisture and subsoil fertilization produced the greatest top and root growth of maize (see Table 69).

Table 69. Effect of degree of soil compaction, moisture and fertilizer application on the growth of maize plants *(Bertrand and Kohnke [1957])*

Soil condition	Weight of tops (g)		Weight of roots (g)		Top: root ratio		Weight of total plant (g)	
	F*	NF**	F	NF	F	NF	F	NF
Loose, wet	39.4	23.5	14.8	10.1	1:0.38	1:0.43	54.2	33.7
Loose, dry	27.5	20.3	9.3	9.3	1:0.34	1:0.46	36.8	29.6
Compact, wet	16.0	17.0	6.5	7.7	1:0.40	1:0.45	22.5	24.7
Compact, dry	20.1	19.3	11.3	9.9	1:0.56	1:0.51	31.4	29.2

* F: fertilized
** NF: not fertilized

Maize has been reported to show serious potassium deficiencies, and possibly other deficiencies too, when grown on heavy glacial till soils compacted by tillage. *Hammond et al. [1955]* have shown that relatively high levels of CO_2 in the soil air in immediate contact with the roots may reduce both root growth and rate of K and water uptake per unit of root surface. The reduced root growth compounds the K-deficiency effect and leads to poor growth and low yields. An additional factor that may be involved

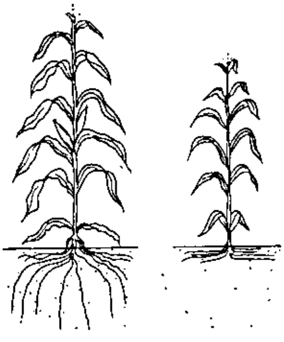

Fig. 151 Effect of soil compaction on the development of the root system of maize plants *(Ohlrogge [1962])*. Left: Root system of plant growing on fertile soil with a good physical structure throughout the profile. Right: Plant growing on soil with tough, impervious subsoil. By courtesy of the Purdue Agric. Experiment Station.

in the case of certain soil types is the antagonistic effect of calcium on K absorption. The application of K fertilizers alleviated the adverse effects of soil compaction.
Experiments conducted on loam and silt soils in Iowa, gave clear evidence that the absorption of potassium by the maize plant is more dependent on soil aeration than is the uptake of N, Ca, Mg, N or P (Table 70) *(Lawton [1945])*. These results explain why large field responses by maize to the application of potassic fertilizers are recorded on poorly drained, dark-coloured soils in Iowa, although they contain a relatively high level of exchangeable potassium *[ibid.]*.

Table 70. Effect of K and soil aeration on cation content and maize yields at 40 per cent soil moisture *(Lawton [1945])*

Nutrient and aeration treatment	Cations K	 Ca	 Mg	 Sum	Corn yield Tops	 Roots
	meq/100 g				g/pot	
NP	24	18	33	75	13.3	5.6
NP+aeration	33	16	29	78	17.3	8.7
NPK	53	24	30	107	18.1	9.0
NPK+aeration	84	16	26	126	27.7	17.8

Bonnie-Baffoe and Blake [1964] studied the effects of various degrees of soil compaction on the dry yield and the uptake of phosphorus and potassium by maize. The dry yield and phosphorus and potassium content of the seedlings were found to decrease as bulk density increased.

14.2.10 Soil moisture

One of the basic problems in plant nutrition is that of adjusting fertilizer applications to the moisture regime under which the plants are expected to grow. This is true for both rain-fed and irrigated maize. Basically, the problem is one of nutrient-soil moisture interactions. At one end of the spectrum, under conditions of sparse rainfall, is the need to limit fertilizer application to rates which will not promote more growth than the available soil moisture can sustain until harvest, or in other words to prevent upsetting the very delicate and critical balance between vegetative and reproductive growth under conditions of limited moisture. At the other end of the spectrum, when the farmer controls the supply of water to his crops, his aim is to ensure a level of nutrient supply that will enable the plant to make full and efficient use of the favourable moisture conditions it enjoys **(Figure 152)**.

The effects of moisture supply and nutrient supply on the crop are extremely interdependent: nutrient deficiencies can restrict root growth, so that water absorption from the soil is reduced, but they also restrict vegetative growth, thereby reducing evapotranspiration. The availability of water determines the plant's requirements for nutrients and its ability to absorb them from the soil.

Water uptake by the plant cannot be adequate, unless nutrient salts are taken up at the time in sufficient quantities to maintain osmotic pressure. Conversely, uptake of nutrient salts, without a concomitant supply of water, is not possible. When the salt supply and hence the water supply are not adequate, breakdown of starch into glucose and organic acids occur, so that osmotic pressure is at least partially maintained, at the expence of dry matter production.

When salt uptake is excessive, a similar process occurs, entailing loss of dry matter. Hence the need for a balanced supply of water and nutrients, according to the specific requirements of each species (*Middelburg [1967]*).

Finally, irrigation water may contain appreciable amounts of calcium, magnesium, sulphur and occasionally nitrogen, and may therefore reduce the fertilizer need for these nutrients (*Barber and Olsen [1968]*).

Favourable soil moisture regimes affect the efficiency of fertilizer use in two main ways: by improving the uptake of nutrients and by increasing dry matter production. When considering the effect of soil moisture level on the uptake of nutrients by plants, indirect effects of soil moisture must also be considered, such as the effects on the physiological activities of the plant and its salt and sugar contents, soil aeration and the osmotic pressure of the soil solution (*Brown et al. [1960]*).

Effect of soil moisture on nutrient uptake

The water content of the soil has both short- and long-term effects on nutrient uptake. The short-term effects involve mainly the distribution of ions between the solution and the absorbed phase or solid phase. The long-term effects are related to the distribution of nutrients among the pools of soluble, absorbed and solid forms (*Viets [1967]*).

– Effect of soil moisture on the mechanisms of nutrient uptake

The three mechanisms involved in nutrient uptake have been discussed in Chapter 7. Here, the effect of water supply on these mechanisms will be considered briefly.

a) Effect of moisture regime on the root system – Root growth considerably reduces the distances over which nutrients need to be transported in the soil. Root elongation by maize reaches 5.1 to 6.5 cm/day for three to four weeks (*Weaver [1925]*). The rate of elongation is highly dependent on available water. *Olsen et al [1961]* have shown that the elongation and turgidity of the roots and numbers of root hairs decrease as moisture tension increases (Table 71).

Table 71. Effect of moisture tension on the dry weight of maize roots and the moisture content of fresh roots (*Olsen et al. [1961]*)

Tension (atmospheres)	Dry weight of roots (gm)	Water content of fresh roots (gm H_2O per gm of dry root)
⅓	0.224	9.6
½	0.213	9.3
1	0.185	8.9
3	0.171	7.3
9	0.143	6.0
	LSD (5% level) 0.010	

Gingrich and Russell [1957], in short-term experiments with maize seedlings, found that radicle elongation rate decreased with increasing moisture stress (**Figure 153**).

This relationship was linear when moisture stress was due to osmotic pressure but not when the stress resulted from soil moisture tension. The authors concluded that a change in soil moisture tension resulted in a change in both free energy and rate of transmission to the root, whilst a change in osmotic pressure involved only a change in free energy.

In addition to moisture tension, the actual moisture content of the soil also affects root elongation. In soils with different water holding characteristics, root elongation was found to increase with increasing moisture content at the same tension. The effect of moisture content was considerably greater at 3 and 8 atm, than at $^1/_3$ and 1 atm. *(Peters [1957])*.

A favourable water supply therefore increases the mass and distribution of the root system; actively growing roots will take up more nutrients by exploring a greater volume and depth of soil. Conversely, nutrient deficiencies can restrict root development, so that uptake of water and nutrients may be impaired, especially from the lower soil levels.

The drying of the soil also increases its shear strength and generally increases the mechanical impedance to root penetration, in particular in dense soils *(Barley [1963])*.

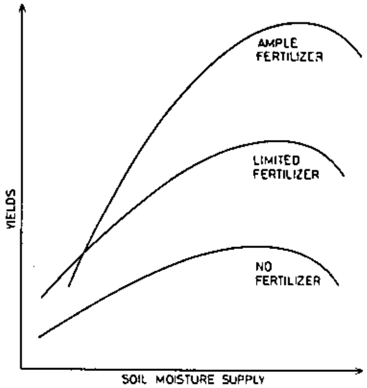

Fig. 152 Schematic graph showing generalized crop response to levels of fertilization in relation to soil moisture regimes.

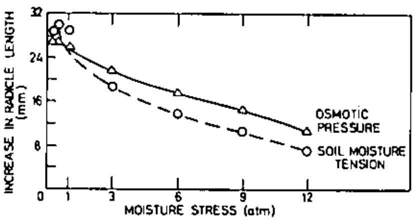

Fig. 153 Effect of soil moisture tension and osmotic stress on the elongation of maize radicles *(Gingrich and Russell [1957])*. By courtesy of the State University New Brunswick, N.J.

b) The flow of soil water transports the more soluble, and therefore mobile nutrients to the roots, along potential gradients for water.
All of the nitrate and chlore, most of the sulphate and part of the boron are in solution and move freely with the soil water. There must be an equivalence of soluble cations to move with them *(Viets [1967])*.

c) Diffusion: The nutrients with limited mobility, such as potassium, calcium, magnesium and ammonia, and the immobile nutrients such as phosphorus, zinc, copper, magnesium and iron, are much less affected, or not at all, by the movement of water in the soil. These nutrients reach plant roots partly through diffusion *(Viets [1967])*.
As plant roots take up the nutrients in their immediate vicinity, the latter may be replaced by ions that diffuse slowly from areas of higher concentrations to the depleted zone around the roots. The distances involved are very small. Autoradiographs of roots of 12-day-old maize plants show zones of depletion of Rb^{86} attributed to diffusion, extending about 5 mm from the root surfaces *(Walker and Barber [1962])*.
Although the distances involved are very small, at most 5–6 mm, this is an important mechanism of nutrient supply to the roots. The diffusion occurs through the films of water surrounding the soil particles. As the soil becomes progressively drier, the water films around the soil particles become thinner, thereby reducing the rate of diffusion of nutrients to the roots **(Figure 154)** *(Place and Barber [1964])*.

– *Effects of moisture on the uptake of individual nutrients*
As a rule, decreasing soil moisture supply is associated with an increase in nitrogen content, a decrease in potassium content and a variable effect upon the contents of phosphorus, calcium and magnesium in the plant tissue *(Richards and Wadleigh [1952])*.

a) Nitrogen
In Mexico, *Laird et al. [1969]* studied the response of maize to increasing levels of nitrogen under conditions of increasing drought severity. The results are shown in **Figure 155.** When drought was severe, yields declined when more than 40 kg/ha of N were applied; with no drought, yields increased almost linearly with increasing levels of nitrogen, up to the highest amount tested – 120 kg N/ha.
In experiments in the northern Negev *(Shimshi [1966])*, the effect of different moisture regimes on the efficiency of uptake of fertilizer-N was ascertained. The results are presented in Table 72.

Table 72. Effect of moisture regime on uptake of fertilizer-N: Ratio of N-uptake × 10^2 to evapotranspiration *(Shimshi [1966])*

No. of irrigations	Integrated moisture stress	Nitrogen levels (kg/ha) 0	52.5	105	210	420
2	2.0	9.4	17.4	29.2	37.4	31.5
3	1.5	9.2	18.5	30.0	36.8	45.1
4	1.0	9.0	17.3	29.4	35.0	48.2
5	0.5	8.4	16.7	26.9	34.8	40.7
9	0.2	6.1	10.7	19.1	26.2	33.6

At any given fertilization rate, the ratio between nitrogen uptake and evapotranspiration is remarkably constant in all the moisture regimes except for the wettest one, for which the ratio tends to be lower. A comparison of nitrogen uptake with the amount applied in the fertilizer (see Table 72) indicates that the utilization of nitrogen was almost complete in the wet treatments, except at the highest fertilization rate; here, a somewhat lower utilization rate (about 60 per cent) may be attributed to early loss of nitrogen through volatilization. As the soil moisture stress increases, a smaller proportion of the applied nitrogen is taken up by the crop; this tendency begins at lower soil moisture stress in the heavily fertilized plots, and is less pronounced in the nitrogen deficient plots.

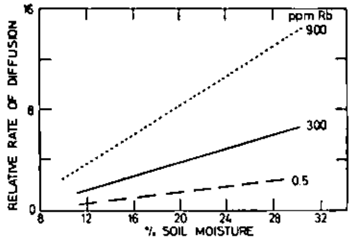

Fig. 154 The effect of soil moisture on the rate of diffusion of rubidium (an element similar to potassium), at three levels of applied rubidium *(Place and Barber [1964])*. By courtesy of the Soil Science Society of America.

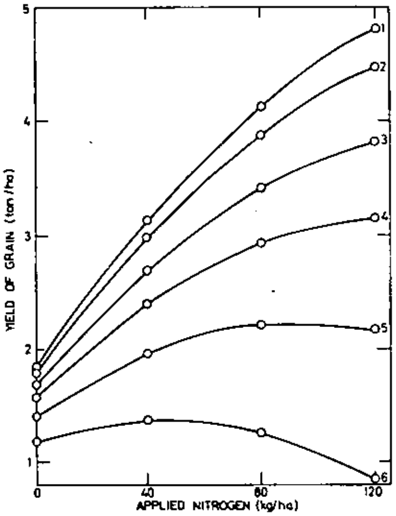

Fig. 155 Yield curves of maize estimated from a general yield function for six degrees of increasing drought severity, as related to increasing levels of N fertilization *(Laird et al. [1969])*. By courtesy of CYMMIT. Centro de Investigaciones Agricolas del Noreste, Sonora, Mexico.

b) Phosphorus

Uptake of phosphorus by maize plants has been found to be a linear function of the soil moisture content for a given soil **(Figure 156)** *(Watanabe et al. [1960])*.

The thickness of water films on the soil particles, the diffusion path length, the degree of hydration and the elongation of the roots are factors that are apparently involved in the relationships between soil moisture and phosphorus uptake.

The effects of moisture tension on P-uptake are also influenced by the concentration of phosphorus **(Figure 157)**. This points to some important practical implications. At low levels, an increase in available water to $^{1}/_{3}$ – bar tension increased P-uptake from 1.4 to 3.4 ug. per g of roots, whilst at high phosphorus levels the P uptake increased from 8 to 23 ug. Consequently, for a crop subjected to alternate periods of low and high amounts of available water – a normal situation for a summer crop like

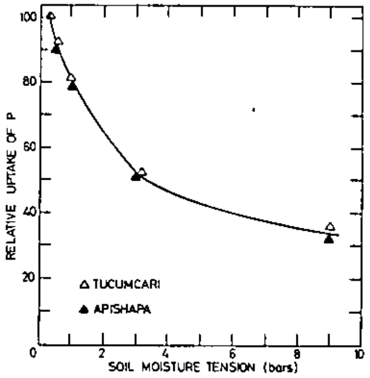

Fig. 156 Relative uptake of phosphorus by maize seedlings in relation to soil-moisture tension for two soils *(Watanabe et al. [1960])*. By courtesy of the Elsevier Publishing Company.

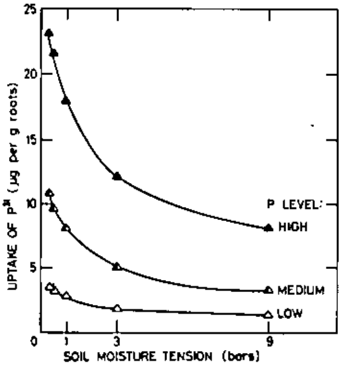

Fig. 157 Effect of P level and moisture tension on P uptake by maize seedlings *(Olson et al. [1961])*. By courtesy of the Soil Science Society of America.

maize – the high P level could ensure a more or less adequate supply of P to the plants, whereas P deficiencies would occasionally occur at times when only low P rates were applied *(Olsen et al. [1961])*.

c) Potassium

Several research workers, working under a wide variety of conditions, report that potassium availability increases as soil moisture tension decreases. The results obtained by *Barber [1959]*, who found a correlation of 0.97 between relative yield without potassium and the amount of precipitation during the active growing period of maize (June-August), are shown in **Figure 158.** It is assumed that in years of high rainfall, the top soil layer, which is relatively rich in available potassium, remains more continuously moist and therefore potassium supply is sustained at a satisfactory level.
In a study of the relation between soil moisture content and potassium uptake by maize, *Mederski and Stackhouse [1961]* found that for each of the three levels of available soil K that were tested, the concentration of potassium in the leaves generally increased with increasing soil moisture, indicating the existence of three distinct levels of K availability, depending on the soil moisture regime.
In **Figure 159a**, it can be seen that the increase in the concentration of K in the leaves, when soil moisture increases from 9 to 16 per cent, is greater at the K_2 level than at the K_0 and K_1 levels of available K in the soil. The effect of increasing the levels of applied potassium on K concentration in the leaves is also greater at the higher moisture levels. These interactions indicate that soil potassium and soil moisture levels have an interdependent effect on K uptake by the plants.
It will be observed that leaf content of K is approximately the same for the combination of high moisture level and low potassium level as for low moisture level and medium K level.
These results may help to clarify the observation made under field conditions that the relative response of maize to potassium fertilizer is usually larger under conditions of relatively limited soil moisture supply. **Figure 159b** shows that at a low soil moisture level, the concentration of K in the leaves may be suboptimal, whilst at the higher soil moisture level K may actually reach optimum concentration, without any addition of fertilizer K. It is therefore clear that K fertilization may raise the K leaf concentra-

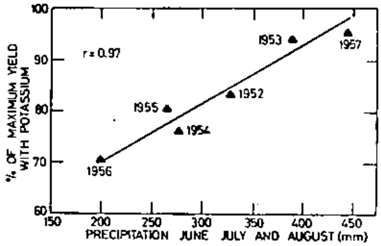

Fig. 158 Relationship between the precipitation for June, July and August and the relative yield of maize without potassium *(Barber [1959])*. By courtesy of the American Society of Agronomy.

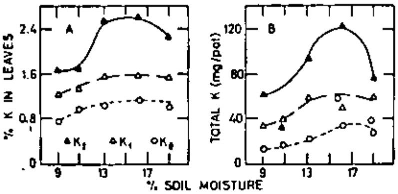

Fig. 159 Effect of interrelationships between soil moisture content and levels of available soil K on (A) K-leaf content, and (B) total K in maize leaves *(Mederski and Stickhouse [1961])*. By courtesy of the Elsevier Publishing Company, Amsterdam.

tion to the optimal level, when the plants are grown with limited moisture, without having a similar effect on plants grown with a high moisture supply.

Therefore, one of the reasons for limited plant growth as a result of high soil moisture tension may be the reduced K uptake, when the levels of available K in the soil are low. This may explain the results obtained by *Barber [1959]* mentioned above.

The total amount of K absorbed by the plants generally increases with improved soil moisture regimes at all levels of soil K. The decrease in total K observed at the highest level of moisture, is the result of decreased dry-matter production.

A number of reasons for increased K-uptake with increasing levels of soil moisture have been proposed. *Schuffelen [1954]* suggests that Donnan effects are responsible (cf. p. 138). *Danielson and Russell [1957]* conclude from their investigations that at a low moisture content, a discontinuity of moisture films may impede the transfer of K from the soil to the root.

Not one but several factors may be involved in the effect of moisture availability on changes of K uptake. The fact that K uptake is related to moisture supply indicates that a relatively large proportion of the K absorbed by plants may be derived from the soil by means other than direct contact exchange. A considerable proportion of the K may be absorbed from the solution phase, with the quantity and mobility of the solution determined by soil moisture content.

d) Micronutrients

The micronutrient cations Zn, Cu, Co, Mn and Fe are so tightly held in well aerated soils, except quartz sands, that there is practically no movement in the soil by water of these elements *(Viets [1957])*.

Little is actually known of the effect of moisture regime on the uptake of micronutrients, although certain findings indicate that it may be important. For example, it is known that drought may cause temporary deficiencies of boron. This may be due to the reduced decomposition of organic matter which normally releases boron, or to reduced boron uptake as a result of the drying out of the upper soil layers in which the main activity of the roots is concentrated.

– Summary

The general conclusion can therefore be drawn that when the soil moisture supply is favourable, the ability of the soil to supply nutrients, and of the plant to absorb them, is optimal, and therefore nutrient availability is at its highest level *(Viets [1967])*.

14.2.11 Nutrient uptake under conditions of excess water

Nutrient uptake under conditions of poor drainage and high water table is influenced by both soil and plant factors. In wet soils, reducing conditions prevail, which increase the solubility of heavy metals such as Al, Fe, Mn and Mo, reduce nitrates to N gases; change the soil pH with a concomitant number of biochemical changes which depend on soil pH *(Lal and Taylor [1970])*.

Undesirable biological activity occurs, causing toxic concentrations of methane, hydrogen sulphide and other substances. Hence, root development slows down and may even cease. Root respiration, essential for certain metabolic processes, is adversely affected, thereby further curtailing nutrient and water uptake; in particular, the uptake of potassium and phosphorus is severely curtailed under these conditions *(Périgraud [1967])*.

In a study of the effect of drainage on maize nutrition, *Lal and Taylor [1970]* found that root hairs were suberized by an excess of CO_2, decreasing the permeability of the roots to water and nutrients; translocation of nutrients within the plant was also probably inhibited because of an indequate supply of oxygen to the root. In brief, improved soil drainage was found to increase the uptake of N, P, K, Zn, Cu, B and Sr, but to decrease the uptake of Al, Fe, Mn and Mo. The leaf concentrations of Ca and Mg were not affected. Based on the results obtained in this study, a qualitative diagram showing the relation between the uptake of 13 nutrients by maize at varying soil drainage levels is given in **Figure 160.**

A high water table also reduces the soil volume from which the roots can take up nutrients.

In research at Cornell University, *Shalhevet and Zwerman [1962]* evaluated the interactions between soil drainage and response to nitrogen of maize grown in lysimeters. Under anaerobic or partially anaerobic conditions, losses of nitrogen by volatiliza-

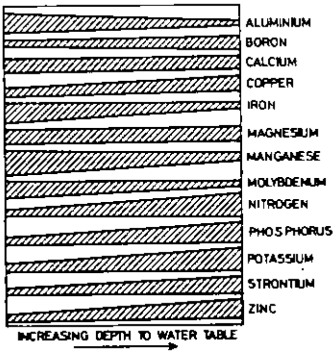

Fig. 160 Diagram showing qualitative relation between drainage status and nutrient uptake by maize *(Lal and Taylor [1970])*. The width of each band indicates the relative uptake of the element. The nutrient concentration at the extreme left side corresponds approximately to the nutrient content of the intermittently flooded plants; whereas that at the extreme right side approximates the nutrient concentration of the plants grown in well drained lysimeters. By courtesy of the Soil Science Society of America.

tion or leaching were rapid. The addition of nitrogen to a continuously saturated silt loam increased grain yields significantly, but the final yields were still well below those of a well-drained soil. Under these conditions nitrate-N was somewhat superior to ammonium-N, probably because of the more rapid uptake of the former. The uptake of phosphorus and potassium was limited only under conditions of continuous saturation; where the poor aeration was not so extreme, uptake of these two nutrients was normal. The authors conclude that the most important reason for poor growth and reduced yields on poorly drained soils is the lack of oxygen, which may incidently reduce the uptake of plant nutrients. However, even in the presence of an adequate supply of plant nutrients, yields on poorly drained soils were still lower than those of plants growing on well-aerated soils. No symptoms of toxicity due to water logging were observed.

The effects of various drainage systems and different levels of nitrogen on maize yields were evaluated for a fine-textured soil in Ohio, during a period of three years. Yields of maize growing on undrained plots were consistently lower than those for the three systems of drainage tested (**Figure 161**). In this trial the relative response of maize on undrained land to low levels of N was lower than that of maize on drained land. At the higher levels, response to N was similar in all treatments tested. The uptake of N, P, K, Cu, Zn and Sr was significantly greater and that of Fe, Al and Mo lower, for maize grown on drained land than on undrained land. The high uptake of Fe and Al in the undrained plots can be ascribed to the increased solubility of these two ions under the anaerobic conditions which prevailed on these plots during periods of excessive soil wetness *(Schwab et al. [1966])*.

On deep tropical black clay soils, high water tables generally occur after each rain, as a result of poor drainage. The high water tables and a lack of available nitrogen limit the growth of maize and reinforce the deleterious effects of each other. Trials on these soils have shown that placement of sufficient fertilizer nitrogen near the soil surface

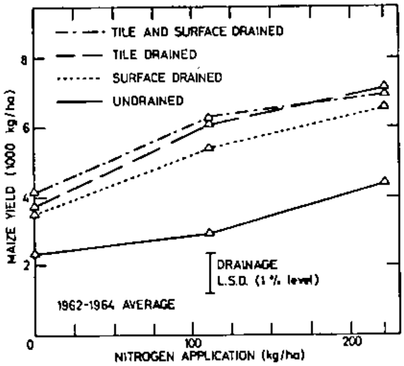

Fig. 161 Effect of drainage at different levels of nitrogen application on grain yields of maize grown on a fine-textured soil in Ohio *(Schwab et al. [1966])*. By courtesy of Soil Science Society of America.

and well above the highest water table solves this problem and enables excellent growth of maize. The investigators suggest that where other nutrient deficiencies occur on poorly drained soils, shallow placement of the required fertilizers may also help to overcome the deleterious effects of high water tables *(Jelley and Kerkhoven [1965])*.

14.2.12 Specific effects of rainfall

The interrelationships between the moisture regime in the soil and fertilizer use by maize, and in particular the need to achieve a critical balance between moisture regime and nutrient supply, have already be discussed on pp. 335—42. Wherever maize is grown as a rain-fed crop, critical periods generally occur during most growing seasons, when the lack of available moisture limits the maximum yields of heavily fertilized maize. It is these critical periods which are the main distinguishing feature between moisture regimes resulting from irrigation and from rainfall, respectively.

– *Nitrogen*

In Iowa, the variability of yields of maize from year to year is greater with an ample supply of nitrogen than when nitrogen is deficient. Heavy fertilization with nitrogen promotes much higher yields in years with ample rainfall but not in dry years. Conversely, adequate rainfall promotes much higher yields if the nitrogen supply is ample, but has little effect on yields under conditions of nutrient deficiency *(Black [1966])*.
The response of maize to fertilizers during dry seasons was found to vary. Occasionally, fertilization reduced yields, when vegetative growth early in the season had been excessive. In most cases, however, moderate amounts of fertilizers either gave small increases or had no effects. The main factor ensuring succes of the crop, and hence response to fertilizer, was the amount of water stored in the soil prior to sowing. When this is adequate, good crops can be obtained even when rainfall is low during the growing season. For example, yields were increased from 1217 to 4064 kg/ha by an application of 132 kg N/ha (in addition to adequate amounts of phosphorus and potassium) in a year of below-average summer precipitation.
Fertilized maize withdrew water from the soil down to a depth of 210 cm, whilst the unfertilized maize exploited only 150 cm of the soil. The amount of extra water obtained was 100 mm; the fertilized maize produced more additional grain per mm of water than did unfertilized maize *(Pesek et al. [1955])*.
In regions with long, dry spells during the summer months, a particular form of nitrogen deficiency is frequently encountered in the maize crop. It has even been observed that most of the nitrogen applied in spring is still present in autumn in the top few centimetres of the soil. The drying of the soil apparently caused an upward movement of nitrates, at the time the roots were penetrating more deeply in the soil, causing a so-called 'positional' deficiency of nitrogen, the ill-effects of which become most apparent at the time of ear formation *(Soubiès et al. [1956])*.

– *Phosphorus*

In dry seasons, phosphorus is less available to plants than in wet seasons, so that much larger applications of fertilizer are required to achieve the highest possible yield levels. The effect of drought on the response of maize to phosphorus was studied on a silt loam in Virginia. The response to phosphorus continued up to a rate of 110 kg P_2O_5/ha in the dry years, whilst the highest yields were obtained with 55 kg P_2O_5/ha in the wet years (Table 73) *(Jones [1964])*.

Table 73. Effect of drought on response of maize to phosphorus *(Jones [1964])*

Phosphorus applied (P_2O_5 kg/ha)	Average yields (kg/ha) Two favourable years	Two low rainfall years
0	4000	1840
27.5	6280	3050
55	6840	3680
110	6540	4190

In dry years, starter fertilizers containing phosphorus often give unsatisfactory results on soils of high inherent P supply. This has been attributed to overstimulation of early growth, which accentuates the damage caused by drought that occurs at later stages of growth. In other cases, the earlier physiological maturity was disadvantageous, when the critical stage of the reproductive cycle coincided with hot, dry weather *(Ward et al. [1963])*.

– *Potassium*

The relative response of maize to applications of potassium fertilizers has been shown to change from year to year. A very high correlation (0.97) was established between the per cent of maximum yield* and the summer rainfall (June–August) (cf. pp. 15—16). Apparently soil potassium is more available in years of high summer rainfall *(Barber [1959])*. However, this correlation does not necessarily show a causal relationship, as other factors such as light duration, light intensity and temperatures may be involved. *Barber* points out that it is possible that the relationship may be due to the root zone from which the plants absorb potassium. In years of high rainfall, root activity of the plants will be concentrated in the upper soil layers, whilst in relatively dry years, roots will have to obtain moisture and nutrients from deeper soil layers. In the soil on which Barber's experiments were conducted, the 15–30 cm layer contained 33 kg of exchangeable potassium, whilst the 30–45 cm layer contained only 22 kg. In years of high rainfall the roots would be absorbing potassium mainly from a soil layer richer in available potassium than that explored by the roots during drier years.

In a statistical study of the effects of June–July rainfall on the response of maize to applications of potassium fertilizer in the course of eight seasons (1952 to 1959), it was found that while actual yield levels may vary with rainfall, the yield response to applied potassium was apparently dependent only upon the rate of potassium application **(Figure 162)** *(Doll and Engelstad [1962])*.

14.2.13 Moisture supply, dry matter production and fertilization

When water supply is deficient the stomata close, uptake of carbon dioxide is reduced and photosynthesis decreases. Less dry matter is produced and fertilizer nutrients are less efficiently utilized.

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* The yield of the no-K treatment expressed as a percentage of the high-K treatment (given 330 kg/ha available K in the soil).

Conversely, a favourable moisture supply increases plant growth, both of the aerial parts and of the roots. The increased root production increases the ability of the plant to take up nutrients from the soil (cf. p. 336). The increased vegetative growth dilutes the concentration of ions in the plant, thereby increasing the capacity of the roots to absorb nutrients, and the diffusion gradient between the soil solution and the root surfaces *(Grunes [1959])*. These interactions of moisture supply and nutrient supply are reciprocal.

The interrelation between soil moisture and fertilizers and their effects on yields have been most intensively studied in a number of crops, and in particular in maize.

The results obtained by *Parks and Knetsch [1959]* are typical of many experiments of this kind. When irrigation water was applied without modification of current practices, including nitrogen fertilization at 67 kg/ha, there was little or no increase in grain yields. As the fertilizer applications were increased, two important relationships were found: (a) limited supplies of irrigation water were used more efficiently; and (b) an increased supply of irrigation water was used with even greater efficiency. The highest yield obtained in this experiment was 8190 kg/ha.

In field trials in Bulgaria, the results shown in Table 74 were obtained from irrigating and fertilizing maize, separately and together *(Delibaltov [1968])*:

Table 74. Effect of fertilizer and irrigation on yields of maize *(Delibaltov [1968])*

Fertilizer	Irrigation	Yields (kg/ha)
none	without	4730
none	with	5770
100–100–60 (oxides)	without	5450–5610
100–100–60 (oxides)	with	9950–10090 kg

Similar experiments carried out on hybrid maize in India gave the results shown in Table 75 *(Singh and Haridas [1969])*.

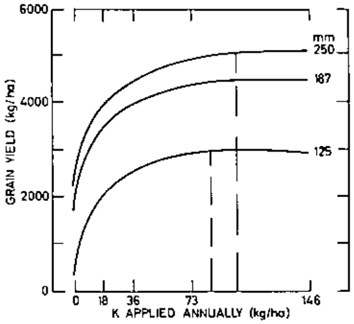

Fig. 162 Yield response of maize to potassium applications at various levels of June–July rainfall (mm) *(Doll and Engelstad [1962])*. Note that while actual yield levels vary with rainfall, the yield response to applied potassium was essentially independent of rainfall. By courtesy of the American Society of Agronomy.

Table 75. Effects of fertilizers on rain-fed and irrigated maize *(Singh and Haridas [1969])*

Fertilizer (N kg/ha)	Yields of grain (kg/ha) Rain-fed	Irrigated	Water use efficiency Rain-fed	Irrigated
None	1466	1625		
40	1895	2919	71	71
80	2403	3014	89	76
120	2555	3138	97	78

In a six-year study of irrigation and nitrogen interactions on maize grown on a clay loam soil in Iowa, yield increases from the application of N fertilizer were more consistent from irrigated maize than from unirrigated maize, although the normal rainfall during the growing season (about 500 mm) is generally adequate in this region. On unirrigated maize, a decrease in yield was obtained in three of the six years, when 44 or 66 kg N/ha were applied. With irrigation, yields were generally increased with N application, from an average high of 875 kg/ha in 1960 to an average low of 370 kg/ha in 1961. During the exceptionally dry year of 1956, there was a negative response to N by both the irrigated and unirrigated maize *(Beer et al. [1967])*.

The effects of soil moisture levels, plant densities and rates of N fertilization on the yields and evapotranspiration of maize grown on a loam soil were studied in North Dakota.

Neither N-fertilizer nor plant density influenced yields of the unirrigated maize. By contrast, yields of the irrigated maize were increased at both plant densities tested (2.5 and 5.0 plants/m^2) as a result of N-fertilizer application. The yield component that was most influenced was the number of kernels produced per unit area. Neither N fertilizer nor plant density appreciably affected the evapotranspiration rate, which was however considerabely greater for the irrigated than for the unirrigated maize *(Carlson et al. [1959])*.

The results of field trials on a silt loam in N. Dakota, in a normally low-rainfall area, indicated that variations in the available water at planting time accounted for 98 per cent of the variation in silage yields and 87 per cent of the variations in grain yields. Under the limited moisture conditions characteristic for this region, nitrogen fertilization occasionally reduced yields whilst phosphorus fertilization did not, as a rule, affect yields *(Alessi and Power [1965])*.

N-uptake per unit of water was increased by the greater supply of available water; increased water supply also increased the amount of N recovered per mm of water used *[ibid.]*.

More detailed investigations on moisture and fertilizer interrelationships in maize were carried out by *Jenne et al. [1958]* and by *Shimshi [1966]*. The effects of soil moisture supply on dry matter production and nutrient accumulation by the maize plant were investigated in a field experiment conducted on a very fine sandy loam in Nebraska *(Jenne et al. [1958])*.

The relative production of dry matter and relative accumulation of nutrients in the above-ground portion of the mature plant in relation to moisture supply are shown in **Figure 163.** Under irrigation, there was continuous accumulation of N, P and Ca and Mg throughout the growing season. Potassium accumulation under the same conditions reached a maximum of 243 kg/ha and then declined to 228 kg/ha.

Table 76. Relative dry matter production and nutrient uptake with adequate moisture, at two growth stages. Relative values* *(Jenne et al. [1958])*

Days after sowing	D.M.	N	P	K	Ca	Mg
68	10	20	20	40	20	20
89	36	55	55	85	73	55

* The values are exposed as percentages of total dry matter production or total nutrient accumulation toward the end of the growing period.

Without irrigation, differences in dry matter production and in accumulation of N, P and Mg due to moisture supply were apparent only 82 days after sowing, when nearly all the available moisture had been exhausted in the upper 75 cm of soil. The irrigated maize was taller and already tasseling. A week later, differences in K and Ca uptake due to moisture stress also became apparent.

Relative dry matter production by the unirrigated maize increased by 14 per cent during the last third of the growing season. At that time, the plants were withdrawing water from depths below 70 cm, with much of it coming from depths below 105 cm. Dry matter production by the unirrigated maize was only 44 per cent of that obtained under irrigation.

During the same time relative nutrient uptake increased by 3 per cent for N, 5 per cent for P, 20 per cent for Mg and 26 per cent for Ca, whilst that of K decreased by 11 per cent. The relative nutrient accumulation of unirrigated maize for the whole season, in percentage of values obtained with full irrigation, was: N, 50 per cent; P, 40 per cent; K, 71 per cent; Ca, 93 per cent; and Mg, 65 per cent *(Jenne et al. [1958])*.

Shimshi [1969] made a detailed study of fertilizer and soil moisture regime interactions in irrigated maize grown on a loess soil in the northern Negev of Israel. Five rates of nitrogen and five moisture regimes were applied in all possible combinations.

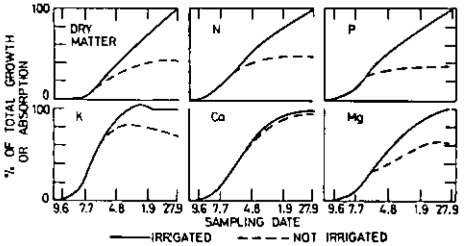

Fig. 163 Relative dry matter production (growth) and relative accumulation of nitrogen, phosphorus, potassium, calcium and magnesium in the above-ground portion of the maize plant in relation to soil moisture supply during the period from June 9 to September 27, 1952. Values obtained on September 27 for maize with adequate moisture considered to be 100 per cent *(Jenne et al. [1958])*. By courtesy of the American Society of Agronomy.

The effect of fertilization on maize yields at five levels of mean integrated moisture stress* is shown in **Figure 164.** As moisture stress increased, the yield levels of all fertilizer rates decreased. The reduction in yield due to increased moisture stress is clearly greater at high fertilization rates. Under the drier moisture regimes, heavy N fertilization actually lowered yields.

The steep negative slope of the moisture stress – yield function at high fertilization rates, and the diminishing values of optimal fertilizer rates at high moisture stress, probably reflect the detrimental effect of the osmotic potential of the soil solution as conditioned by the fertilizer application and the lack of dilution by insufficiently frequent irrigation *(Shimshi [1969]).*

In **Figure 165** are shown the combined effects of soil moisture stress and of nitrogen fertilization on the yields of maize, and the maximum grain yields that can be achieved at each level of fertilization in relation to soil moisture stress *(Shimshi [1969]).*

Many more experiments of this kind have been reported in the literature, with maize and other crops, with extraordinarily consistent results showing that nutrient and water requirements are intimately linked, and that fertilization increases the efficiency with which crops use available water; furthermore, adequate water regimes make possible fertilizer applications at levels which would be entirely ineffective under conditions of less favourable water supply.

14.2.14 Effects of fertilizers on water relations of plants

The ratio K/Ca has a marked influence on the water relations of plants. Potassium apparently stimulates water absorption and also the closure of stomata. Calcium inhibits stomata closure. Potassium favours a higher cuticular transpiration than does calcium. Lack of nitrogen induces xeromorphy, whilst plants supplied with abundant nitrogen transpire more and wilt easily *(Evenari [1962]).* Phosphorus has been found to cause a decrease in transpiration, which is proportional to the amount of fertilizer phosphorus applied *(Arland [1952]).*

*14.2.15 Consumptive use of water***

In field trials at Marandellas, Rhodesia, changes in soil moisture were measured under maize receiving 22 kg N/ha (low fertility), 132 kg N/ha (medium fertility) and 132 kg N/ha+farmyard manure at 15 tons DM/ha (high fertility), using gypsum blocks placed in the maize rows at depths down to 150 cm. High-fertility plants used the most water, depleting soil moisture to a depth of 120–150 cm in both 1965/66, a year with drought in the middle of the rains, and 1966/67 – with a normal, well-distributed rainfall. Low-fertility plants exhausted soil moisture only to 120 cm in 1965/66 and in 1966/67 did not exhaust the moisture at any depth. This was reflected in yield differences of 594 kg/ha in 1965/66 and 5764 kg/ha in 1966/67 between high-fertility and low-fertility plots *(Willatt [1969]).*

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* Mean integrated moisture stress, is an index integrating all the local and instantaneous moisture tension values over the relevant soil profile and the growth period *(Taylor [1952])*

** Consumptive use: The total amount of water used by a crop per unit area.

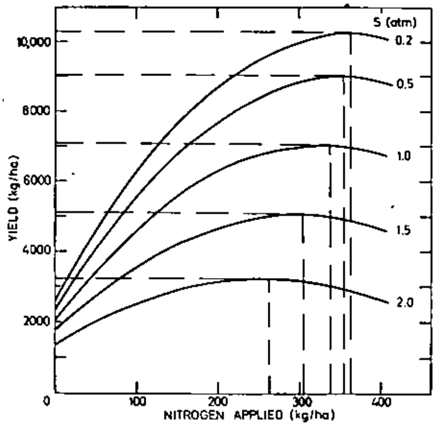

Fig. 164 The effect of nitrogen fertilization on maize yields at five given levels of mean integrated moisture stress (S, atm). (Horizontal lines denote maximum yields, and vertical lines denote fertilizer rates which produce maximum yields.) By courtesy of the Volcani Institute of Agricultural Research.

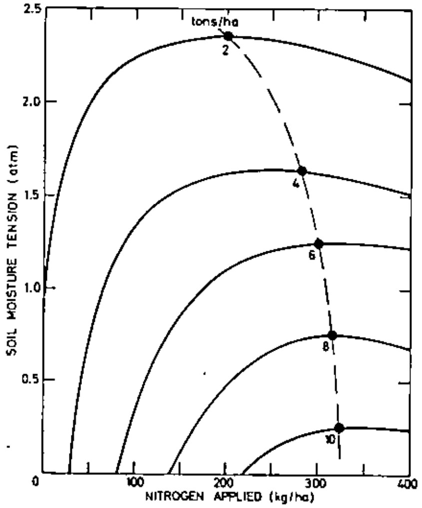

Fig. 165 Isoequivalents of the combined effects of nitrogen fertilization and soil moisture regime on grain yields of maize *(Shimshi [1966])*. The broken line joins points of maximum grain yields, for each level of fertilization. By courtesy of the Volcani Institute of Agricultural Research.

In experiments in the northern Negev, the combined effects of soil moisture regimes and N-fertilization on evapotranspiration were ascertained (Table 77, *Shimshi [1969]*).

Table 77. Effects of moisture stress and nitrogen fertilization on seasonal evapotranspiration (in mm) *(Shimshi [1969])*

No. of irrigations	Integrated moisture stress	Nitrogen levels (kg/ha) 0	52.5	105	210	420
2	2.0	342	378	391	394	381
3	1.5	349	394	407	462	479
4	1.0	388	472	516	526	559
5	0.5	476	532	602	644	675
9	0.2	693	786	827	830	817

For each fertilizer treatment, an increase in irrigation frequency caused an increase in evapotranspiration; conversely, under each moisture regime, nitrogen deficiency lowered the rate of moisture depletion, and the soil moisture stress did not rise at the end of each irrigation cycle to the same degree in the less-fertilized as the well-fertilized plots, resulting in a lower integrated moisture stress for the former *(Shimshi [1969])*.

From the data presented in Table 77, it is clear that under a given moisture regime, fertilized maize tends to extract more water from the soil than do unfertilized plants. The increased rates of evapotranspiration following N-fertilization may be due to the following factors:

a) Increased vegetative growth and hence an increase in the transpiring surface area. This effect will be most marked in dry climates or where advective vapour transfer is active.

b) Fertilization may increase the depth of root penetration, making possible the extraction of moisture from soil layers which would otherwise remain untapped.

Under dryland conditions, the subsoil is frequently dry, but under more humid conditions, subsoil moisture may be an important source of available water. In 12 experiments with maize in Nebraska, nitrogen fertilization increased water use by 32.5 mm as compared with unfertilized maize. This additional moisture came from throughout the 180 cm profile *(Olson et al [1960])*. The yields were increased by 60 per cent (+2670 kg/ha) and water use efficiency by 44 per cent.

In Iowa, unfertilized maize was shown to extract soil moisture from less than 150 cm of soil, whereas well-fertilized maize removed water to the depth of 210 cm.

c) Nutrient deficiencies impair the proper functioning of the stomata which therefore fail to open widely under conditions which would normally cause maximum stomatal opening. This has been shown to occur with K-deficiency *(Peaslee and Moss [1966])*, and with N- and Fe-deficiencies *(Shimshi [1966])*.

Nutrient-deficient plants frequently fail to show the typical wilting symptoms under moisture stress which would induce wilting in 'normal' plants. This has been ascribed to the greater rigidity of the crop tissues of nutrient-deficient plants, which usually have a higher proportion of cell-wall materials than do normal plants.

14.2.16 Relationship between crop transpiration and yield at different levels of N-fertilization

When the data obtained from experiments on fertilizer moisture relationships in maize (grown under irrigation in the northern Negev; *Shimshi [1969]*, cf. p. 350) are used in plotting yields against evapotranspiration **(Figure 166)**, the limiting-factor type of interaction becomes very evident.

The yield-evapotranspiration function at the highest level of fertilization is linear, whilst the functions for lower fertilization levels start at this same line, but branch out horizontally at progressively lower values of yield and evapotranspiration. *DeWit [1958]* states that as long as water limits plant growth, the relationship between production and transpiration is linear. When water does not limit plant growth, crop yields will be determined by other growth factors specific to the location, such as soil characteristics, fertilizer supply, etc. *Shimshi [1969]* interprets **Figure 166** as follows: at the highest level of nitrogen fertilization, practically the entire range of response represents water-limiting conditions; at lower levels of nitrogen, a horizontal break from linearity occurs as the nitrogen supply gradually becomes the limiting factor. The fact that the regression line does not pass through the origin, but intersects the evapotranspiration axis at about 260 mm, is attributed to two causes: (1) direct evaporation from the soil before the formation of full leaf canopy; and (2) transpiration by maize during the later stages of grain maturation, when there is no appreciable net production of dry matter.

14.2.17 Water use efficiency

Water-use efficiency *(WUE)* is the yield of marketable crop produced per unit of water used in evapotranspiration. Therefore,

$WUE = \frac{Y}{ET}$ where Y = yield of marketable crop and ET = evapotranspiration.

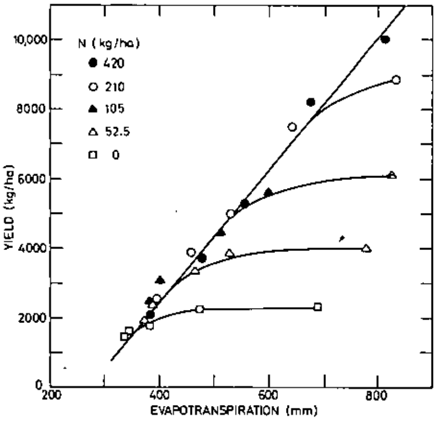

Fig. 166 The relation between seasonal evapotranspiration and maize yields at five rates of nitrogen fertilization *(Shimshi [1966])*. By courtesy of the Volcani Institute of Agricultural Research.

If yield were proportional to *ET, WUE* would be a constant. Actually, both the numerator and the denominator of the equation are influenced independently or differently by crop management and environment. The numerator Y is the most amenable to crop management practices, such as fertilization, whilst the denominator ET is mainly dependent on climate and on soil moisture supply. Once the crop covers the soil completely, crop management – with the exception of water supply – has little or no effect on ET.

As a general rule it can be stated that considerable increases in crop yields can be obtained by improved management practices without causing a corresponding increase in ET.

According to *Penman [1948]*, under an optimal water supply ET is *not* dependent on the height of the plant canopy, provided the soil is adequately covered.

Under these conditions, increasing the amount of plant canopy will therefore have little or no effect on ET. Conditions of unlimited water supply are the exception in maize production, even under irrigation. However, even when water deficiencies occur, whether transient or continuous, crop production may be increased without markedly increasing ET. This results from the fact that water deficiencies have a greater effect on transpiration than on photosynthesis.

With an adequate moisture supply, fertilization generally increases yields of maize considerably with a relatively small increase in evapotranspiration and therefore markedly improves WUE.

A striking example, based on the work of *Shimshi [1969]*, is shown in **Figure 167**, indicating that when nitrogen was not limiting, WUE increased with increasing supplies of water to the crop. By contrast, at low levels of nitrogen application, WUE decreased with increasing water supply.

In another experiment in which evapotranspiration of unfertilized maize was compared with that of fertilized maize (175 kg N/ha), water was used more rapidly by the fertilized maize as long as the moisture supply was ample, and more slowly as the available moisture became exhausted **(Figure 168)**. The total ET for the growing period was practically the same for the fertilized and unfertilized maize (22 mm and 22.2 mm) and the corresponding yields were 2.5 and 1.8 tonnes/ha *(Linscott et al. [1962])*.

Moisture-use evaluations were made in Nebraska, at 33 locations in which field fertilizer experiments were carried out with maize. Maize yields were increased by fertilization by an average of 2880 kg/ha (from 5510 kg/ha to 8390 kg/ha) or 52 per cent, whilst water was increased by an average of 25 mm. Water use efficiency was increased from 6 kg to 8.6 kg per m^3 of water, or 43 per cent *(Olson et al. [1964])*.

Generally, under conditions of deficient water supply, nutrient deficiencies will reduce WUE. Therefore, a moderate amount of suitable fertilizers, adjusted to the soil moisture level, will increase WUE. If, however, the fertilizers increase water use in the early stages of growth, so that severe water stress occurs at the critical stages – such as flowering and grain formation – the opposite effect will result *(Viets [1966])*.

– *Summing up:*

The examples given above suffice to demonstrate the general rule: all factors which optimise production, including fertilization, do so without markedly increasing the amount of evapotranspiration, and will therefore improve WUE. This will increase with supplies of all nutrients, up to those associated with maximum yields *(Black [1966])*. Hence, the conclusion that a favourable environment and good crop management are preconditions for the most efficient use of water by maize.

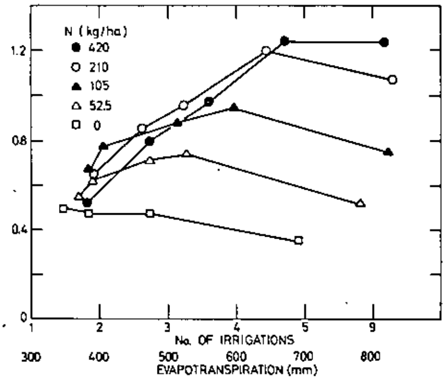

Fig. 167 Relationship between soil moisture regime and water use efficiency at five levels of fertilizer application *(Shimshi [1966])*. N_0 = control, N_1 = N – 52.5 kg/ha, N_2 = N – 105.0 kg/ha, N_3 = N – 210.0 kg/ha, N_4 = N – 420.0 kg/ha. By courtesy of the Volcani Institute of Agricultural Research.

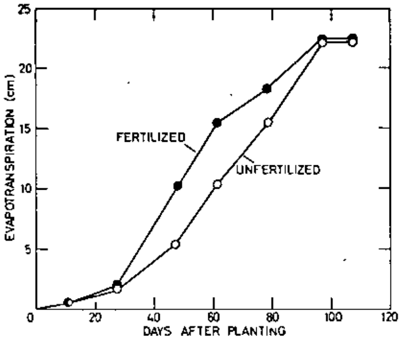

Fig. 168 Evapotranspiration from fertilized and unfertilized maize throughout the growing period *(Linscott et al. [1962])*. The fertilized maize received 157 kg/ha of nitrogen. By courtesy of the American Society of Agronomy.

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15. Fertilizer use in relation to crop management practices

15.1 Interactions of fertilization with crop rotation

Prior to World War II, nitrogen for maize production in the Corn Belt of the United States came almost entirely from the soil reserves and from symbiotic nitrogen fixation by legumes *(Kurtz and Smith [1966])*. These were sources not sufficient to produce high yields, and consequently phosphorus and potassium requirements were also relatively low. After adequate supplies of fertilizer became obtainable at reasonable cost, the situation changed entirely. Not only did yields increase steadily from year to year, but a greater flexibility in, and a greater intensification of cropping systems became possible. Even maize monoculture lost many of its negative aspects and as a result, the practice of growing consecutive maize crops on the same land is on the increase *(Englehorn et al. [1964])*. Whilst this matter has been discussed in detail in chapter 2, the implications of changes in cropping systems on fertilization will be dealt with here.

15.1.1 Fertilizer requirements of maize as affected by rotation

The following estimates of nitrogen fertilizer requirements of maize under different cropping systems are based on average yields obtained during a seven year period in a rotation experiment in Iowa *(Shrader et al. [1962])*.

Table 78. Estimates of nitrogen fertilizer required for maize yields of 6500 to 7500 kg/ha under different cropping systems *(Shrader et al. [1962])*.

Cropping sequence	*Year of maize*	*Nitrogen (kg/ha)*
Continuous maize	All	110–130
M-M-O	Second	90–110
M-M-O	First	80–100
M-Sb	All	80–100
M-M-O-L	Second	55
M-M-O-L-L	Second	35
M-M-O-L-L-L	Second	0
M-M-O-L	First	0
M-M-O-L-L	First	0
M-M-O-L-L-L	First	0

M = Maize, O = Oats, Sb = Soybean, L = Ley.

The effect of one year of legume on the first-year maize crop was equivalent to 110 to 130 kg N/ha applied annually to continuous maize. When maize was grown after one or more years of good ley*, nitrogen fertilizer did not increase the yields of the first crop of maize. A second crop of maize, following a single year of ley, required 55 kg/ha of nitrogen for maximum yields, while after two years of ley only 35 kg/ha were required. After three years of ley only a slight response to nitrogen fertilizer was recorded *(Shrader et al. [1962])*.

With higher expected yields of maize, these estimates would, of course, have to be adjusted upwards.

One of the most important rotations in the maize-growing regions of northern India is maize – wheat. The usual practice is to grow heavily-fertilized maize one year and grow unfertilized wheat the following year to benefit from the residual effect of the plant nutrients supplied to the maize. A residual response of 4.6, 2.3, and 2.9 kg of wheat was recorded per kg of nitrogen applied to the maize, at the rates of 67, 134 and 201 kg N/ha, respectively. Approximately 25 per cent of the cost of the fertilizer could be debited to the wheat crop *(Sing et al. [1965])*.

In Ohio, an investigation was made on the relative value of lucerne turned under as green manure, and of KH_2PO_4, applied as fertilizer, as sources of phosphorus to maize *(Nielsen et al. [1953])*.

The results obtained indicate that the phosphorus in the lucerne was not so available as that in the fertilizer; however, the decomposition of the lucerne increased the availability of residual P. The phosphorus from the lucerne was most available 46 to 64 days after the green manure was turned under. The reasons for the effect of lucerne in increasing availability of residual phosphorus, is ascribed to one or more of the following factors: (a) Certain organic acids formed during the decomposition of the lucerne may release phosphorus tied up as iron or aluminium phosphates; (b) increased production of CO_2, as a result of the decomposition of organic matter, may increase solubility of calcium and magnesium phosphates; and (c) the decomposition of the fresh organic matter may have a priming effect on the decomposition of residual organic matter, accelerating the process in the latter.

In eastern Oklahoma, large areas of former cropland have been planted to Bermudagrass. When these pastures were turned under for maize production, it was found that available phosphorus was the first limiting plant nutrient and that the highest yields from maize were obtained from an initial application per ha of 22 kg N, 20 kg P, and 36 kg K at planting, plus a side-dressing of 44 kg N **(Figure 169)** *(Brensing and Lynd [1965])*.

In South Africa, maize was grown for five years on plots that had previously been under continuous maize, and under seven leys (five perennial grasses, pearl millet and lucerne) for two, three and four years, respectively. All plots received superphosphate at the rate of 220 kg/ha annually. No nitrogen or nitrogen at the rate of 150 kg/ha was applied annually to the leys and to the maize in monoculture. The maize test crops received no nitrogenous fertilizer.

The application of nitrogen to the leys increased the subsequent average grain yields of the maize significantly. When no nitrogen was applied to the leys, maize following

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* Mixed lucerne, clover and grass.

lucerne gave significantly higher yields than maize following the grass leys. The annual yields of maize increased significantly, though not considerably, the longer the duration of the leys *(du Plooy et al. [1965])*.

A study of the yields of maize produced with various cropping systems and four levels of nitrogen (0, 45, 90 and 270 kg N/ha) was carried out over a seven-year period in the southern Piedmont Plateau of the United States. This area is characterised by an average annual rainfall of 1270 to 1520 mm, resulting in severe water and soil losses on clean-tilled crops, such as maize. The soils are highly leached and only moderately productive. A high level of phosphorus and potassium was maintained in all plots, based on annual soil tests.

Nitrogen applied at the rate of 45 kg N/ha significantly increased maize yields with all the cropping systems, except when maize was grown after vetch as a green manure. A further increment of nitrogen to 90 kg N/ha resulted in significant yield increases of maize grown continuous by, or in rotation with grasses. Increasing nitrogen rates to 270 kg/ha gave no further significant increase in yields, regardless of the cropping system in which maize was grown *(Adams et al. [1970])*.

A four-year trial was carried out in Bulgaria to test the effect of a number of preceding crops on maize *(Petrov [1968])*. The results obtained are shown in Table 79.

Table 79. The effect of preceding crops on maize yields *(Petrov]1968[)*

Preceding crops	*Yields (kg/ha)* *Fertilized*	*Not fertilized*
Beans	5420	4810
Vetch and oats	5490	4840
Sunflowers	4560	—
Sugar beets	—	3870
Wheat	5160	4650

The highest yields of maize were obtained after beans and after a vetch and oats mixture, both in the fertilized series and in the not fertilized series. The lowest yields were obtained in the fertilized series after sunflowers and in the unfertilized series

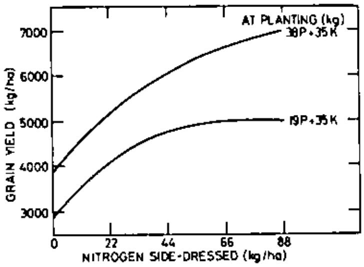

Fig. 169 Response of maize to fertilizer applications, on Bermuda grass pastures turned under for maize production *(Brensing and Lynd [1965])*. By courtesy of the Oklahoma Agricultural Experiment Station.

after sugar beets. It will be noted that the effect on the maize crop of the fertilizers applied to the preceding crop is as great, and in many cases greater, than differences in the crops themselves. Whether this is due entirely to direct residual nutrient effects or to indirect effects, such as improved N-uptake or increased amounts of crop residues, could not be ascertained from these trials.

In Bulgaria, yields of irrigated maize grown after lucerne or grass/legume mixtures fell by 8% in the second year and by 39% in the third year when no N fertilizers were applied. Fifty kg ammonium nitrate and 200 kg superphosphate/ha in the first year, and 100 and 300 kg, respectively, in the second year, maintained the yields at about 7000–7500 kg grain/ha. In the third year, further mineral fertilization was required *(Zhechev and Raikova [1967])*.

The most dramatic effects of fertilizers were recorded in maize monoculture. In 1955, the Morrow Plots at Illinois were modified and started to receive large amounts of nitrogen, phosphorus and potassium. Phenomenal yield increases were obtained on those plots that had been under continuous maize since 1915. Following these experiments it was concluded that growing maize continuously for many years is possible provided adequate rates of fertilizers are applied annually, such as 132 kg N, 94 kg P and 94 kg K/ha *(Englehorn et al. [1964])*.

In Iowa, a rotation experiment in which continuous maize had been grown since 1915 was redesigned in 1952, and new treatments including four levels of N, with and without P and K superimposed on the old treatments. Yields of maize on plots on which this crop had been grown continuously for 37 years, were increased to high levels by application of N up to 176 kg/ha, P at the rate of 27 kg/ha and K at the rate of 55 kg/ha.

The addition of phosphorus and potassium did not increase yields on the old plots of continuous maize with nitrogen during the first years of the experiment; response to the P and K in conjunction with N increased in later years, as soil reserves of these elements became depleted by the high yields obtained. The authors conclude that continuous maize can be grown successfully on soils of low fertility if an adequate fertilizer program is followed *(Engleton et al. [1964])*.

Monoculture of maize may accelerate the decline in yields on soils deficient in a certain essential element. *Dartigues and Lubet [1967]* have shown that on Zn-deficient soils in southwestern France, the yields of maize declined steeply in the course of five years of continuous maize, from 2800 to 500 kg/ha. The percentage of sterile plants varied from 12 to 92 per cent! With appropriate applications of zinc fertilizer, the situation was remedied and yields of 5400 to 8900 kg/ha were subsequently recorded under the same general conditions.

In tropical Africa, yields generally decline rapidly under continuous cropping, and a resting period under grass is frequently resorted to in order to restore soil fertility. A series of long-term fertilizer experiments was started in 1959/60 in Buganda and western Uganda, to estimate the rates at which crop yields declined and nutrient deficiencies developed in the years of cropping following a resting period, and to study the effects of fertilizers and farmyard manure in arresting this decline *(Stephens [1969])*.

The experiments were carried out on 16 sites, situated in regions with mean annual bi-modal rainfalls of 1100 to 1350 mm, and on a variety of soils differing in pH, clay content and general level of fertility. A two-year experimental rotation was followed at each site.

The mean yields and treatment effects for maize are shown in Table 80.

Table 80. Mean yields of maize and treatment effects in successive cycles *(Stephens [1969])*

Cycle	*Mean yields (kg/ha)*					*Treatment effects(kg/ha)*			
	Average all			*with*					
	Treat-ments	Con-trol	N	NPK*	D**	N	P	K	D
1	2383	2023	2459	2624	2142	436	195	–30	119
2	2564	2116	2669	2823	2306	552	19	135	189
3	2099	1453	2342	2512	1686	977	108	63	233
Decline in yields from lst to 3rd cycle (%)	11.9	28.1	4.7	4.7	21.3				

N* = Ammonium sulphate (21 per cent N) 132 kg/ha; P = Triple super phosphate (42 per cent P_2O_5) 60 kg/ha; K = Muriate of potash (60 per cent K_2O) 66 kg/ha.

D** = Dung, 5 tons/ha.

Yields were found to decline between the first and the third cycles for all crops included in the rotation, at all sites. The average decline for all treatments, for all crops except maize, was 13 to 20 per cent. Maize appeared to be less affected, as the corresponding figure is 11.9 per cent. The steepest decline in maize yields occurred on the plots that received neither fertilizers nor dung. Nitrogen appeared to be quite effective in reducing the decline due to continuous cropping to a 4.7 per cent. Although absolute yields were higher with NPK than with N alone, the overall decline in yields was similar for both treatments.

Noteworthy is the response to potassium, from negative in the first cycle to positive in the second and third cycles. The author concludes that one of the main functions of the 'grass rest' appears to be to ensure the supply of available potassium to the succeeding crops.

15.1.2 Crop rotation and soil fertility

– Soil organic matter

In the past, when only low to moderate amounts of nitrogen were applied to maize, experience had shown that the organic supply in the soil declined more rapidly with continuous maize than under a rotation system which included a sod-forming crop. An accompanying decline in maize yields was also recorded.

The heavy use of fertilizer implicit in the successful production of hybrid maize also implies the production of huge amounts of crop residues which may enhance the fertility status of the soil. The combination of favourable temperatures and moisture that are typical of good maize-growing seasons make possible a considerable increase in microbial activity, and the ensuing decomposition of the crop residues. More recent investigations, using higher levels of nitrogen, have confirmed that organic matter levels can be even increased, through incorporating into the soil the large amounts of crop residues resulting from heavy fertilization of the crop **(Figure 170)** *(Sutherland et al. [1961])*.

If the stover is incorporated into the soil after harvesting the grain, a considerable amount of organic matter is added. The quantities involved with high-yielding maize are about 5000 to 6000 kg/ha of dry matter, corresponding to the quantity of humus supplied by an application of approximately 200 tons of stable manure. The roots and stubble supply an additional 1600 to 2000 kg/ha of dry matter. In order to hasten the decomposition of these crop residues and to prevent a temporary immobilisation of soil nitrogen, it is recommended to add from 5 to 8 kg nitrogen per ton of crop residues turned under *(Zscheischler and Gross [1966])*.

According to experimental data from Rhodesia, the ploughing under of the crop residues after maize, whether browsed or not, increases maize yields by approximately 330 kg/ha, in comparison with land from which the stover is removed *(von Burkersroda [1965])*.

– *Soil structure*

Rotations which improve soil structure maintain or even increase yield levels, whilst those in which structure is degraded, show a rapid decline in yields of maize. Under these conditions, no large or consistent increases are obtained from fertilizers; occasionally even a loss of yield is recorded *(Page and Bodman [1951])*. In Table 81 are shown the results of some rotation trials in Ohio, on a heavy clay, with a high level of natural fertility. These yields were obtained on land that had been cropped, but not fertilized, for a number of years.

Table 81. Average unfertilized maize yields and response to fertilizer (kg/ha) in various rotations *(Page and Bodman [1951])*

Rotation	*Average yield (3 seasons)*	*Gain from fertilizer*
4 year: maize, oats, lucerne (two years)	3970	247.6
3 year: maize, oats, sweet clover	3560	88.9
2 year: maize, oats	2320	553.5
Continuous maize	1035	530.2

The soils under the different rotations showed great differences in their physical properties, especially aggregation and the resultant porosity and aeration. In particular, the maize was very poor on the continuous maize plots, and the plants showed many deficiency symptoms for various nutrients, even on those plots that received regular applications of fertilizers. In this case, it was the physical condition of the soil that limited growth of the plants, and though there was a marked response to fertilizers, the addition of fertilizers was not able to raise yields to an economic level *[ibid.]*.

15.1.3 Residual effects of fertilizers

The higher the rates of fertilizers applied to maize the more important becomes the problem of the residual effects of these fertilizers. These effects may be beneficial or detrimental. The amounts remaining in the soil after harvesting the crop to which they were applied, will depend on the amounts added, the yield of the crop and the manner of harvesting.

The residual effect of a fertilizer may be due to one or more of the following factors: (a) the amount applied to the crop was in excess of its actual requirements, (b) slow release of a nutrient from a partly soluble carrier, and (c) part of the added nutrient was fixed by the soil or combined by microbial activity into organic forms from which they are slowly released *(Beckett [1970])*.

In soils in which the penetration of roots is not impeded by high acidity, compact horizons, bedrock or other unfavourable conditions, water and nutrients must be considered as accessible to maize roots down to depths of at least 150 to 180 cm *(Herron et al. [1968])*. Consequently, any soluble nutrients such as nitrates, mineralized from the soil organic matter or remaining as residues from applied fertilizers, should not be considered as lost for crop use as long as they remain within this zone.

– *Nitrogen*

Notwithstanding the extreme mobility of the nitrogen applied in fertilizers, and the potential losses by leaching, N-fertilizer applications have a marked residual effect, as shown by the following examples:

In investigations in Iowa, the residual effect of 66 kg/ha N, applied to maize, gave yield increases of 320 to 500 kg/ha in the following maize crop. Residual effects may continue for more than one year. An increase of 180 kg/ha was obtained on the third maize crop grown after applying the nitrogen fertilizer. The residual effects were largest in fields in which maize showed the largest responses to N fertilization *(Dumenil and Nicholson [1952])*.

The carry-over of nitrogen may be due to unused fertilizer in its original form (probable a minor source), to ammonium fixation by the clay minerals, to nitrogen temporarily immobilised by microorganisms, and – to increased amounts of crop residues. The average carry – over for a number of years on silt loams and on heavier-textured soils has been found to be about 25 per cent, somewhat more in dry seasons (25 to 33 per cent) and somewhat less in wet seasons (15 to 20 per cent). Very little carry – over is observed on sandy soils. Maize makes more efficient use of residual nitrogen than do shallow-rooted crops *(Dumenil et al.]1954])*.

Rates of recovery of spring-applied nitrogen fertilizers were found to decrease with increasing rates of application, and amounted to little more than 50 per cent at the normally used rates. Marked residual effects were found over a period of one and half years. When 220 kg N/ha was applied to one maize crop, the amount of residual N utilized by the following maize crop averaged 27 kg/ha, and by the third crop – 37 kg/ha *(Pearson et al.]1961])*.

Hunter and Yungen]1955] investigated the residual effects of nitrogen, applied at different rates, to maize grown on a sierozemic soil in Oregon. Their results are shown in Table 82.

Table 82. Residual effects of nitrogen applied to the maize crop* *(Hunter and Yungen [1955])*

Treatment	Maize			Wheat (kg/ha)	
N (kg/ha)	Yield (kg/ha)	Increase	N recovery (%)	Yield	Increase
0	4293	—	—	2114	—
55	5069	776	42.4	2374	260
110	6547	2254	35.1	3740	1626
165	6363	2070	21.9	4324	2210
220	7182	2889	23.1	4864	2750
LSD (0.05)	768			571	

* On sierozemic soil in Oregon.

Here too, rates of recovery of nitrogen, by the crop to which it was applied, decreased with increasing rates of N-fertilization, from a maximum of 42 per cent, when 55 kg/ha was applied, to a low of 22–23 per cent, with rates of 165 kg N/ha or more. Marked increases in the following wheat crop, due to the residual effects of the nitrogen, were recorded. The additional yields obtained increased with higher rates of N-application.

Substantial increases in wheat yields grown after maize have also been recorded from high rates of nitrogen applied to the preceding maize crop, on a relatively heavy soil (Table 83). The yields of the maize crop were reduced by drought during its growing period *(Garner [1961])*.

Table 83. Residual effect of nitrogen applied to maize on yield of wheat *(Garner [1961])*

Nitrogen applied (kg N/ha)*	*Yield of wheat (kg/ha)*	*In % of control*
0 (Control)	1970	100
36	3048	154
72	2860	144
144	3240	164
220	3430	174

* In addition to a starter fertilizer of 9.9 kg N, 17.3 kg P and 32.9 kg K/ha, applied to all treatments.

Highly significant residual effects of applied nitrogen have even been obtained on light soils and under conditions of abundant rainfall *(Pearson et al [1961])*. The first maize crop recovered 60 per cent of the nitrogen applied at the lowest rate (55 kg N/ha) and only 40 per cent at the highest rate (220 kg N/ha). All rates of nitrogen applied increased the yields of the following forage and maize grain crops (Table 84). Whilst the residual effects of nitrogen applied at low rates were relatively small, those due to the high rate were quite substantial.

The total recovery in the above-ground parts of the three crops was 77, 75 and 70 per cent, for the 55, 110 and 220 kg N/ha applications, respectively, indicating that there were no important differences in this respect between the lowest and highest rates of nitrogen applied.

– *Phosphorus*

An example of the residual effects of phosphorus fertilizer is provided by *Kamprath [1967]* of North Carolina, who gave large initial applications of concentrated superphosphate to high P-fixing soils, very low in available phosphorus. An application of 670 kg P/ha was still supplying sufficient phosphorus for high yields of maize nine years later **(Figure 171).**

Response of maize to a band application of 24 kg P/ha was significantly affected by the superphosphate applied nine years earlier! These investigations also showed the importance of achieving a high level of phosphorus in the entire root zone of high P-fixing soils and not only in localized bands.

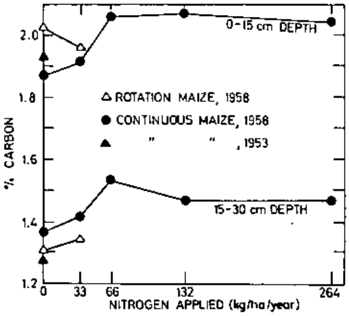

Fig. 170 Effect of nitrogen fertilizer application to maize on the maintenance of organic matter levels in the soil *(Sutherland et al. [1961])*. By incorporating residues of highly fertilized maize it has been found possible to maintain, and even increase, the organic matter level of a silt loam soil in Iowa. By courtesy of the American Society of Agronomy.

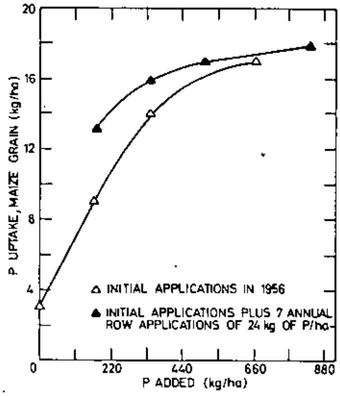

Fig. 171 Residual effects of initial P treatments applied in 1955, and of annual row applications, on P-uptake by maize in 1964 *(Kamprath [1967])*. By courtesy of the American Society of Agronomy.

Table 84. Residual effects of nitrogen on light soil *(Pearson et al. [1961])*

Nitrogen applied to the preceding maize crop (kg/N/ha)	*Average oven-dry forage yield small grain (kg/ha)*	*Average maize yields, second crop (kg/ha)*
0	871	1270
55	1081	1460
110	1531	1714
220	2631	2480

After a time it is possible to achieve an optimum level of phosphorus in the soil, at which maize will no longer respond directly to P fertilizers, and only starter or maintenance dressings of phosphorus will be required. The length of time required to reach this stage will depend on the initial level of phosphorus in the soil and the amounts of P fertilizer applied annually.

From the foregoing it is clear that the failure of maize to respond to P-fertilizer applications is not necessarily evidence of rapid fixation of the P by the soil, but may possibly be due to the accumulation of residual P from fertilizer applications to previous crops.

– *Potassium*

The residual effect of broadcast K-fertilizer on the following maize crop has been found to be relatively large on Iowa soils. Yield responses to residual K in the second year following application were only slightly smaller than the response in the year of application, even at original rates as low as 33 to 44 kg of K/ha. The K carry – over from one maize crop to the next has been estimated at 60 to 80 per cent, when only the grain is removed. When the maize is harvested for silage, large amounts of K are removed in the stalks, and the carry – over generally does not exceed 30 to 40 per cent. This may still be sufficient to increase legume yields in the following year *(Dumenil et al. [1959])*.

– *Zinc*

In cases of zinc deficiencies, the Zn applied to the preceding crop will also improve maize yields. In field trials in Bulgaria, on a soil containing 0.14–0.16 ppm Zn, zinc was applied to a sugar beet crop at the rate of 4 kg Zn/ha, in addition to the standard NPK dressing. Maize grown after the Zn-fertilized sugar beet yielded 41–69 per cent more grain than when grown after sugar beet that had received no Zn. Zn applied directly to maize increased yields of grain by 13–70 per cent, depending on the preceding crop *(Antonav [1969])*.

15.1.4 Fertilization of the rotation

In the past, small amounts of fertilizers were generally used and it was logical to apply these to the individual crops in the rotation. With the heavy rates of fertilizer application that are now commonplace, there is reason to reconsider this practice.

The complex interactions between crops and fertilizers, the gradual build-up or depletion of nutrients from the soil, the effects of the crops included in the rotation and management practices on the fertility status of the soil, and in particular its organic matter content, justify fertilizing within the framework of the rotation rather than for individual crops. However, very little research has as yet been carried out on the relative merits of applying fertilizers to all crops in the rotation, to a few specific crops, or as a one-time massive application for each rotation cycle.

Nelson and Hansen [1968] state, for example, that in a simple maize-soybean rotation, heavy rates of phosphorus and potassium applied to maize may be sufficient for the following crop of soybeans.

Various crops in the rotation respond to a different degree to the same levels of potassium fertilization. On a soil testing 45 ppm of exchangeable K, the average yield increases from applications of potassium over a ten-year period were found to be: maize, 26 per cent; soybeans, 23 per cent; wheat, 6 per cent; and hay, 26 per cent *(Barber and Humbert [1963])*. These results demonstrate the responsiveness of certain crops, in particular maize, to potassium fertilization when this element is deficient; other crops, such as wheat, are far less responsive. This suggests that it would be desirable to apply the fertilizer to the most responsive crop in the rotation, and allow the less responsive crops to utilize the residual fertilizer.

The basic objective of rotation fertilization is to ensure that plant nutrients should never be limiting, so that each crop in the rotation is able to achieve its maximum potential yield. Rotation fertilization is a long-term programme.

For acid soils, an essential first step in building up soil fertility is of course to raise the soil pH to the desired level by liming, at intervals indicated by soil tests.

For phosphorus and potassium the first aim is to build up the soil level of these nutrients to an optimum; this is done over a number of years, the amounts to be applied being based on annual soil tests. When this objective has been achieved, it is necessary to continue to supply maintenance amounts, in particular to the crops that are responsive. The danger of discontinuing fertilizer application, even after satisfactory levels have been built up, is illustrated by experiments carried out in Illinois in a rotation of maize, soybeans, wheat and legume hay, with a long history of lime, phosphorus and potassium application. On one site (Newton) the supply of potassium had averaged 55 kg K_2O/ha over 43 years. Potassium applications were discontinued in 1954; maize that received no potassium showed almost no decline in yield until 1959 **(Figure 172a)**. Thereafter, yields of maize could no longer be maintained on the potassium reserves accumulated from previous applications. After 1959, yield loss from a continued omission of K fertilization averaged 6 per cent per year. By 1965, maize that received no potassium fertilizer yielded only 63 per cent of that fertilized with 88 kg K_2O/ha.

On a second site (Ewing) **(Figure 172b)**, the rotation had received fertilizers from 1910 to 1928. Potassium was then omitted from 1929–1952. Here again, yields did not at first decline significantly, indicating that the reserves of potassium, accumulated over 18 years, were sufficient to maintain yields for three years only, without K fertilization. A steep decline in yields then occurred, which became stabilized at about 60 per cent of the fertilized crop. When the annual rate of 55 kg K_2O/ha was renewed in 1952, yields increased rapidly, reaching 82 per cent of the continuously fertilized maize in the first year and 95 per cent by the fourth year *(Johnson and Miller [1966])*.

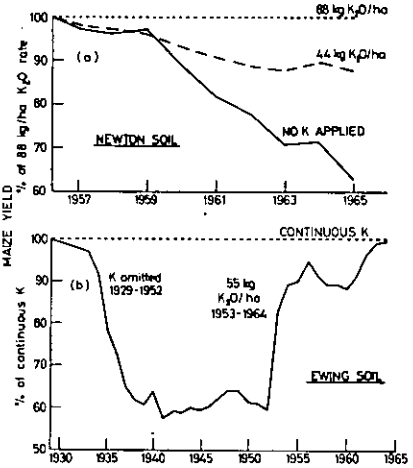

Fig. 172 Effect of potassium fertilization on the yields of maize grown continuously on the same land, on two different sites in Illinois *(Johnson and Miller [1966])*. By courtesy of the American Potash Institute.

A build-up of high nitrogen levels, similar to the procedure for phosphorus or potassium, is generally not feasible, and the amounts of nitrogen required will, as a rule, have to be applied according to the needs of the individual crops in the rotation. These amounts will depend very much on whether or not legumes are included in the rotation.

For example, the following rates of nitrogen/ha are recommended for maize, according to the type of rotation practiced: following legumes for forage, 55 to 75 kg; following soybeans or wheat, 110 to 130 kg; and for continuous maize, 110 to 165 kg *(Tisdale and Nelson [1966])*.

Continued heavy applications of nitrogen may, however, build up important reserves of nitrogen. This is due to the turning under of heavy crop residues which gradually release nitrogen to the crops in the rotation. Appropriate nitrogen applications should be made when incorporating residues in the soil, so as to ensure that nitrogen fixation by the microorganism involved in the decomposition of the crop residues should not compete with the nitrogen requirements of the crop, at any stage of its growth.

15.1.5 Nutrient removal as influenced by harvest method

Harvesting of the grain only will lead to far lower depletion of nutrients from the soil than harvesting the entire crop for silage. The major part of the nitrogen and phosphorus supplies are contained in the grain; zinc and molybdenum are about equally distributed between grain and stover; while potassium, calcium, magnesium, iron, manganese, boron, copper and chlorine are concentrated in the stover *(Barber and Olson [1968])*.

It is estimated that a crop of maize, when the stover is incorporated into the soil, removes the following amounts of nutrients (shown in Table 85).

Table 85. Amounts of N, P and K removed by a maize crop when the residues are incorporated into the soil (in kg/ha) *(Zscheischler and Gross [1966])*

Grain yield (kg/ha)	N	P_2O_5	K_2O
4000	64	30	20
5000	80	38	25
6000	96	45	30
7000	112	52	35

When the crop is harvested for forage, nutrient removal is much more considerable. For 7 hybrids grown on a sandy soil and irrigated, averaging 17 540 kg of dry fodder/ha, the average uptake per ha of N, P and K was found to be 203, 38 and 153 kg, of N, P and K respectively, when high rates of fertilizers (332–98–27) were applied **(Figure 173)** *(Robertson et al. [1965]).*

Benne et al. [1964] have investigated the amounts of nutrients removed from the field by a mature crop of maize that produced 18.7 tons of dry matter per ha, of which 7.4 tons/ha were in the grain under different harvesting methods. The total amounts of nutrients accumulated by the crop were as follows (in kg/ha): nitrogen, 232.1; phosphorus, 34.4; potassium, 226.1; calcium, 47.3; magnesium, 50.1; sulphur, 22.3; iron, 6.23 and zinc, 0.44. The results are summarized in Table 86.

When the crop was harvested for silage, only 16.4 kg of nitrogen were left in the residues in the field, and practically all the phosphorus, potassium, calcium, magnesium and sulphur accumulated by the crop was removed from the field. However, as the silage is probably intended for consumption on the farm, a considerable proportion of these nutrients may still be returned to the field in the form of organic manure.

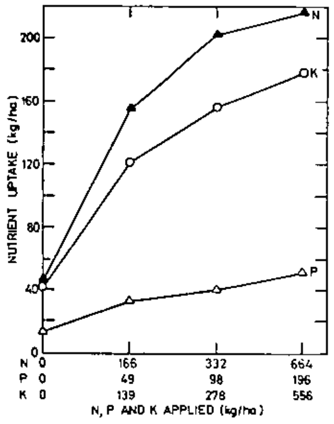

Fig. 173 Uptake of nitrogen, phosphorus and potassium by hybrid maize grown for silage, as affected by fertilizer rates (Based on data from *Robertson et al. [1965]).*

Table 86. Effect of method of harvesting on removal of plant nutrients by maize (kg/ha) (*Benne et al. [1964]*)

Constituent	Harvested with					
	Picker-sheller		Picker		Field-chopper	
	Removed in grain	Left in field	Removed in grain+ cobs	Left in field	Removed in silage	Left in field
Nitrogen	133.3	98.8	138.9	93.2	215.7	16.4
Phosphorus	25.2	9.2	25.7	8.7	32.9	1.5
Potassium	25.2	201.0	34.0	192.2	189.9	36.3
Calcium	6.7	40.6	8.2	39.1	42.6	4.7
Magnesium	11.8	38.3	13.9	36.2	44.1	6.0
Sulphur	9.6	12.7	9.9	12.4	20.0	2.3
Iron	0.14	6.09	0.18	6.05	2.74	3.49
Zinc	0.19	0.25	0.21	0.23	0.39	0.05

15.2 Plant population and competition for nutrients

The optimum number of plants per unit area depends on a number of factors, among which availability of plant nutrients is of considerable importance. When plants are widely spaced, they may be able to obtain from the relatively large volume of soil available to the individual plant an adequate supply of plant nutrients. However, when moisture is not limiting, the high potential yielding ability of maize hybrids can be achieved only at plant densities at which competition between plants for nutrients is relatively severe; an adequate supply of nutrients is therefore essential under these conditions.

Bray [1954] distinguishes between the 'root system sorption zone', which includes the whole volume of soil within the major part of the root system, and the 'root surface sorption zone', which relates only to the thin volume of soil adjacent to each root or root hair surface, from which the plant effectively obtains nutrients with limited mobility, such as exchangeable potassium or adsorbed phosphorus. *Bray* postulates that competition between neighbouring plants for nutrients (and for water) occurs in three stages, which he calls the 'plant competition sequence'. When the plants are so far apart that none of their root sorption zones overlap, no competition for nutrients occurs. When the root system sorption zones of neighbouring plants interpenetrate, competition for the relatively mobile nutrients occurs. It is only when the root surface sorption zones interpenetrate, that competition for the nutrients with limited mobility takes place. Therefore, depending on plant density, there may be no competition for nutrients between neighbouring plants, competition for mobile nutrients only, or competition for both relatively mobile nutrients and those with limited mobility.

As plant density increases, with resultant yield increases, competition for the relatively mobile nutrients is intensified. Amounts that would have been adequate for lower plant population densities become deficient and limiting, so that soil nutrient requirements increase. For the relatively immobile nutrients, such as exchangeable potassium, the increased competition results in more efficient uptake and the soil nutrient requirement will change much more slowly with increases in plant density than is the case for the more mobile nutrients.

Many investigations have shown that it is possible to increase the yield potential of maize considerably if plant population densities and fertilizers are increased simultaneously, provided moisture supply is adequate. This is especially true for hybrid maize with its high yield potential.

In a study on maize concerning the relationship between density of population and different levels of nitrogen supply, it was found that the higher the level of nitrogen, the greater the plant population that was required for achieving maximum yields (**Figure 174**). With a low supply of nitrogen the maximum yield of grain was 4720 kg/ha, which was obtained with a population density of 3 plants/m²; with a medium nitrogen level, the maximum yield was 5800 kg/ha, obtained with 4 plants/m²; with a high nitrogen level, the highest yield was 7430 kg/ha, which required a density of 5 plants/m² *(Lang et al. [1956])*.

In a spacing × fertilizer experiment carried out on a fine sandy loam in Mississippi, nitrogen was applied at rates of 0–66 and 132 kg/ha in combination with stands of 1 and 3 plants/m², respectively. Ample amounts of phosphorus and potassium were supplied to all treatments *(Jordan et al. [1950])*. With the low-population stand, only the first increment of nitrogen augmented yields moderately. With the denser stand, substantial yield increases were obtained from each increment of nitrogen.

With reasonably adequate nitrogen (66 or 132 kg/ha), total production of dry matter increased as the plant population density increased. The behaviour of the crop with no nitrogen shows the characteristic response to a nutrient deficiency, in that dry

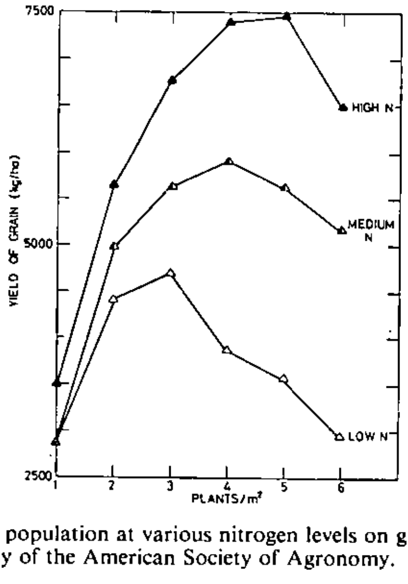

Fig. 174 Effect of plant population at various nitrogen levels on grain yield of maize *(Lang et al. [1956])*. By courtesy of the American Society of Agronomy.

matter production was restricted to the point of being almost identical for two widely different plant densities. The combination of high plant density with high nitrogen application gave the highest daily production of dry matter; This amounted to 173 kg/ha from the time the tassels appeared until the so-called 'roasting ear' stage **(Figure 175)**.

The plants were analysed at five successive stages of growth and the following patterns of nutrient uptake were recorded.

(a) Nitrogen

Nitrogen uptake by the whole plant was continuous throughout growth. The N-levels in the vegetative parts increased until the tassel stage, after which some of the N was translocated to the developing grain **(Figure 176)**. With the low-population stand, there was a progressive increase in the N-content of the grain with increasing levels of N-fertilization. In the higher-population stands, the N-content of the grain did not increase with increasing fertilization, indicating that the nitrogen was used more effectively than in the sparser stands.

(b) Phosphorus

As with nitrogen, phosphorus uptake by the whole plant was continuous throughout the season. The total uptake increased with higher levels of N fertilization and with the heavier stand. The highest recorded rate of uptake occurred in the knee-high to tassel period, during which time the amounts taken up were equivalent to 0.55 kg P_2O_5/ha/day. After the tassel stage, some of the P_2O_5 was translocated from the vegetative parts to the grain **(Figure 177)**.

(c) Potassium

The pattern of potassium uptake was different from that of nitrogen and phosphorus uptake, in that potassium absorption was not continuous throughout the season

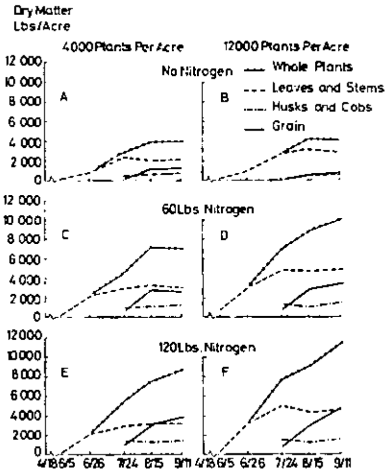

Fig. 175 Production of dry matter by maize with different nitrogen rates and plant populations *(Jordan et al. [1950])*. By courtesy of the American Society of Agronomy.

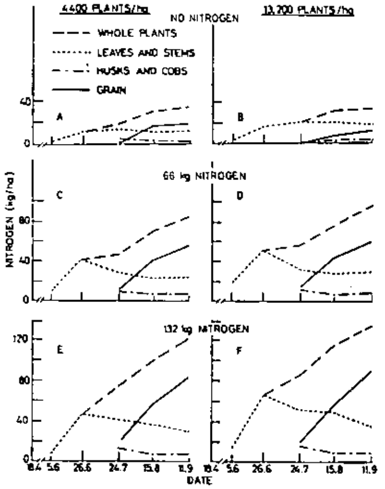

Fig. 176 Nitrogen uptake by maize with different nitrogen rates and plant populations *(Jordan et al. [1950])*. By courtesy of the American Society of Agronomy.

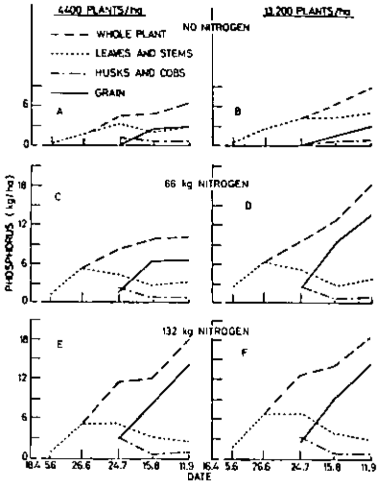

Fig. 177 Phosphorus uptake by maize with different nitrogen rates and plant populations *(Jordan et al. [1950])*. By courtesy of the American Society of Agronomy.

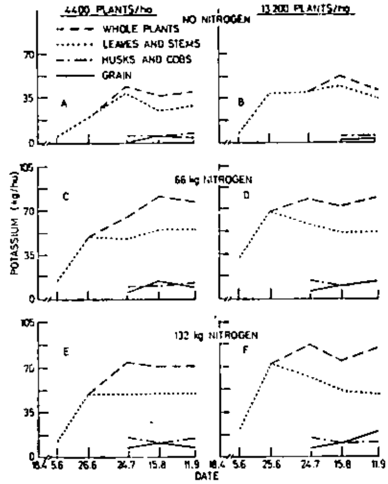

Fig. 178 Potassium uptake by maize with different rates and plant populations *(Jordan et al. [1950])*. By courtesy of the American Society of Agronomy.

(Figure 178). The most rapid rate of uptake occurred in the knee-high to tassel period and uptake ceased entirely in August. During the 21-day period of peak requirement, the high-nitrogen × high population plants absorbed potassium at an average rate of 2.4 kg/ha/day. The largest proportion of potassium accumulated in the vegetative parts, especially the stem, with little translocation to the grain.

In a study in Illinois on a silt loam, on the relation of planting rate and applied nitrogen to the yield and composition of hybrid maize grain, the need for adjusting population density and nitrogen supply was again demonstrated *(Earley [1967])*. It was shown that without nitrogen fertilization*, increasing plant populations above 3 pl/m^2 had no effect on yields; conversely, the highest rate of nitrogen application (176 kg N/ha) could not be profitably applied, unless plant population was increased to 6 pl/m^2.

The interaction of plant density and nitrogen applications was even more striking for total protein yield than for total grain yield **(Figures 179, 180)**. Similar relationships between yields, plant density and intensity of fertilization are reported from recent trials in India *(Sharma and Gupta [1968])*, Chile (San *Cristobal [1965]* and the U.S.S.R. *(Bykhun et al. [1968])*.

Under conditions of an assured water supply, as provided by irrigation, a high plant population density, concurrently with a heavy rate of fertilizer application are both essential in order to achieve the high yield levels that are possible under irrigation and essential for irrigation to be economic.

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* All treatments received 660 kg/ha of 0–14–7 ploughed under.

The results of an experiment with irrigated maize conducted in 1966 in the Lot-et-Garonne area in France are shown in **Figure 181** *(Gros [1967])*.

At low levels of nutrient supply, dense populations may have specific adverse effects on crop plants. For example, in dense stands, lodging is increased and there may be a high incidence of blind stalks and barren ears. The relationship between nitrogen supply and the percentage of barren plants at different population densities is shown in **Figure 182** *(Lang et al. [1956])*. On soils with low boron availability, the incidence of blind stalks and barren ears may be aggravated by a lack of boron *(Berger et al. [1957])*.

In field experiments carried out on maize grown under irrigation on a calcareous soil in Indiana, important positive interactions of plant population with applied zinc fertilizers and with applied boron fertilizers were demonstrated. These results indicate that limited Zn or B may be one of the reasons for severe yield decreases resulting from planting maize too thickly. High rates of applied Zn or B (90 to 180 kg/ha)

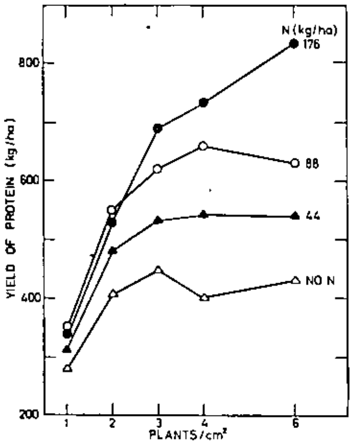

Fig. 179 Interactions of nitrogen levels and plant population densities on total protein yield (Based on data from *Earley [1967]*).

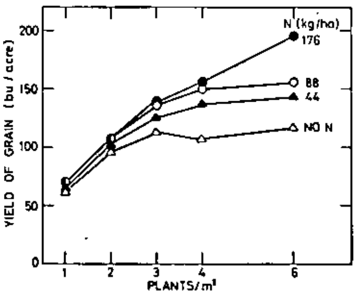

Fig. 180 Interactions of nitrogen levels and plant population densities on total grain yield (Based on data from *Earley [1967]*).

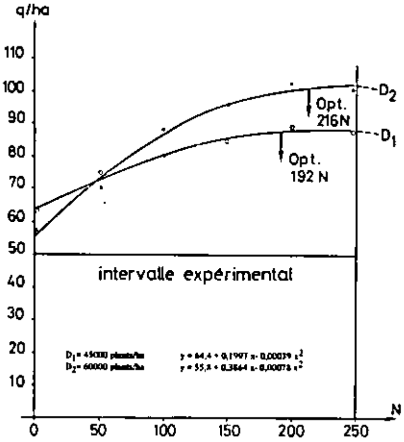

Fig. 181 Combined effects of plant population density and nitrogen fertilization on yields of irrigated maize in the Lot-et-Garonne area of France (Based on data by *Gros [1967]*).

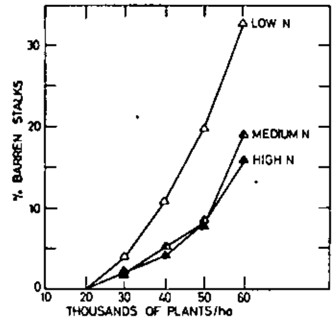

Fig. 182 Effect of nitrogen supply at different plant population densities on the percentage of barren stalks *(Lang et al. [1956])*. By courtesy of the American Society of Agronomy.

reduced grain yields at plant populations of 4.0 to 5.3 plants/m^2, whereas yields were increased at the higher densities of 8.0 to 9.3 plants/m^2. Therefore, levels of Zn and B that would normally be considered toxic at the usual plant densities, can actually increase yields of maize when the plant population is high. High levels of Zn and B may therefore be essential if further increases in plant population density are contemplated as a means of securing maximum yields of grain *(Fuehring [1966])*.

15.3 Fertilizer practice in relation to tillage

15.3.1 Effects of tillage on nutrient uptake

A direct relationship is known to exist between the degree of tillage and the nitrogen requirements of the crop. The rate at which nitrogen is released from soil organic matter and from recently incorporated residues tends to be proportional to the intensity and frequency of tillage operations. Tillage promotes aeration and hence the decomposition of organic matter (provided moisture conditions are favourable), and as a result increases the amounts of nitrogen available to the crop.

Bower et al. [1944] were the first to demonstrate that tillage had a direct effect on the availability of nutrients. In their experiments, they showed that maize grown on land prepared by discing or subsurface tillage showed distinct nitrogen deficiency symptoms, even when nitrogen was applied. Maize grown on ploughed land showed no such symptoms. Similar though somewhat less drastic results were obtained with potassium. Where no potassium was applied, the K content of maize grown on ploughed land was 70 per cent higher than that of maize grown on disced or subsurface tilled land. Soil tests showed no differences in the levels of exchangeable potassium in the differently tilled soils, but there was a higher content of ferrous iron in the plots which had not been ploughed, indicating a lack of aeration or reducing conditions. It was therefore assumed that the effect on ploughing was indirect, and that it increased K absorption as a result of the improved oxygen supply *[ibid.]*.

In other investigations on the effect of different tillage practices on nutrient uptake from the soil by maize, it was found that the influence of tillage methods on the availability of nitrogen and potassium may be markedly different in different soils. On well-managed permeable soils, with good tilth and a high organic matter content, there was no evidence of nutrient deficiencies, regardless of the method of tillage used. On poorly managed soils, depleted of organic matter, and on slowly drained soils, nutrient deficiencies were more severe with tillage practices that do not loosen the soil as much as when the land is prepared with the plough *(Lawton and Browning [1948])*. These authors, too relate their results to the better aeration provided by ploughing, which stimulates biological activity in the soil and improves potassium absorption, which is dependent on an adequate supply of oxygen.

Tillage – induced microrelief can also affect soil temperature; seed zone temperature was markedly reduced by listing, for example, as compared with conventional tillage *(Olson and Schoeberl [1970])*. That the uptake of nutrients is affected by soil temperature has already been shown on p. 328–30.

15.3.2 Depth of tillage

Increasing the depth of tillage may be effective in providing the roots of the plant with a greater volume of soil which is in a favourable physical condition; but this advantage cannot be fully exploited unless appropriate amounts of lime, phosphorus and potassium are applied so as to maintain these elements in the larger soil volume at the desired levels.

Many subsoils in humid temperate regions are compacted, acid and low in plant nutrients. The compact soil layer restricts root growth and impedes the downward movement of water.

The significance of deep placement of fertilizers has been discussed in chapter 13. The responses obtained from deep placement of fertilizer and deep tillage are very variable and dependent on certain physical and chemical properties of the soil as well as on the amount and distribution of rainfall.

Experiments conducted in Louisiana over several years on four soil types, showed that greater root development in the subsoil, associated with increases in yield, may be expected from deep fertilizer placement and from deep tillage on soils that have a hardpan. The effects on yield were most marked in years of less than average rainfall. The increased root development in the subsoil due to the treatments enabled the crop to withstand dry periods between rains *(Patrick et al. [1959])*.

A study was carried out in Illinois on the effects of deep tillage and subsoil fertilization in a soil composed of a thin layer of loess, overlying a thick, tight, compact layer of clay, starting about 35–50 cm below the soil surface and extending to a depth of 100–115 cm. It was found that deep tillage and subsoil fertilization increased rooting depth; the plants were also more vigorous and taller and wilted less than plants grown on soil tilled and fertilized to a depth of 23 cm. However, these advantages were not reflected by higher yields. The lack of yield response to deep tillage was attributed by the investigators to a reduction in organic matter content of the topsoil and increased content of clay as a result of mixing the topsoil with subsoil *(Vavra et al. [1966])*.

Subsoiling has rarely given lasting increases in productivity, unless fertilizers were applied at the same time at subsoil depth. Exceptions are those cases in which the subsoiling has caused a radical change in the nature of the soil profile.

In field experiments in Indiana, it was found that subsoiling, without deep placement of fertilizers, had very little beneficial effect on root growth. By contrast, applying fertilizers providing N, P_2O_5 and K_2O, each at the rate of 110 kg/ha in a vertical band, beginning from the bottom of the plough layer down to the full depth of loosening (from 20 to 50 cm), greatly increased the growth of maize roots (Plate 12). To be effective, the subsoiling must be done in relatively dry soil *(Kohnke and Bertrand [1956])*.

In investigations in Iowa, applications of phosphorus plus nitrogen fertilizer produced somewhat lower yields of maize when placed deep in the subsoiled channel than when the same amounts were ploughed under in the conventional manner *(Larson et al. [1960])*.

In investigations carried out on a number of soil types in Florida, yield increases of maize were obtained from subsoiling and fertilizer placement in the subsoil, wherever organic hardpans, compact clay zones or plough soles were found beneath the surface soil. On soils where there was nothing in the profile to impede root penetration, shallow placement of the fertilizer gave results as good as subsoil fertilization.

When a severe drought occurred, no crop responses were obtained on heavy clay soil, whilst on light soils, yield increases were obtained. For example, on a Leon fine sand, subsoiling alone gave a yield increase of 637 kg/ha, and subsoiling plus fertilizer resulted in an increase of 1300 kg/ha *(Borries [1956])*.

Investigations in Missouri showed that it is possible to grow good crops of maize on claypan soils with poor drainage and a low level of fertility, provided that the subsoil is shattered by appropriate tillage methods, and that there is deep placement of lime and fertilizers *(Woodruff and Smith [1947])*.

15.3.3 Mulch-tillage

When crop residues are maintained on the soil surface, a depression in nitrogen and potassium uptake by maize frequently occurs. As a result, plant growth is retarded early in the season, symptoms of N-deficiency appear, and grain yields are depressed *(Schaller and Evans [1954])*.

The decreased nitrate content of the soil, in particular during the early part of the season, has been attributed to a number of factors, including poor aeration, resulting from inadequate loosening of the soil, and increased soil moisture *(Schaller and Evans [1954])*; or to increased microbial immobilisation of nitrogen *(Parker et al. [1957])*. Additional factors are lower soil temperatures, resulting in less mineralization of nitrogen *(Parker and Larson [1965])*, and nitrogen leaching out of the row zone because of water concentrating in soil furrows *(Larson and Blake [1966])*.

However, when nitrogen fertilizer is added in adequate amounts, the yields of maize obtained from leaving the residues on the soil surface as a mulch, were found to be higher than when the residues were incorporated into the soil *(Parker et al. [1957])*.

In experiments in Ohio, mulch-tillage usually gave somewhat lower yields than conventional tillage. This was ascribed to the higher bulk density and reduced potassium uptake by the maize plants (Table 88) *(Borst and Mederski [1957])*.

Table 88. Potassium content of maize plants on ploughed and mulch-tilled soil *(Borst and Mederski [1957])*

	July 1954	August 1954	July 1955	Average
Ploughed	2.05	1.54	2.26	1.95
Mulch-tilled	1.89	1.39	2.27	1.85

The reduction observed frequently in potassium uptake by maize growing on mulched soil, is generally ascribed to differences in the physical condition of the soil as a result of the tillage operations *(Schaller and Evans [1954])*.

In Iowa, maize plants grown on mulched soil were found to contain less manganese than those grown on conventionally tilled soils. The reduced uptake of the manganese was ascribed to the lower temperature and higher moisture content of the soil under mulched than under non-mulched conditions *(Parker [1962])*.

In Nebraska, a reduction in growth accompanied by chlorosis of maize grown on mulched soil was observed, and ascribed to the production of phytotoxic substances during the decomposition of the crop residues *(McCalla and Haskins [1964])*.

In dry years, when soil moisture is a limiting factor, mulching generally increases maize yields. The favourable effect is due to improved water infiltration and higher soil moisture contents in dry years. Erosion was also reduced by mulch-tillage, as compared with the ploughing under of crop residues *(Borst and Mederski [1957])*.

15.3.4 No-tillage

The conventional method of preparing land for maize consists in ploughing and then pulverizing with one or more discings and/or harrowings. The fertilizers are broadcast before ploughing or before discing.

It might seem that with no-tillage, incorporation of fertilizers into the soil might be a problem. The procedure usually adopted is to apply broadcast on the soil surface, or to apply about 80 per cent broadcast and 20 per cent in bands using the conventional corn-planter.

Phosphate fertilization by broadcasting on the surface of no-tilled soil was compared with incorporating into the upper 12 cm of the soil with a roto-tiller, on a soil low in available phosphorus *(Singh et al. [1966])*. Phosphorus uptake, phosphorus content of the maize leaves, and grain yield were generally equal or even somewhat higher from the surface applied phosphorus in no-tillage than from phosphorus incorporated in the soil with a rototiller. These results indicate that surface application is a practical method of applying fertilizers in no-tillage systems, and can provide adequate nutrient availability while causing a minimum of mulch destruction. It was further reasoned that as phosphorus is one of the least mobile nutrients, these results could serve as an indication that other nutrients too can be surfaced-applied.

Shear and Moschler [1969] investigated the long-term effects of no-tillage and conventional tillage on maize, in relation to fertilization. Equal annual applications of 560 kg/ha of 5–10–5 fertilizer were applied in all treatments by broadcasting immediately after removal of the maize crop, which was handled as an ensilage crop; the land was lightly disced. After six successive years of maize growing, tillage methods showed a distinct stratification effect of pH and available phosphorus with a less pronounced stratification on available potassium (Table 89).

Table 89. Available phosphorus and potassium (in ppm) and soil pH at various depths on tilled and untilled soil after six years of continuous maize *(Shear and Moschler [1969])*

Tillage	Soil depth (cm)	Unlimed			Limed		
		pH	P	K	pH	P	K
Tilled	0– 5	4.8	68	213	5.0	59	159
	5–10	5.0	50	125	5.4	38	108
	10–15	5.2	40	113	5.6	33	104
	15–20	5.3	23	111	5.7	11	98
Untilled	0– 5	4.5	246	184	5.4	238	149
	5–10	4.6	23	111	5.0	18	97
	10–15	5.2	12	126	5.9	11	105
	15–20	6.0	7	122	6.2	8	93

The effect was more evident on untilled soil than on soil that had been tilled every year. While liming did not affect the availability of phosphorus, tillage treatments affected both availability and distribution.

The total available phosphorus in the upper 20 cm of soil was 75 per cent higher in the untilled plots than in tilled soil. Available phosphorus (average of limed and unlimed treatments) in the upper 5 cm of soil that had received 672 kg/ha during the six-year period, had 242 ppm P in the untilled soil as compared with 63 ppm in the comparable layer of tilled soil. Below 5 cm (5 to 20 cm), there was a steep decline in available phosphorus in the untilled soil. The amount in the tilled soil was consistently higher than in the untilled.

The total amounts of available phosphorus in the 0–20 cm layer show that there is less fixation of phosphorus with no-tillage. As the surface-applied phosphorus remains to a large extent in the surface soil layer, it might be expected that it would not be readily accessible to the crop. Even so, the uptake of phosphorus by the maize plants was more rapid during the first six weeks of growth on the untilled soil than on the tilled soil, provided moisture supply was adequate.

Both leaf analyses and yield data showed that under average to slightly below average rainfall for the area in which the experiment was carried out, maize was able to obtain an adequate phosphorus supply from the surface application.

Potassium availability showed no relation to tillage. There was a greater amount of potassium in the top 5 cm of soil than in lower layers. Liming reduced the total amount of potassium in the top 20 cm of soil.

Acidic residues of the nitrogen fertilizer applied had no effect on soil pH at the 15–20 cm depth, after six years of no-tillage. Tillage caused a mixing of the acidifying residues of the nitrogen fertilizer with a greater volume of soil, thereby diluting them in the soil. As a result, the surface layer of the tilled soil was slightly less acid than the comparable layer of non-tilled soil. By contrast, the 15–20 cm layer was more acid.
In a similar investigation by *Triplett and Van Doren [1969]*, the long-term effects of no-tillage and conventional tillage were studied, but somewhat different techniques were used. No cover crops were grown between consecutive maize crops but the crop residues from the previous year were chopped; they were left on the soil as a mulch in the no-tillage treatment and incorporated into the soil in the conventional tillage treatment. Fertilizers were applied partly in the band and the rest broadcast. The tilled plots were ploughed, disced, sown and cultivated whilst the no-tillage plots were sprayed and planted, and there was no subsequent cultivation. In both treatments, sowing was carried out either with a grassland drill opener or with a maize-planter equipped with disc-openers.

The fertilizers were applied at the following rates: N: 67, 134 and 268 kg/ha; P: 9 kg/ha in the row and 55 kg/ha broadcast; and K: 19 kg/ha in the row and 110 kg/ha broadcast.

Nitrogen: Nitrogen content of the leaves sampled after tasseling was not affected by tillage method. However, the maize crop responded with increased yields to the second increment of nitrogen on the no-tilled treatments, but not on the tilled treatments.
Phosphorus: In the untilled treatments most of the broadcast phosphorus remained in the top 2.5 cm of the soil, whilst below the plant rows, the phosphorus was uniformly distributed to a depth of 7.5 cm, reflecting annual band applications near the rows. In the ploughed treatment most of the phosphorus was in the 5 to 18 cm depth.
Potassium concentration decreased with sampling depth in the no-tillage treatments but was uniform in depth with the tilled treatments. The gradient in K concentration with depth in the no-tillage plots indicates that some of the surface applied potassium moved downwards.
The contents of both P and K in the plant tissues were higher in the no-tillage treatment, when sampled at the 8 to 10 leaf stage and equal for both treatments after tasseling. These results indicate that P- and K- uptake were at least as good for plants grown without tillage as for those grown with tillage.
In summary: broadcast applications of phosphorus and potassium tended to accumulate near the soil surface with the no-tillage treatments. Downward movement was somewhat greater for potassium than for phosphorus. The mulch cover, provided

either by the chemically-killed sod in the first investigation or by the chopped crop residues in the second investigation, apparently maintained adequate soil moisture near the soil surface for root growth. As a result, phosphorus and potassium, applied to the mulch-covered soil surface, were as available and possibly more available to the plants, as the same amount of nutrients incorporated into a bare soil.

The most desirable procedure for untilled maize appears to be to apply part of the P and K in a band below and to the side of the seed, and to broadcast the remainder on a well-mulched surface.

15.3.5 Effect of land-leveling on fertilizer requirements

Where surface irrigation is to be practiced, land-leveling operations are generally necessary. These remove valuable surface soil and hence problems of restoring fertility to these soils arise. Similar problems are caused by soil erosion due to wind or rain. Most subsoils are lower in nitrogen than the surface soil. They are also generally lower in organic phosphorus and readily available phosphorus. By contrast, many subsoils are higher in calcium, magnesium and available potassium than are the related surface soils *(Carlson et al. [1961])*.

The effects of removing the topsoil of a silt loam on the yields of maize, and means of improving the fertility of exposed sub-soils, were studied in Ohio *(Bachtell et al. [1956])*. In the first year after removal of the topsoil, the level of nitrogen in the subsoil was about 33 per cent of that in normal-depth topsoil. Yields obtained on the subsoil without fertilization were 61 per cent of those on the topsoil. Fertilization and manuring increased the N level of the subsoil during the experiment to 50 per cent of that of the topsoil, and yields of maize to 87 per cent of that of fertilized and manured topsoil. Although yields were improved, it was not possible in the course of a 20-year period to raise the physical and chemical properties of the subsoil in this particular case to the same level as that of the topsoil.

In an experiment in the Northern Great Plains (USA), maize was grown on a fine sandy loam, the first and third years after leveling. Where the topsoil had been removed, the most deficient element was nitrogen, followed by phosphorus and then zinc. It was necessary to apply adequate amounts of N, P, Zn and manure, to bring yields on the subsoil up to those on the undisturbed soil.

Applications of Zn increased the yields of maize, both during the year it was applied and two years later. Manure applied the first year after leveling increased maize yields and supplied residual P and Zn to the maize sown two years later. However, applications of manure gave lower yields than N+P+Zn fertilizer applications *(Carlson et al. [1961])*.

On a silt loam in Iowa, it was found that the yields of maize on an exposed subsoil, without nitrogen, were 285–320 kg lower than on the corresponding surface soils. However, by providing adequate nitrogen fertilizer, it was possible in this case to obtain equal yields on the subsoil and the normal surface soil. The production of maximum yields of maize required 38–57 kg of N more per ha than a normal soil *(Engelstad and Shrader [1961]* **(Figure 183)**.

As phosphorus and potassium fertilizer in adequate amounts were applied to both the surface and exposed subsoil, it is evident that the difference in productivity between the two soil layers was due mainly to marked nitrogen deficiency of the exposed subsoil.

15.4 Fertilizers in relation to disease, pest and weed control

15.4.1 Diseases

The nutrient status of a crop may have a considerable effect on the ability of the plant to withstand disease, and the resistance of undernourished plants to disease may be considerably weakened. The high fertilizer rates associated with the productivity of modern maize hybrids are bound to affect the reactions of these hybrids to disease and insects. The heavy fertilization may even help to control one particular disease and to encourage another.

Walker [1946] has shown that the effect of several wilt diseases – which are of great importance in irrigated soils – can be greatly reduced by appropriate potassium fertilization in soils deficient in this element.

In particular, the increasingly heavy rates of nitrogen usually applied to hybrid maize may have a marked detrimental effect on plant resistance, especially if the nitrogen is not balanced by appropriate amounts of phosphorus and potassium. The formation of soft tissue facilitates penetration by the agents of disease, and the production of high concentrations of soluble nitrogen compounds provides a favourable medium for fungal parasites and bacteria. The heavy vegetative growth favours contact transmission of leaf diseases and creates a humid microclimate that aids spore germination.

– *Stalk-rots and root-rots*

One of the principal factors involved in the lodging of maize, with its attendant reductions in yields and increased difficulties of harvesting, is rot of the stalk and root. The effect of fertilizers, and in particular of potassium, on stalk rots and root rots of maize has been the subject of many investigations.

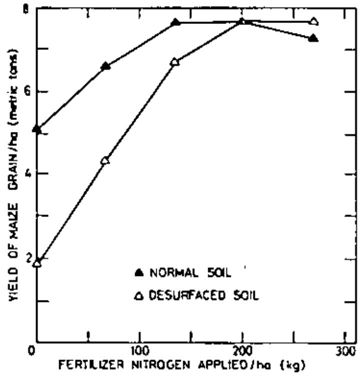

Fig. 183 Effect of increasing levels of nitrogen fertilizer applications on a silt loam soil, in its normal condition and after removal of the surface soil *(Engelstad and Shrader [1961])*. By courtesy of the Soil Science Society of America.

The incidence of *stalk rot* generally increases with soil fertility. For example, on the famed Morrow plots at the University of Illinois, on continuous maize plots with 4.0 plants/m^2, the incidence of disease was 77.7 per cent on the fertility plots and only 28.5 per cent on the low fertility plots *(Hooker [1962])*.

Most of the available evidence indicates that it is not the high level of fertility *per se* that is the cause of the increased disease incidence, but the lack of balance between nitrogen and potassium which seems to play the major role in the development of stalk rot and the resulting lodging of plants. When the fertility level of the soil is out of balance, and in particular where supplies of potassium are not adequate, root rots appear to develop more readily. A low potassium/nitrogen ratio was found to increase the incidence of root rot, as shown in Table 91.

Table 91. Effect of fertilizer applications on maize stalk rot *(Hooker [1962])*
Amounts of fertilizer applied (kg/ha)

N	P_2O_5	K_2O	Stalk rot (%)	Yields (kg/ha)
0	0	0	16	5080
88	0	0	40	5334
0	38.5	0	21	5334
0	0	72.6	17	5588
88	38.5	0	69	(not given)
0	38.5	72.6	13	5397
88	38.5	72.6	17	6985

Whilst an application of nitrogen (88 kg/ha) and phosphorus (38.5 kg/ha) increased stalk rot from 16 to 69 per cent, adding potassium reduced stalk rot practically to the same level as in unfertilized maize. The highest yield of maize was obtained by a balanced application of nitrogen, phosphorus and potassium.

Initial infection by certain root-rotting organisms early in the season occurs in the root or crown, and subsequently spreads to other parts of the plant.

Early mineral nutrition may therefore influence the incidence of the disease in certain cases. *Parker and Burrows [1959]*, who investigated this problem, report that the level of available nitrogen was the major cultural factor involved. Under conditions in which the potassium supply to the plants was adequate, as indicated by the potassium content in the plant tissues, fertilizing with potassium had less influence on the disease than did nitrogen.

Koehler [1960] working in Illinois, found that when the nitrogen content of the soil was low, potassium deficiency had little effect on the disease, but when nitrogen alone was added, stalk rot increased considerably.

Similar results were obtained in field studies in New York State. It was found that in general the severity of root-rot increased with increased rates of nitrogen application and decreased with an increased supply of potassium. A balanced supply of nitrogen and potassium reduced root rot incidence, in comparison with an excess of nitrogen *(Otto and Everett [1956])*.

The form in which the nitrogen fertilizer is applied may be relevant to its effect on a disease. For example, nitrate nitrogen decreases the severity of stalk rots of maize caused by *Fusarium* or *Rhizoctonia* spp, whilst the ammonia form aggravates the disease *(Huber [1966])*.

Studies on the effects of high Cl levels on the lodging of maize have produced conflicting results *(Carther and Lathwell [1967])*.

Younts and Musgrave [1958] report that stalk rot incidence was decreased as a result of increased potassium chloride applications but not with potassium sulphate or potassium metaphosphate. They attribute the favourable effect to a desirable chloride level in the plant, since the application of chloride at the rate of 45 kg/ha resulted in earlier maturity, less stalk rot and a higher chloride level in the plant at the time it is attacked by *Gibberella*. Heavier rates of Cl (100 kg/ha) had the opposite effects.

In Wisconsin, ammonium chloride used as the source of N on NP plots, produced the same number of lodged plants as on plots where the nitrogen source contained no chloride *(Anon. [1965])*.

In a recent work, *Martens and Arny [1967]* confirmed the observation of *Younts and Musgrave [1958]* on the effects of KCl in reducing stalk rot. However, their results suggest that the beneficial effects cannot be attributed to Cl alone, as they obtained a considerably greater response from KCl than from Cl alone.

They also failed to confirm that high levels of Cl have an adverse effect; the rates they applied (158 kg/ha of Cl) were actually far higher than those of the earlier investigations. They attribute this disparity to differences in soil types, available Cl, and moisture levels, and to genetic differences in the lines used.

Since stalk rot is usually initiated by the advance of the pathogen from the roots, the investigators assume that the progress of the pathogen in the root and from there into the stalk is delayed by both Cl and K treatments.

Pappelis and Boone [1966] studied the effects of fertilizer applications on the incidence of dead tissue in the lower nodes of maize stalks. They found that the areas of dead parenchyma cells in the stalk tissue, as well as the percentage of affected plants were generally greater in plants given nitrogen or phosphorus than in unfertilized plants. The response to limestone and potassium in their trials was not consistent: in some treatments the addition of potassium or limestone reduced the incidence of the disease, whereas in others it increased it. The reduction in susceptibility as a result of potassium was generally greater and more striking than the increase in susceptibility. Following an intensive investigation of root and stalk rot of maize in Ontario, it was found that no single causal organism was responsible for this disease, but that several fungi and even some bacteria may be involved *(Mortimore and Ward [1964])*.

Although various rotting organisms may invade the root at a relatively early stage of plant growth, root and stalk rots are essentially diseases related to the onset of senescence. No specific symptoms are visible until the plant has reached physiological maturity. The disease is actually a premature degradation of the stalk, in which a number of common decay organisms are involved. Resistance appears to depend upon the maintenance of the physiological vigour of the stalks during the period after physiological maturity, when the maize is left standing in the field until the grain loses sufficient moisture to permit harvesting.

Physiological vigour can be maintained by a steady respiration rate supported by a continuous and steady supply of carbohydrates, provided there is a regular and adequate supply of nutrients.

Under ideal conditions, the maize plant can produce sufficient carbohydrates to meet all requirements of both ear and plant. Under conditions of stress, which restrict photosynthesis or interfere with carbohydrate metabolism, the amounts of carbohydrates produced are no longer sufficient to satisfy all demands. Then the demands of the developing ear are met first, and as a result the level of carbohydrates in the stalks is reduced.

When the vigour of a plant is reduced below a certain level due to these stress conditions, the plant becomes susceptible to invasion by certain saprophytes and weak parasites *(Mortimore and Ward [1964])*.

A number of investigations have shown that there is a negative association between total and reducing sugars in the pith of maize stalks at physiological maturity, and root rot susceptibility. A hybrid resistant to the rots had a higher sugar content than a susceptible hybrid, when grown under recommended cultural practices.

High population densities, which increase the tendency to stalk rot, also cause a reduction in sugars. Conversely, treatments which increase resistance to rots, such as the prevention of kernel development, result in high levels of sugar in the pith *(Mortimore and Ward [1964])*.

Craig and Hooker [1961] demonstrated that increases in total sugar, sucrose and reducing sugar, and high pith density, were associated with resistance to stalk rot. They therefore concluded that a decrease in the sugar level in the stalk causes the senescence of pith tissue, indicated by a decrease in pith density, and that plants with senescent pith tissues become susceptible to stalk rot.

The findings of *Martens and Arny [1967]* also confirm that resistance to stalk rot is associated with high sugar levels in the pith tissue of the stalk. Conversely, these authors found a negative association between resistance and organic nitrogen levels – in the same tissues. In lines resistant to stalk rot the sugar/nitrogen ratio was higher than in susceptible lines. It is possible that high sugar/nitrogen ratios are suboptimal for pathogen growth in the stalk, or, that the high sugar concentrations cause osmotic inhibition which retards the development of the fungus. K, Cl and N could presumably affect resistance to the pathogen by influencing the sugar/nitrogen ratio, the first two favourably and the last one unfavourably.

– *Leaf blight*

Marked differences in the severity of northern leaf blight *(Helminthosporium turcicum)* were observed in fertilizer experiments on maize in Illinois. P and N fertilizers caused a slight increase in the incidence of leaf blight, and limestone, in the absence of K, almost doubled the leaf blight scores. By contrast, the addition of K substantially reduced the severity of the disease. This was most marked on plots which also received limestone. It is assumed that the increased incidence of the disease following limestone application is due to the exhaustion of K in the limed plots, as yields were substantially greater following liming *(Hooker et al. [1963])*.

Gorsline et al. [1963] have demonstrated that the severity of *Helminthosporium* leaf blight was positively associated with calcium and zinc content of the leaf, and negatively with potassium content. However, the data available did not allow a separation of cause and effect, and it was not possible to establish whether the levels of these elements influence in some way the susceptibility of the plant to leaf blight or whether the disease influences the accumulation of the nutrients.

– *Fusarium ear-rot*
In field tests in Illinois, applications of phosphoric fertilizer were found to decrease the incidence of *Fusarium* ear rot significantly, but had no marked effect on *Diplodia* or *Gibberella* ear rots *(Koehler /1959/)*.

– *Smut*
Susceptibility to smut is associated with tender, succulent, and vigourously growing tissues; hence, high applications of nitrogen have been observed to increase smut infection *(Hooker /1962/)*.

15.4.2 Insects

Insects are not affected in the same way as animals by mineral deficiencies in the plants on which they feed. *Haseman /1946/* found that, in a number of cases, a shortage of certain minerals actually proved beneficial rather than detrimental to insects. It was found that the chinch bug matures faster, lives longer and is more prolific when it feeds on maize grown under conditions of N-deficiency. Thrips have also shown differential preference for plants with a low level of nitrogen nutrition. *Haseman /1946/* claims that as insects generally require smaller amounts of minerals than do plants, it is quite possible that plants with a low mineral content may be more favourable hosts than those with a higher mineral content. Depletion of soil nutrients, associated with irrigation, either directly through leaching or indirectly through increased yields, may therefore increase susceptibility to insect damage, unless offset by appropriate fertilization. On the other hand, heavy fertilization, by increasing vegetative growth, may favour the increase of certain insects, such as aphids.

Nitrogen application at the rate of 88 kg N/ha have been shown to produce maize stalks with a lower crushing strength, thinner rinds and consequently higher rate of infection by European maize borers *(Ostrinia nubilalis) (Zuber and Dicke /1964/)*.

By contrast, *Klostermeyr /1950/* found that nitrogen fertilization caused significant differences in maize earworm *(Heliothis armigera)* infestation and damage to field maize and sweet maize. An increase in nitrogen resulted in less earworm damage (**Figure 184**). The infestation decreased from 100 per cent on unfertilized plants to 81 per cent on fertilized plants, and the percentage of injured kernels from 21.6 to 4.1. As no significant differences were found in respiration or growth rate of the worms, the differences in infestation and damage are attributed to lower moth populations due to the following effects of the fertilizers: (a) earlier silking; (b) greater number of ears; (c) increased length and tightness of husks; and (d) larger size of ears, with the result that less kernel consumption was needed to satisfy the food requirements of the worms. Presumably, other nutrients affecting the plants in a similar way, would therefore also be beneficial in reducing earworm damage.

Hill et al. /1948/ studied the interaction between crop rotation and fertilization in relation to the control of certain insects attacking maize. Crop rotations were found

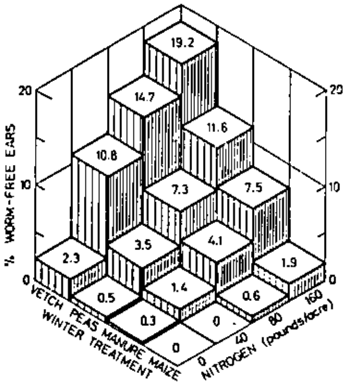

Fig. 184 Effect of preceding crop or winter treatment, and of nitrogen fertilizer, on the infestation by maize earworms in sweet maize *(Klostermeyr [1950])*. By courtesy of the American Association of Economic Entomologists.

to give fairly good control of the northern rootworm *(Diabrotica longicornis)*, the western corn rootworm *(D. virgifera)* and the southern corn rootworm *(D. undecimpunctata howardi) (Hill et al. [1948])*. The application of fertilizers enhances the effects of the crop rotation in overcoming the yield reductions due to insects – without actually controlling the insects, by ensuring satisfactory yields even under conditions of moderate infestation. Nitrogen was found to enable quick recovery of plants attacked by rootworms. There is also some evidence that potassium salts may have some direct deleterious effects on the larvae of the rootworms in the soil *[ibid.]*.

15.4.3 Weeds

Interactions between weeds and fertilizer applications relate to (a) the influence on the weed population, (b) competition between maize and weeds for nutrients, or (c) to the effects of specific herbicides on nutrient uptake and utilization by maize.

– Fertilizer effects on weed population

It is self-evident that fertilizer applications will also be beneficial to weeds. Fertilizers that are broadcast and superficially incoporated into the seed bed will stimulate weed growth more than the same amounts applied in the band or ploughed under. Late spring or summer applications will stimulate weed growth more than earlier applications *(Barber and Olson [1968])*.

– Competition between maize and weeds

Pop-up fertilizers and fertilizers applied in the row will give maximum stimulation to the young maize plants and enable them to compete more effectively with weeds. The more rapid growth of the maize also makes earlier cultivation between rows possible, and hence, more effective mechanical control of weeds.

Competition between maize and foxtail *(Setaria lutescens)* was found to be primarily for soil moisture and nutrients, particularly nitrogen *(Staniforth [1957])*. Maize yields were reduced by mature foxtail infestation by 890 kg/ha, when no nitrogen fertilizers were applied. Yield losses due to the competition of the weeds were reduced to 635 kg and 318 kg/ha, respectively, with applications of 77 kg and 154 kg of elemental nitrogen per ha. Maize responded two to three times more strongly than foxtail to the applications of the fertilizer. Apparently, the fertilized maize plants developed more extensive and deeper root systems than the foxtail, and were thus better able to utilize soil moisture when it became increasingly by limiting in mid-summer.

In pot trials carried out in Ukraine *(Veselovskii and Man'ko [1969])*, simazine applications effectively controlled weeds in maize and showed striking interactions with fertilizer applications (Table 92).

Table 92. Interactions between weed control in maize by simazine and levels of fertilizer application *(Veselovskii and Man'Ko [1969])*

Amount of fertilizer (g/kg soil)			Dry matter yield per plant (g)		Percentage increase in yield due to weed control
N	P	K	without simazine	with simazine	
0	0	0	3.79	10.50	166
0.3	0.2	0.3	45.20	82.20	81
0.6	0.4	0.6	52.60	66.70	28
0.9	0.6	0.9	47.40	62.10	31

The decreasing relative effect of weed control on the productivity of maize with increased fertilization is a clear indication that competition between maize and weeds for nutrients was very severe. Of particular interest is that effective weed control cut in half the level of nutrients required for maximum yield.

In field trials with maize in the Ukraine, a decrease in weed population from slightly more than 3 million to 100 000 pl/ha, was accompanied by increases in uptake of N by maize from 9.1 to 170 kg/ha, of P_2O_5 from 22.1 to 87.1 kg/ha, and of K_2O from 15.1 to 105.7 kg/ha. Simultaneous decreases occurred in the uptake of N by weeds from 98.2 to 0.25 kg/ha, of P_2O_5 from 197.2 to 13 kg/ha, and of K_2O from 189.9 to 8 kg/ha *(Fisyunov [1969])*.

– Interactions between herbicides and nutrient uptake

Freney [1965] has shown that simazine applied at 0.06 ppm in solution culture increased the yield of maize tops by 36 per cent, the uptake of nitrogen by 37 per cent, of phosphorus by 25 per cent, of potassium by 41 per cent, and of magnesium by 24 per cent. When simazine was applied at 1.5 ppm to the soil, dry matter yields and N uptake were similarly increased, provided additional nitrogen was supplied to the soil. The effect of simazine at these levels was not due to an appreciable increment of nitrogen or to weed control. The simazine apparently stimulated early growth of maize; if the supply of available nitrogen was exhausted the effect of the simazine was nullified. The results obtained by *Freney [1965]* suggest that simazine increased plant growth by a direct effect on plant metabolism and not through any interactions with the soil.

However, *Tweedy and Ries [1967]* demonstrated that the efficiency of nitrate utilization by maize, following applications at non-toxic levels of simazine, is expressed only at sub-optimal levels of low nitrate and low temperatures. Under these conditions they found that simazine, applied to the root-zone area, increased dry weight production by 26 per cent and total nitrogen content by 21 per cent. Nitrate reductase activity of leaf extracts grown under these conditions increased almost ten-fold as a result of simazine applications, so that the beneficial effect of simazine appears to be due to a more rapid assimilation of nitrate *[ibid.]*.

Atrazine and simazine have generally been found to generally increase nitrogen uptake, and as a result also increase the nitrogen and crude protein content of maize. Simazine treatments gave greener and taller plants. Nitrogen deficiency symptoms disappeared in maize plants after applications of simazine *(Eastin and Davies [1967])*. *Gramlich et al. [1965]* found that atrazine treatments in the field usually resulted in higher shoot: root ratios in maize plants, and a higher percentage of both protein and non-protein nitrogen than non-treated plants. Nitrate reductase activity generally increased as a result of atrazine treatment *(Gramlich et al. [1965])*.

By contrast, 2,4-D generally retards the normal transformation of nitrate to protein in maize, resulting in a higher nitrate content in silage. For this reason cultivation, if sufficiently effective, will be preferred to 2,4-D applications when maize is grown for silage *(Kurtz and Smith [1966])*.

Atrazine, applied in the field at rates that had no apparent effect on the growth of maize, increased P concentrations in the leaf blades but not in the grain *(Rudgers et al. [1970])*.

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16. Heredity and fertilizer utilization

16.1 Nutrition variation due to genetical factors

It is well known that there are considerable differences among plant species in their ability to take up mineral nutrients from relatively unavailable sources. There are also marked differences among the different varieties, inbreds and hybrids of maize, in this respect.

Four main forms of nutrition variation due to genetical factors can be recognized: (a) differential nutrient uptake, (b) differential yield response, (c) requirements for specific elements, and (d) differential resistance to mineral toxicities *(Vose [1967])*.

In the past, much of the breeding work for maize was done on soils of average fertility, and the varieties or hybrids available at the time were not capable of fully exploiting the higher yield potentials that could be achieved by raising soil fertility levels. Conversely, at the traditional levels of fertilization employed in the past, genotypes with high potential yielding ability were not revealed. It is only fairly recently that the need for testing genetic material and hybrids at various levels of soil fertility and plant population density, and adjusting these factors to each another, have become fully appreciated.

16.1.1 Nutrient uptake

Different inbreds and hybrids, grown under identical conditions of nutrient supply, may have greater differences in mineral content than the differences occurring within a genotype receiving different amounts of fertilizers. Inbreds and hybrids may also differ in their susceptibility to toxicity from high concentrations of an element *(Gerloff [1963])*.

An example of the wide range in the concentration of nutrients in maize hybrids is shown in Table 93 *(Baker et al. [1967])*.

After analysis of a large number of maize leaf tissues, *Benton Jones [1960]* found that many lines have marked differences in their nutrient contents. He was able to classify these lines as low, medium or high accumulators of specific elements. Those elements which showed the widest variation among lines were N, K, Mn and B.

Benton Jones undertook a number of experiments to test the reaction of two groups of inbreds to potassium levels in the medium.

In previous trials, inbreds Pa 56 and Ohio 43 had been found to be high K accumulators, and Pa 26, Pa 11 and Ohio 07 were representative of low K accumulators. In one experiment, Pa 56 and Pa 11 were grown in nutrient solutions with increasing concen-

Table 93. Range in concentration of nutrients in corn hybrids *(Baker et al. [1967])*

Nutrient	Concentration in ear leaf*		
	Low	Average	High
Phosphorus	0.14	0.33	0.65
Potassium	1.70	2.06	2.80
Calcium	0.60	0.82	1.19
Magnesium	0.18	0.30	0.45
Manganese	19	45	84
Iron	86	106	147
Copper	11	19	34
Boron	7	14.5	23
Aluminium	26	47.6	94
Zinc	12	57	104

* Concentrations of P, K, Ca and Mg expressed in per cent, and of all others in ppm. Leaf samples were taken 20 to 30 days after mid-silk.

trations of potassium. The growth of Pa 56 was markedly accelerated by the increasing concentration of K in the growth medium, while that of Pa 11 was barely affected **(Figure 185a)**. In a second experiment, with inbreds Ohio 43 and OH 07, the growth of both lines was increased by increasing levels of K in the solution, but OH 43 reacted much more strongly than OH 7 **(Figure 185b)**. Two double crosses, Ohio K 62 and Ohio W 64, were grown in nutrient solutions with ten different levels of potassium (ranging from 0 to 200 ppm K). They were also found to respond differently to the increasing levels of K in the growth media. Ohio K 62 developed more rapidly at lower K concentrations than Ohio W 64, but decreased in weight more rapidly than Ohio W 64 at higher (excessive) levels of K. The dry weights of the plants of the two hybrids versus their K content, are shown in **Figure 186**.

Sayre [1961] found marked differences among a number of inbreds regarding their Mg requirements. Certain inbreds grew equally well in solutions with low or high Mg contents, while others failed to develop properly on low Mg levels, but grew normally at higher Mg levels.

The total amounts of nutrients taken up by different lines and hybrids will vary still more considerably. Ranges in the nutrient contents of five hybrids grown in Florida, at different plant densities, are shown in Table 94 *(Robertson et al. [1968])*.

Table 94. Range of differences in nutrient uptake among five hybrids (kg/ha)

Plants/m^2	N	P	K
4.7	77–155	11–25	95–144
7.0	99–150	12–25	106–175
9.7	109–169	13–24	138–211

Corn hybrids grown for silage were also found to differ widely in the amount of nutrients they recovered (see **Figure 187**) *(Robertson et al. [1965])*.

Thomas [1963] established that the differential accumulation of nutrients in different lines of maize was under partial genetic control. The differential concentration of certain elements in the leaf tissue was established early in the life of the plant.

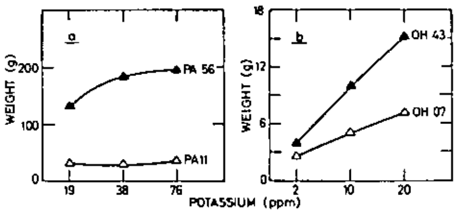

Fig. 185 Effect of increasing levels of potassium on the growth of two contrasting pairs of inbreds *(Benton Jones [1960])*. By courtesy of Elsevier Publishing Company, Amsterdam.

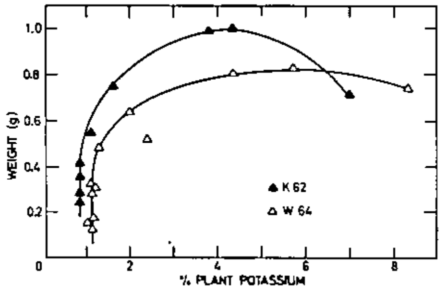

Fig. 186 Relationship between dry weight and K content of the plant tissues for two contrasting hybrids, K^{62} and W^{64}, when grown at 10 different levels of K in the growth media *(Benton Jones [1960]*. By courtesy of Elsevier Publishing Company, Amsterdam.

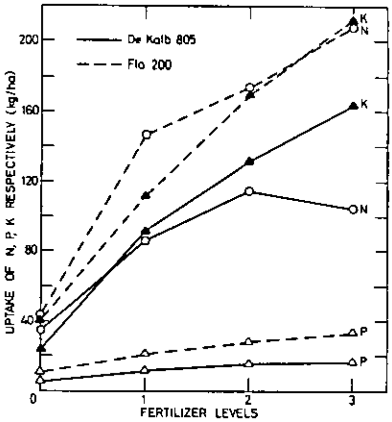

Fig. 187 Differential uptake of nitrogen and phosphorus by two contrasting hybrids grown for silage *(Robertson et al. [1968])*. By courtesy of the Soil Science Society of America.

Genetically controlled differences in phosphorus accumulation between inbred lines and their hybrids were demonstrated by *Barber et al. [1967]*, even though no relationship of leaf phosphorus content to grain yield was established in this study.

Loué [1963] showed that there are considerable differences in K_2O consumption between different varieties. These differences range from 110 to 180 kg/ha at the period of peak requirement, which occurs about three weeks after silking. Thereafter, the total accumulation of K_2O declines until maturity in all varieties **(Figure 188).**

Bradford et al. [1966] analysed more than 50 000 maize leaf samples from different genotypes grown under field conditions. They concluded that corn hybrids accumulated different amounts of Ca, Sr, P, Mg and K. They were also able to show that the differences between four single cross hybrids in respect to concentrations of Ca, Sr, K and Mg could be predicted from the chemical element accumulation characteristics of their parents. Partial genetic control of chemical element accumulation by these hybrids was apparent.

Differential accumulation of calcium, magnesium and potassium was found to occur for simple crosses and inbreds of maize *(Gorsline et al. [1961])*. This differential accumulation was highly inherited, essentially on an additive basis in respect to calcium and magnesium, but included non additive elements for potassium.

Halim et al. [1968] working with different inbreds and hybrids of maize, showed that genetically different lines had different accumulations of zinc and phosphorus in the leaf tissues. Lines could be classified as low, intermediate or high zinc or phosphate accumulators. Most lines showed an intermediate zinc content of 20 to 22 ppm. The investigators could not establish a minimum or critical level of zinc which would be applicable to all lines or hybrids of maize.

In trials with two maize varieties on chernozem soil, applications of $ZnSO_4$ at the rate of 3–8 kg Zn/ha, over a basal dressing of 10 kg P_2O_5/ha, increased grain yields by 8.8–27 per cent; higher rates were more effective than lower rates, and VIR-156 showed a greater response to all rates than VIR-42 *(Dibrova [1968])*.

Mutations may occur in maize which are less efficient in the uptake of certain nutrients than normal plants. One such mutation is yellow-stripe-1 which is inefficient in the

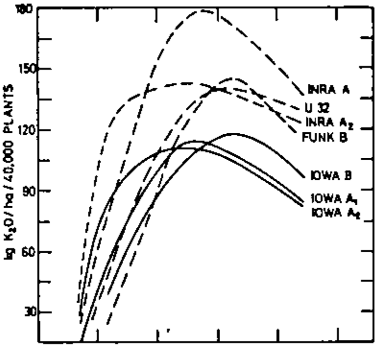

Fig. 188 Differential uptake of potassium (in kg of K_2O/ha) by seven maize hybrids *(Loué [1963])*. By courtesy, Editor, World Crops.

uptake of iron, and develops iron chlorosis on soils on which another line (Pa 54) grows normally (*Brown [1967]*). It was found that the two genotypes absorb and translocate PO_4 differentially from organic PO_4. Since iron deficiency is accentuated by PO_4, this differential uptake might be associated with Fe utilization *[ibid.]*.

In a more recent work (*Brown and Bell [1969]*), the data show that the Fe-inefficient plants have less reducing capacity at the roots, require less Fe stress for maximum uptake of Fe, are less tolerant to PO_4, are less efficient at taking Fe from FeDTPA, and are less efficient at lowering the pH of the prenutrient than the iron-efficient plants. The efficiency of Fe uptake of the maize is controlled by a recessive gene.

Another differential response in the two genotypes is related to copper uptake. The addition of Cu to a Cu-deficient soil decreased the absorption and translocation of Fe much more in Pa 54 than in the yellow-stripe-1 mutant. As a result, the distribution of Ca into the top leaves was enhanced, and the appearance of typical Cu-deficiency symptoms, such as twisted and necrotic leaves, was prevented (*Brown [1967]*).

16.1.2 Yield response

Most genetic differences in nutrient uptake and utilization will probably result in differential yield responses. There is therefore reason to assume, that at least in some of the conflicting results recorded in the yield responses of maize to fertilization, hereditary differences among the varieties, strains or hybrids that were used, were involved.

For example, maize was found to respond markedly to applications of copper by *Teakle et al. [1940]*, who proposed it as an indicator plant for copper deficiency, whereas *Brown and Holmes [1955]* found that maize showed only moderate symptoms of Cu-deficiency on a soil in which wheat was severely affected.

Marked differences in the response of the maize hybrids to phosphate fertilization were reported by *DeTurk et al. [1933]*. The hybrid which responded to higher levels of applied phosphorus matured earlier and gave increased yields as a result of P-fertilization. The investigators assumed that the non-responsive hybrid is better able than the responsive hybrid to absorb P from a limited supply, but when the supply was adequate it was not able to maintain a high absorption rate.

However, the most striking differences in response to fertilizers are those between open-pollinated varieties and the newer hybrid varieties.

Most of the open-pollinated varieties developed by natural or oriented selection are simply not capable, under the conditions of low fertility that are characteristic of primitive agriculture, of making *efficient* use of fertilizers; the economic use of fertilizers in developing countries may therefore be dependent on replacing the primitive varieties by others which are capable of responding to high fertility levels.

For example, indigenous Mexican maize varieties are capable of yielding under much lower conditions of productivity than American varieties of open-pollinated maize. The yield of grain per plant averages around 60 gm, and with fertilizers may increase to 80 gm, as compared with average grain yield per plant of more than 200 gm for the old open-pollinated American varieties. The process of selection in low productivity conditions in Mexico has probably resulted in ecotypes that are capable of producing

ears – however small – under condition of nutritional stress under which more potentially productive varieties would be barren *(Miller et al. [1950])*.
The responsiveness of hybrid maize to high fertilizer applications is also demonstrated by the results of the *FFHC Fertilizer Programme* experiments obtained in Honduras *(FAO [1965])*.

Table 95. Differential response of varieties and hybrids to fertilizers *(FAO [1965])*

	Number of demonstrations	Treatment N-P_2O_5-K_2O (kg/ha)	Yield increase (kg/ha)	%	Net return (\$/ha)	Value/cost ratio
Local unimproved varieties	7	45–45–45	745	30	18	1.6
Local improved varieties	28	45–0–0	630	19	27	2.8
Hybrid maize	9	90–90–90	5013	105	272	5.3

In developed countries, if further advances in crop yields are to be achieved, and a maximum return obtained from the large investments in fertilizers applied to the maize crop, deliberate selection for nutrient efficiency appears to be justified *(Vose [1963])*.

16.1.3 Mechanisms for differential uptake and accumulation of nutrients

The differences between maize strains and hybrids in their ability to take up nutrients such as phosphorus and potassium from the soil, under conditions where diffusion of nutrients governs their availability, may be due in part to the relative extents of their root systems, their transpiration ratios and their ability to lower the concentration of the nutrients to a very low level at the root interface *(Barber [1962])*.
Other factors that are probably involved are the ease of translocation of the absorbed nutrients, metabolic mechanisms, disease resistance, etc.

– *Root morphology*
When a number of hybrids were grown in the field, significant differences in their ability to absorb calcium in preference to strontium, or vice versa, were recorded *(Baker et al. [1967])*. The same hybrids, however, showed no differences in this respect when grown in a greenhouse, where the plant roots were restricted to a homogeneous substrate. This suggests that significant differences in differential uptake of Ca and Sr among maize hybrids in the field are due to inherent differences in the depth of rooting among the hybrids tested.
In studies on zinc deficiency in several inbreds and single crosses of maize *(Halim et al. [1968])*, it was found that the degree and pattern of zinc deficiency symptoms depended largely on genotype. Certain inbreds were susceptible to zinc deficiencies in the early stages of growth, but revived at later stages. Other inbreds showed the opposite effects. Some lines and hybrids showed a high degree of resistance to zinc deficiency. The highly resistant lines had normal and healthy root development, whereas susceptible lines had reduced root development and decayed root tips when grown under conditions of zinc-deficiency.

– *Exchange – absorption*
It has been shown that the higher the cation-exchange capacity of plant roots, the more effective is the plant in using soil phosphorus *(Drake and Steckel [1955])*.

– *Active uptake*
In a study by *Halim et al. [1968]*, it was found that lines and hybrids of maize showed considerable differences in the influence of high phosphorus levels on zinc uptake by the plants. In certain lines and hybrids, zinc uptake was inhibited by high phosphorus levels, whereas in others, zinc uptake actually increased as the level of phosphorus increased. Finally, there were also other genotypes in which no noticeable change in zinc level was induced by applications of large amounts of phosphorus.
The conflicting results reported on the influence of high levels of phosphorus on zinc uptake may therefore be due to genetic differences among the lines or hybrids involved.

– *Translocation*
Foy and Barber [1958] demonstrated that the low levels of magnesium in the leaves of a maize inbred with 'low magnesium feeding power' (Ohio 40B) were not due to any lack of magnesium adsorbing or absorbing ability on the part of the roots of this genotype. Actually, the roots of Ohio 40M had a higher total cation-exchange capacity and adsorbed magnesium more rapidly than WF9, an inbred with 'high magnesium feeding power'. Whilst WF9 always had a higher concentration of Mg in the leaves than Ohio 40B, the latter consistently had a higher concentration of Mg in the stems. The investigators concluded that the low concentration of magnesium in Ohio 40B leaves is due primarily to the immobilization of Mg in the stems of the Ohio inbred *(Foy and Barber [1958])*.

– *Metabolic effects*
The balance between iron and phosphorus and between iron and manganese has been shown to be responsible for disturbed Fe metabolism in a number of crops, and confirmed for maize by *Odurukwe and Maynard [1969]* who studied the mechanism of differential response to Fe nutrition of two inbred lines, Oh 40B and WF9. Oh 40B accumulated more P and Mn and showed more chlorosis than WF9. On the other hand, levels of Fe that caused toxicity symptoms in WF9, had no such effects on Oh 40B. The authors conclude that Oh 40B is more susceptible in the seedling stage to chlorosis than WF9 because of its low Fe: P and Fe: Mn ratios and the lower amounts of available Fe. Conversely, WF9 is more susceptible to Fe toxicity because of the greater concentration of available Fe in its tissues, as indicated by the higher Fe: Mn ratios.
A differential response to different nitrogen levels has also been found between maize hybrids, and has been ascribed to the higher level of nitrate reduction activity of the more efficient hybrid *(Hageman et al. [1963])*.

– *Disease resistance*
In East-Central Hokkaido, the northern Island of Japan, applications of nitrogen at the rate of 165 N/ha increased yields of the hybrid Wisc. 335 A by 2030 kg/ha, in comparison with the low rate of 24 N/ha; an average increase of 35 kg of grain per

kg of applied N. Under the same circumstances, the yields of Mich. 250 were increased by only 800 kg/ha, or an average increase of 5.7 kg of grain per kg of applied N. For a third hybrid, Mass. 63, the high rate of nitrogen increased yields by only 70 kg/ha. The lack of response of the last hybrid is ascribed to its susceptibility to leaf blight *(Drake et al. [1962])*.

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17. Fertilizer practice

In the preceding chapters, an attempt has been made to review the present state of knowledge on the nutrient requirements of maize, and how these are affected by environmental and cultural practices.

In this chapter, general recommendations will be presented, the use of fertilizers in actual field practice in a number of countries will be briefly described, and the economics of fertilizing maize will be discussed.

17.1 General recommendations

17.1.1 Nitrogen

Maize requires large amounts of nitrogen for high yields in intensive systems of agriculture, and few soils supply enough nitrogen for this purpose.

As a general rule, and provided other growing conditions are not limiting, maize responds favourably to large applications of nitrogen. Yield increases of 3000 kg/ha following nitrogen fertilization are common with hybrid maize. The lower the inherent fertility of the soil, the greater the response. Maximum response is also dependent on a sufficiently high plant population. The expected size of the crop sets the minimum amount of nitrogen that has to be supplied. As a rule of thumb, it is assumed that for every 100 kg of grain produced, 1.8 kg of N in the grain and 1 kg in the above-ground parts of the plant are required, and must be supplied by the soil and the fertilizer *(Kurtz and Smith [1966])*.

The usual rates of application vary from 40 to 200 kg N kg/ha, depending on the soil moisture regime, soil fertility and whether or not organic manures have been applied.

17.1.2 Phosphorus

Although the response of maize to phosphorus is less spectacular and more variable than that to nitrogen, phosphorus deficiency will severely limit yields. In particular, a marked response will be obtained on soils that have been heavily cropped in the past, without adequate restitution of phosphorus. By contrast, after several years of fertilizing with phosphorus, response may become negligible, as a result of a cumulative residual effect. The usual rates of application vary from a low rate of 6 kg P/ha to rates as high as 50–60 kg P/ha.

17.1.3 Potassium

In most arid zone soils, maize usually shows little or no response to potassium when limiting factors, such as an inadequate moisture supply, keep yields low. However, as cropping becomes more intensive and yields increase as a result of irrigation and the higher productivity of the hybrids grown, potassium deficiencies appear sooner or later *(Arnon [1971])*.

In the humid regions, the response to potassium is generally pronounced and repeatable, particularly on soils with a low level of exchangeable bases *(Loué [1963])*.

When soils in the Corn Belt of the United States were first cultivated, maize was usually able to obtain sufficient potassium from the natural soil sources, and little potassium fertilizer was used. However, continued cropping of these soils has greatly reduced the levels of available potassium in the soils. At present, many of these soils test low or very low in available potassium *(Barber and Mederski [1966])*.

Hanway et al. [1962], on the basis of fertilizer experiments in various locations of the Corn Belt, found that the uptake of fertilizer potassium was inversely related to exchangeable soil potassium, and that yields of maize ranging from 2000 to 8000 kg/ha were correlated with potassium levels in the leaves at silking.

The amount of potassium taken up by the maize plant is only somewhat less than that of nitrogen. A crop of 10 000 kg/ha of grain may require approximately 180–200 kg of potassium. However, most of the potassium does not move to the grain, and a very small part appears to move back into the soil through the root system *(Sayre [1955])*. The amounts of exchangeable potassium in the root zone must be far in excess of the actual amounts removed by the crop, because most of the potassium has to diffuse to the root surface before it can be taken up by the maize plant and its mobility in the soil is very low *(Kurtz and Smith [1966])*.

Periodic sampling of the soil is highly desirable, as an indication of potassium requirements before critical deficiencies occur. Potassium fertilization of maize will generally be justified on soil which have an exchangeable K content of less than 0.22 meq per 100 g of soil (i. e., 100 ppm K_2O). In general, on soils which exceed 220 kg/ha of exchangeable potassium, little response to added potassium is to be expected.

When a soil has only 60–70 kg/ha of available K, at least 140 kg K/ha should be applied to obtain the maximum yield response *(Barber and Mederski [1966])*.

When only medium yields are expected, the rates of application of potassium required vary generally from 65 to 120 kg K/ha. In regions with very favourable growing conditions and with late hybrids, applications may generally range from 100–150 kg K/ha *(Loué [1963])*.

On the basis of experimental evidence from a number of countries, *Jacob and von Uexküll [1963]* arrived at the following general recommendations for fertilizing maize:

Organic soils are generally deficient in potassium and phosphorus. Recommended fertilizer mixtures are 0–12–20, 1–10–10 and 2–12–6.

Heavy soils respond well to phosphorus, and a high proportion of P is included in the mixtures: 4–12–4, 6–10–7, 6–8–4; these are eventually supplemented by a side-dressing with nitrogen.

Light, sandy soils are generally deficient in potassium: fertilizer formulas such as 13–13–21, 8–16–16 and 4–8–10 are recommended.

When farmyard manure is applied, it is balanced by fertilizer mixtures in which phosphorus predominates: 4–12–4, 5–10–5 and 2–12–6. If maize follows a legume, such as lucerne, suitable mixtures are those with a low proportion of nitrogen – 5–10–10, 8–12–12, 8–16–16, 13–13–20. However, if the legume received a heavy phosphorus fertilizer application, the P constituent in the mixture can be appreciably reduced. When maize follows another cereal, grass or maize, mixtures such as 10–10–10 are recommended.

17.2 Fertilizing for maximum yields in the United States

The high potential yielding ability of maize, when grown under a favourable moisture regime, justifies the application of large amounts of plant nutrients. A grain yield of 10 000 kg/ha corresponds to a total dry matter production of approximately 25 000 kg/ha, of which a large proportion consists of the starch constituent of the grain. Production at this level requires about 300 kg/ha nitrogen, 45 kg/ha phosphorus and 200 kg/ha potassium, of which a considerable proportion – generally not less than 50 per cent – provided by fertilizers.

Yields of over 12 000 kg/ha have been reported quite frequently. Almost always these yields were obtained with high rates of fertilizers. In Table 96 are shown a few examples of the yields and fertilizer rates on high-yielding fields.

Table 96. Fertilizer rates used on high yielding fields in the United States *(Barber and Olson [1968])*

Year	Location	Yield (kg/ha)	Fertilizer applications (kg/ha)			Remarks
			N	P	K	
1963	Edgar County, Ill.	12 587	132+124	248	496	Applied at planting
1965	Shelby County, Ill.	12 400	203	154	220	
1966	Thomas County, Kans.	12 648	451	117	33	+11 Zn+11 Mn.
1956–68	Indiana	11 230–14 438	165	132	154	

The problem of the maximum amount of fertilizer that could be applied to maize was investigated in central Iowa over three years. Thirty-one different combinations of N, P and K were applied to six single-crosses, grown on a silty clay loam. The highest annual fertilizer application tested was 1320 kg of N, 495 kg of P, and 990 kg of K per ha. The yields on plots receiving no fertilizer averaged about 10 tons/ha. The lowest yield (3 tons/ha) was obtained with the 0–248–495 rate and the highest yield (20 tons/ha) with the 220–83–198 rate. Higher rates of application did not increase yields above those obtained with the latter rate. In third year of application yields began to decrease at rates of nitrogen above 330 kg/ha at one location, and 440 kg/ha at another.The yield decreases were attributed to salt accumulation and decreases in soil pH. Other possible factors may have been micronutrient deficiencies or nutrient imbalance. The incidence of certain diseases also increased *(Powell and Webb [1969])*.

17.3 Fertilizer use patterns in a number of selected countries

7.3.1 Europe

– France

The following fertilizer rates are recommended for maize *(Barloy [1970])*.

a) Nitrogen

The rates of nitrogen to be applied depend on whether farmyard manure is applied before maize and on the expected moisture regime, as shown in Table 97.

Table 97. Recommended nitrogen rates (kg/ha) *(Barloy [1970])*

Moisture regime	with F. Y. M. (40 t/ha)	No F. Y. M.
Marked summer droughts	40– 50	60– 80
Normal rainfall	80–100	120–150
Irrigated	120–140	150–200*

* Up to 250 for late-maturing varieties in the Languedoc area.

b) Phosphorus

The recommended rates of phosphorus are based mainly on soil P levels. In general, on soils with 0.20 to 0.25 per mil available P_2O_5, 80 to 120 units/ha are considered to be amply sufficient; on poor soils, 140 to 160 units/ha are justified. On an average, 90 to 100 units/ha are generally applied in the southwest and 160 to 170 in the Parisian Basin. Under irrigation in the southwest, with yields of up to 10 000 kg/ha, 90–100 kg/ha of P_2O_5 are applied.

c) Potassium

Extensive trials carried out by *Loué [1963]* enable the following conclusions: Where organic manuring is not practiced, maize shows marked responses to high rates of application, such as 125–130 kg K/ha. However, when farmyard manure at the rate of 25 tons/ha is applied, lower amounts of potassium (80 kg K/ha) are required for near maximum yields.

Applying the high rates of potassium is effective in gradually increasing the reserves of exchangeable potassium in the soil (Table 98).

Table 98. Effect of annual application of potassium on levels of exchangeable K (initial level: 60 ppm) *(Loué [1963])*

Amounts of fertilizer applied (kg/ha)	Exchangeable K in soil (ppm) After 4 years	After 8 years
0	70	50
66	90	80
100–130	140	120

Identical results were obtained in other trials.

The rates recommended by *Barloy [1973]* are based on the levels of available K in the soil, on soil moisture regime, on the supply of other nutrients, on expected K losses from the soil, and on returns in the form of FYM or crop residues.

Table 99. Recommended potassium rates (kg/ha) *(Barloy [1970])*

Moisture regime	With F. Y. M. residues incorporated	No F. Y. M. residues partly incorporated
Marked summer droughts	70–100	100–140
Normal rainfall	100–120	120–160
Irrigated	120–150	140–180

On soils with fair levels of K (0.25 to 0.30 per thousand), the recommended rates are 70-120 units of potassium. On leachable and poorer soils, rates should be increased to 100–180 units.

In certain regions in which the rotation maize-wheat-barley is practiced, 0–300–300 units/ha are applied to the maize and the two following cereal crops receive only nitrogen fertilizer.

In general, there is a good response to fertilizers in all regions (**Figure 189**).

A special case is the sandy moors in southwestern France that have been reclaimed for maize production, an area where semi-late and late hybrids of maize can be grown successfully and high grain yields are achieved. A three-fold deficiency of K, Ca and Mg frequently occurs on these soils.

Fertilizer practice consists in incorporating magnesium limestone at the rate of 1500 kg/ha into the soil by shallow tillage. In addition, muriate of potash is applied at the rate of 350 kg/ha in the first year, 300 kg/ha in the second year and 250 kg/ha in subsequent years *(Loué [1963])*.

– *Federal Republic of Germany*

In Germany, the rates of nitrogen are adjusted to moisture conditions, soil fertility and the crop objective. Under drought conditions, 70–100 kg/ha N are applied. Where moisture regimes are favourable, 100 to 150 kg N/ha are given. Under these favourable conditions, it is estimated that for each kg of nitrogen applied, grain yield is increased by 20–25 kg, and protein content is increased., The higher rates are used for maize grown for silage.

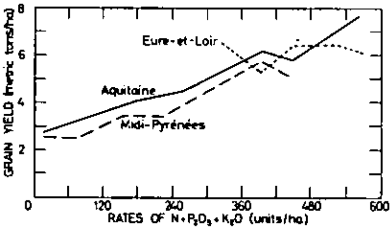

Fig. 189 General response of maize to fertilizers in different regions of France *(Barloy [1970])*. By courtesy of «Engrais de France».

The recommended rates of phosphorus fertilization range from 100 to 140 kg/ha of P_2O_5, depending on the P-status of the soil. The corresponding rates of K are 140–160 kg K_2O for grain and up to 200 kg for silage *(Zscheischler and Gross [1966]).*

– *Bulgaria*
In Bulgaria, optimum fertilizer rates for maize were found to be 140 kg N, 90 kg P_2O_5 and 120 kg K_2O on a parapodzol soil, and 110 kg N, 60 kg P_2O_5 and 200 kg K_2O on a sandy chernozem soil *(Sestic and Teofilovic [1966]).*

– *Rumania*
In fertilizer experiments on a reddish-brown forest soil in Rumania, on both rain-fed and irrigated maize, the most effective fertilizer rates for rain-fed maize were found to be 50–65 kg N/ha plus 30–50 kg P/ha, and for irrigated maize 100–130 kg N/ha plus 50–100 kg P/ha. Yield levels were increased by fertilization from 3150 to nearly 3900 kg/ha for rain-fed maize, and from 6140 to 7700 kg/ha for irrigated maize. There was no response to potassium fertilizers. The periodic application of farmyard manure at the rate of 30 tons/ha increased the effectiveness of the fertilizers applied to the irrigated maize *(Dorneanu et al [1969]).*

In the Pruth Valley of Rumania, 128 kg of N, 64 kg of P and 80 kg of K per ha were found to give optimum results on irrigated precision-sown hybrid maize. Optimum sowing time was during the last ten days of April, and optimum plant density was 5.5–6.2 plants/m^2 *(Albinet [1968]).*

Davidescu [1965], summarizing the results of a large number of tests in Rumania, declares that in the majority of cases, maize responds first and foremost to nitrogen and phosphorus fertilizers. The mean increase in yield per kg of nitrogen was found to be 5.7 to 15.5 kg of grain for unirrigated maize and 25 kg for irrigated maize. The mean increase in yield per kg of P_2O_5 was 3 to 6 kg of grain for unirrigated maize, and 7 to 24 kg under irrigation.

On certain soils and under certain conditions of production, potassium applications were found to be essential for the obtention of consistently high yields. Response to potassium fertilizers was generally greater on alluvial sandy soils and on soils rich in calcium, than on clay or loam soils with low calcium content. On podsolic soils, and under irrigation, the need for potassium applications becomes increasingly evident. In the course of the decade 1955 to 1965, trials carried out at Marculesti, Lovrin, Tirgul Frumos, Solbagel, Suceava, Sercaia and elsewhere, showed that the application of potassium fertilizers to maize increased yields, per kg of K_2O, by 2.8 to 13 kg of grain, with an overall average of 6 kg. The most marked responses were obtained on alluvial sandy soils.

– *Italy*
In the Po Valley, average yields of maize, before World War II, were 5000–6000 kg/ha, obtained with open-pollinated varieties receiving 30–50 tons/ha of farmyard manure, occasionally complemented by 200–400 kg/ha of nitrogenous and phosphorus fertilizers. The present yields of maize in the same region average 8000 to 12 000 kg/ha, with occasional records of 15 000 kg/ha. Yields of forage maize range from 50 to 70 tons/ha, with occasional records of up to 100 tons/ha.

These yield levels are achieved by using highly productive hybrids, supplementary irrigations and heavy applications of organic and/or mineral fertilizers. The latter consist of 50 tons well-rotted farmyard manure plus 100–150 kg N, 60–100 kg P_2O_5 and 60–100 kg K per ha. When only fertilizers are given the rates applied are increased to 150–250 kg N, 100–150 kg P_2O_5 and 100–150 kg K_2O per ha *(Lanza [1970])*.

– *Switzerland*

Gisiger [1965] has made a detailed study of the nutrient requirements of locally adapted hybrid maize under the climatic conditions of Switzerland. On the basis of these investigations *Gisiger* makes the certain fertilizer recommendations, as shown in Table 100.

Table 100. Fertilizer recommendations for maize in Switzerland *(Gisiger [1965])*

P and K levels in the soil	Nutrient requirements in kg/ha		
	N	P	K
high	200	—	—
satisfactory	200	50	50
low	200	90	200

If farmyard manure has been applied, 200 kg/ha of Nitrochalk, ammonium nitrate or ammonium sulphate should be given before sowing, and a further 300 kg/ha of one of the two latter carriers or 150 kg/ha urea top-dressed when the plants are 20 to 40 cm tall. The farmyard manure generally does not need to be supplemented with phosphorus or potassium when available levels of these nutrients in the soil are satisfactory; when these levels are low, 200 kg/ha each of superphosphate and of muriate of potassium need to be applied.

Where no farmyard manure has been turned under, nitrogen applications before sowing must be increased to 400 kg/ha of a 20 per cent N-carrier; phosphorus and potassium applications increased to 300 kg/ha of single superphosphate and 100 kg/ha muriate of potash for soils with satisfactory levels of available P and K; and 500 kg/ha single superphosphate and 350 kg/ha muriate of potash for soils with low levels of available P and K.

17.3.2 The Mediterranean region

Sanchez-Mongé [1962] made an interesting comparison of the amounts of fertilizers recommended by agricultural advisors on the basis of research findings, and the amounts actually used by farmers in some Mediterranean countries (Table 101). Nitrogen and phosphorus are almost generally applied, although frequently in less than the recommended amounts. Potassium is not always applied, even in those regions in which it is officially recommended. Wherever it is applied, it is usually at rates lower than those recommended.

The low rates of potassium applied in Spain, in contrast to the amounts recommended, are particularly intriguing in view of the high response of maize to this nutrient reported from 127 trials carried out in Spain in several maize-growing areas (Table 102).

Table 101. Amounts of macroelements used in fertilizing maize, compared with the amounts recommended *(Sanchez-Mongé [1962])*

Country and region	Farmyard manure (tons/ha)		P_2O_5 (kg/ha)		N (kg/ha)		K_2O (kg/ha)	
	Utilized	Recommend.	Utilized	Recommended	Utilized	Recommended	Utilized	Recommended
Portugal (North)	—	—	50–90	90–110	40–80	70–100	0	60–110
Portugal (Center + South)	20–30	20–30	90	70–130	40–60	50–80	0–40	40–70
Spain (North)	30–60	30–40	0	70–90	20–40	50–70	0	80
Spain (Ebro + N. E.)	—	—	70–130	150	70–80	100	0–60	110
Spain (South)	—	—	70	90	60–80	120–160	0–60	90
Spain (Levante)	—	—	90–110	—	80–120	—	60–90	—
France (South, Pyr.)	—	0–25	—	—	—	—	—	160–180
France (South, Aude)	—	—	*	150	*	50	**	90
France (South, Hérault)	—	—	*	90–160	*	40–120	**	70
Italy (N. E.)	20–30	—	100–140	—	40–80	—	0	—
Italy (North)	50–60	—	90–110	—	30–60	—	0–60	—
Italy (Center)	—	—	50–70	—	20–30	—	0–40	—
Italy (South)	0–12	—	40–70	—	30–50	—	0–20	—
Jugoslavia	—	—	90–110	—	90–120	—	60–80	—
Turkey (Black Sea)	—	—	100	—	100	—	0	—
Morocco	—	—	—	60	40	40	0	50

* Less than recommended ** Much less than recommended.

Table 102. Response of maize to potassium application in Spain *(Sanchez-Mongé [1962])*

	Yield, in kg/ha	
	Open-pollinated varieties	Hybrids
Without K	2868	5087
With K	3742	5893

17.3.3 Irrigated maize

The fertilizer rates shown in Table 101 are typical of fertilizer practice in regions with unreliable rainfall. High yields in these regions are possible only with irrigation. However, irrigation becomes an effective tool for increased production *maintained on a high level* only when applied in conjuction with the most intensive cultural practices, of which an appropriate fertilizer regime is one of the most important.

With the transition from rain-fed to irrigated agriculture, it is essential that the farmer break away from the traditional fertilizer practices evolved under rain-fed production, and adopt an entirely different approach, appropriate to the new situation. A farmer accustomed to the fertilizer rates applied to rain-fed maize will, at first, usually apply to the irrigated crop rates that are at best 50 to 100 per cent higher than those he used previously. The responses obtained from these amounts are generally so unspectacular as to create the impression that further increases from fertilizer application are not to be expected. It is only when rates of application are increased three or fourfold and even more, that the potentialities of heavy fertilizer application for increasing yields, and the efficiency of water use, are fully realized. In maize for grain or forage production in particular, really astonishing yield increases are obtained by heavy fertilizer dressings. The most consistently spectacular responses are obtained from nitrogenous fertilizers. Rates of up to 200 kg N/ha give economic returns *(Arnon [1963])*.

The high rates of nitrogen applied call almost automatically for an increase in phosphatic fertilizers. Most of the soils of the Mediterranean regions are poor in this element. However, response to phosphorus is usually erratic, and largely dependent on the fertilizers applied to previous crops in the rotation. After several consecutive applications at the rate of 150–200 kg P_2O_5 per ha, the response of maize to this element tends to decrease.

Most of the soils of the Mediterranean regions are known to be relatively rich in potassium. With the low yields usually obtained in these regions under rain-fed cropping, the liberation of fixed potassium from the soil has usually been able to keep pace with the removal of this element by the crops. When irrigation is first practiced on these soils, the response to potassium fertilizers is usually slight or inexistent. However, it has been found that this situation is not necessarily static, and that the soil reserves of K are not always able to keep pace with the high rate of production possible under irrigation.

17.3.4 America

– United States

In the United States the average rates of nitrogen applied to maize have increased from 45.4 kg N/ha in 1959 to 70.4 kg N/ha in 1964 (55 per cent); of phosphorus from 41.1 kg P_2O_5/ha in 1954 to 51.4 kg P_2O_5/ ha in 1964 (25 per cent); and of potassium from 40.3 kg K_2O/ha to 47.1 kg K_2O/ha in 1964 (17 per cent) *(Ibach and Mahan [1968])*. The relationship between increasing fertilizer rates and increasing yields is shown in **Figure 190** *(Barber and Olson [1968])*.

The amounts of fertilizer applied to maize during 1964 in different regions of the USA are shown in Table 103 *[ibid.]*.

Table 103. Amounts of N, P_2O_5 and K_2O applied to maize, by regions in the USA *(Ibach and Mahan [1968])*

Region	(kg/ha) N	P_2O_5	K_2O
Northeast	45.5	53.1	50.5
Lake States	36.7	48.6	45.5
Corn Belt	75.2	53.7	45.4
Northern Plains	79.8	36.5	17.1
Appalachia	94.5	57.0	54.6
Southeast	80.5	50.9	60.9
Delta	86.1	41.0	38.4
Southern Plains	56.2	41.0	24.8
Mountain	96.8	51.4	36.9
Pacific	143.3	54.2	42.9
Contiguous U. S.	70.4	51.4	47.1

Up to 1942, very few experiments had been carried out in which high rates of nitrogen were used. A summary of 12 years of results from fertilizer experiments in Alabama, showed that yield response to nitrogen increments up to 40 kg N/ha was nearly linear. Most of the tests used open-pollinated varieties with relatively wide spacings between the plants. The low potential yielding ability of these varieties combined with the low plant population, would not in any case have resulted in a response to higher rates of application *(Jones and Rogers [1949])*. The average yield of maize in the United States from 1909–13 was 1208 kg/ha. From 1909–45 no appreciable increase in yield was recorded. Naturally, without high rates of nitrogen application, there was no justification for high rates of phosphorus or potassium. With the advent of hybrid maize, and the use of high plant population densities, and high rates of nitrogen and phosphorus, the situation changed entirely *[ibid.]*.

The evolution of the use of potassium in the Corn Belt is of particular interest. In Indiana only 0.5 kg/ha of potassium was applied in 1920. The ratio of phosphate to potassium changed from 1:0.1 in 1920 to 1:0.52 in 1930 and to 1:0.67 in 1940. By 1963, more potassium than phosphorus was being used, and the ratio was 1:1.15 *(Quackenbush et al. [1960])*. The amounts applied per cultivated hectare had increased to an average of 42.5 kg K, and rapidly approached the amounts removed from the soil by the crop, or lost by leaching and erosion *(Barber and Mederski [1966])*.

Similar trends occurred in other parts of the Corn Belt, as is evident from the figures given in Table 103.

The relationship between exchangeable K in the soil, leaf content of K and the yield increase from applications of potassium at a number of locations in Kansas, is shown in Table 104.

As can be seen in Table 104, a low content of exchangeable K in the soil is associated with a very low content of K in the leaves. On soils with less than 220 kg/ha exchangeable K, leaf content was lower than the critical level of 1.3 per cent K. On soils with more than 220 kg/ha exchangeable K, leaf content was well above the critical level. In all soils (except possibly one), the application of 88 kg/ha of K_2O raised the K leaf

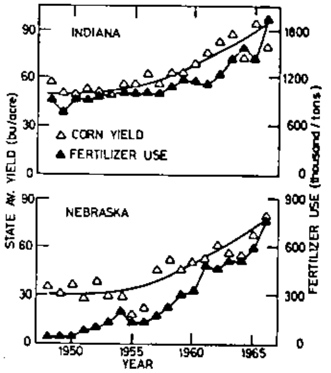

Fig. 190 Changes in fertilizer use and maize yield for Indiana and Nebraska in the period 1948–1966 *(Barber and Olson [1968])*. By courtesy of the Soil Science Society of America.

Table 104. Relationship between soil K, leaf K and yield increase from the application of K fertilizer *(Ellis et al. [1956])*

Location	Exchangeable K in soil (kg/ha)	K content of leaves with no K applied	K content of leaves with 88 kg K_2O/ha	Increase in grain yield with application of 88 kg K_2O/ha
Oswege	86	0.39	1.99	11.7
Wier	89	0.56	1.46	5.5
Columbus	110	0.77	1.64	1.0
Girard	113	0.63	1.46	11.8
Thayer (a)	119	1.27	1.92	none/drought
Thayer (b)	142	0.68	1.81	none/drought
Parker	179	0.61	1.27	3.2
Mound City	196	0.87	1.74	none
Garnett	286	2.35	2.93	none
N. E. Kansas (avg. of 3 locations)	581	2.05	2.13	none

content above the critical level. Wherever leaf content was lower than the critical level, there was a marked yield response to potassium fertilizer, provided moisture supply was adequate.

In a review of fertilizer practice in the USA, it was found in 1960 that maize farmers applied higher rates of nitrogen in Indiana, Nebraska and South Carolina, higher rates of phosphorus in Ohio, Indiana, Illinois, Michigan, Wisconsin, Nebraska, Kansas, Virginia, Alabama and Arkansas, and higher rates of potassium in the Corn Belt, Michigan, Wisconsin, South Dakota, Nebraska, Kansas, Virginia, North Carolina, Alabama and Texas, than the amounts officially recommended by the respective experiment stations and extension services *(Ibach and Mahan [1968])*. The general tendency in the United States appears to be to play safe and ensure that in no case should the lack of nutrients limit yields.

The fertilizer requirements of one of the agriculturally important soils in western Florida – a fine sandy loam – were investigated in a five level NPK factorial experiment. These soils are very high in their phosphorus-fixing capacity, so that phosphorus is the first limiting factor in maize production. The initial potassium supply in the virgin soils is high enough to produce good maize yields for one or two years without K fertilization.

In these experiments phosphorus, as expected, brought about the greatest yield response but the amount of phosphorus required to give a maximum yield decreased from year to year. Potassium brought about a positive response each year, with the degree of response increasing from year to year as a result of gradual depletion of soil potassium on plots receiving small annual applications of potassium fertilizer. Nitrogen showed an excellent yield response in years in which rainfall was adequate and well distributed *(Hutton et al. [1956])*.

In investigations on the fertilizer requirements of maize in Texas, *Fisher [1954]* demonstrated that nutrient balance was more important in grain production than the level of any single nutrient. On an average of three years, unfertilized maize produced 1741 kg/ha with 54 per cent of the plants lodged. Nitrogen, applied at the rates of 44, 88 and 132 kg/ha, when used alone, had no beneficial effect on yields. Supplying nitrogen together with phosphorus was also not effective in increasing grain yields, but increased lodging markedly up to 77 per cent when 80–40–0 fertilizer was used. The highest yield – 3810 kg/ha – was obtained with an application of 40–80–80 applied at sowing, in bands below and to the side of the seed. This treatment resulted in a lodging rate of 27 per cent.

In Iowa, the most profitable rates of fertilization for maize are considered to be: On soils testing very low or low in P and/or K: 20 to 77 kg P/ha and 36 to 146 kg K/ha; on soils testing medium to high in P and/or K: less than 20 kg P and 36 kg K/ha applied in the band *(Dumenil et al. [1965])*.

Irrigation in areas where dryland farming used to predominate has caused considerable changes in fertilizer practice. In Nebraska, for example, nitrogen application was almost doubled for irrigated maize (102 kg N/ha as compared with 55 for dryland maize) *(Ibach and Mahan [1968])*.

– *Mexico*

Fertilizer trials on maize were conducted for five years at 26 locations in the tropical regions of Veracruz, Mexico. Soils ranged in pH from 5.5 to 7.9 and in organic matter content from 1.35 to 9.94 per cent. In the absence of applied nitrogen, grain yields ranged from 0.3 to 6.8 tons/ha; Ist and 2nd increments of 44 kg N/ha increased yields by an average of 870 and 220 kg/ha, respectively. In 60 per cent of the cases, higher yields were obtained by splitting the application of nitrogen. In 26 per cent of the cases, 40 kg P_2O_5/ha increased grain yields by an average of 1.81 tons/ha. In only one instance were yields increased by potassium *(Puente et al. [1963])*.

Laird and Rodriguez [1965] investigated the fertilizer requirements of maize in an area of central Mexico, south of León, at altitudes of 1550–1870 m. Significant responses to nitrogen were observed in almost all of the 47 trials, significant responses to phosphorus in 19 trials, and responses to zinc in 14 trials. For the time being, applications of 120 kg N and 40 kg P_2O_5 per ha are being recommended on the basis of these findings.

Fertilizer experiments were also carried out by *Laird et al. [1969]* with rain-fed maize at 82 locations in the western part of the El Bajio, during a four-year period (1962–1965). The average annual rainfall in the area varies from about 500 mm in the north to about 900 mm in the south. The soils are derived from relatively old extrusive volcanic materials, varying from basaltic to rhyolitic in composition. Two-thirds of the soils had pH values above 6.5. Organic matter contents were generally less than 2 per cent. The available calcium, magnesium and potassium contents were highly variable, but in most cases adequate for maize. The levels of available phosphorus varied from very low to very high.

Grain yields of unfertilized maize (an adapted hybrid was used in all trials) varied from 0.20 to 4.43 ton/ha with an average of 1.50 ton/ha. Maize responded significantly to the application of nitrogen at all locations except two.

Average increases in yield due to the application of 40, 80 and 120 kg N/ha were 1.02, 1.84 and 2.39 ton/ha, respectively.

Grain yields were increased by phosphorus in 57 per cent of the cases. Average increases in yield due to the application of 30 and 60 kg of P_2O_5/ha were 0.66 and 0.79 ton/ha, respectively.

Applications of zinc sulphate at the rate of 75 kg/ha increased vegetative growth during the early part of the growing season at about half the locations. However, a significant increase in grain production was recorded in only one experiment.

Table 105. Fertilizer recommendations for growing unirrigated maize on four soil conditions in regions receiving different amounts of rainfall *(Laird et al. [1969])*

	Average annual rainfall in mm			
Soil properties	525–600	600–675	675–800	800–950
	kg/ha N and P_2O_5, resp.			
Heavy clay 90 cm in depth*	60–30	70–35	100–40	120–45
Heavy clays 70 cm in depth or light-textured soils 110 cm deep	55–30	65–30	95–40	118–45
Heavy clays 50 cm in depth or light-textured soils 75 cm deep	45–30	60–30	85–35	110–40
Heavy clays 30 cm in depth or light-textured soils 45 cm deep	0–0	45–30	55–30	90–35

* Depth of root penetration.

The recommended amounts of phosphorus are adjusted to the optimal nitrogen rates as shown in **Figure 191**.

The effects of limiting factors on the response of maize to fertilizer are very well illustrated by the results of 22 fertilizer experiments carried out in Mexico (see Table 106).

These results show that fertilizer application is effective in overcoming to a large degree the effects of disease and of excess moisture. However, the full benefit of the fertilizer was obtained only in the absence of limiting factors. With irrigated maize in the Toluca Valley in Mexico, maximum yields were obtained from a stand density of 5 plants/m^2 and with 120 kg N/ha as the most economic rate of nitrogen *(Ramirez and Laird [1960])*.

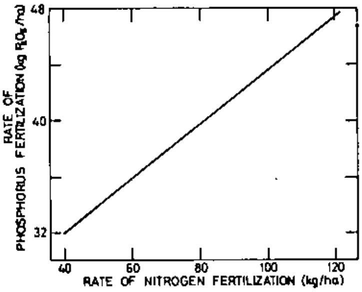

Fig. 191 The relationship between the recommended rates of nitrogen and phosphorus fertilization *(Laird et al. [1969])*. By courtesy of the International Maize and Wheat Improvement Center, Mexico.

Table 106. Grain yields (ton/ha) of unirrigated maize with different rates of nitrogen fertilization in 22 experiments, Bajio *(Rockefeller Foundation [1965])*

	Rate of nitrogen fertilization (kg/ha)*			
	0	40	80	120
Average for the 22 experiments	1.08	2.14	3.08	3.71
Average for 12 experiments not seriously affected by drought	1.16	2.47	3.65	4.41
Average for 3 experiments severely affected by drought	1.71	2.26	2.13	2.28
Average for 5 experiments affected by *Helminthosporium turcicum*	0.53	1.41	2.47	3.13
Average for 2 experiments severely affected by an excess of soil moisture	0.89	1.04	1.78	2.54

* All experiments received 60 kg/ha of P_2O_5.

– *Trinidad*

Recent work at experiment stations in the Caribbean has shown that yields of maize may be raised above current levels by increasing plant population density, by applying irrigation when necessary and by higher levels of fertilization. High yields of grain (up to 9300 kg/ha) were obtained in trials in Trinidad by increasing the plant population of mass selected farm maize to 5 plants/m^2, fertilizing with 154 kg N* applied as ammonium sulphate and *two units per acre* each of muriate of potash and triple superphosphate.

The potassium and phosphorus fertilizers were applied and ploughed under before sowing; one third of the nitrogen was applied at planting by injection in the side of the ridges, and the remaining two-thirds when the maize was 60–70 cm high. Weed and insect pests were controlled, and water was not a limiting factor at any stage of growth *(Gibbon [1966])*.

– *Northern Latin America*

Since 1960, an intensive field programme of demonstrations and trials with fertilizers has been under way in a number of countries of northern Latin America (El Salvador, Honduras, Costa Rica, Guatemala, Colombia, Ecuador). As the pattern of the economy and agricultural production in all these countries is very similar, they are treated as a group in the FAO's report on its activities in the fertilizer scheme.

Maize is the major food crop in this region. Yield responses were from moderate to very good for single nitrogen applications in the lowland areas and for more balanced NPK treatments at higher elevations (Table 107).

The results show that fertilizer applications to maize were always profitable, and most frequently very profitable. And yet, fertilizer use on a food crop like maize, grown mainly by small peasand farmers, is still very limited. By contrast, for export crops, fertilizer use is a well-established practice and accounts for over 80 per cent of all fertilizer applications. As a result, food crop production is declining and this area has become a net importer for maize. The FAO experts estimate that by the use of

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* Without nitrogen, yields under otherwise identical conditions were 500 kg/ha.

Table 107. Provisional fertilizer recommendations for maize in countries of northern Latin America *(FAO [1965])*

Country and/or region, variety	Number of trials	Treatment N-P_2O_5-K_2O (kg/ha)	Yield increase kg/ha	%	Net return (S/ha)	Value/cost ratio
Guatemala						
Low region	26	75–40–0	735	28	7	1.2
Medium region	24	75–60–0	1434	66	47	2.0
High region	14	100–80–0	2001	80	68	2.1
Honduras						
Local improved	28	45– 0–0	630	19	27	2.8
Local unimproved	7	45–45–45	745	30	18	1.6
Hybrid	9	90–90–90	5013	105	272	5.3
El Salvador						
Central	93	90–90–0	1912	72	108	3.4
East	42	90–90–90	1266	32	56	2.2
West	27	90–90–90	1720	66	93	3.1
Costa Rica						
High and low regions	40	80–60–0	927	26	27	1.7
Low regions (trials)	29	80–60–40	1262	46	46	2.0
Ecuador						
Highland maize	28	45–45–0	1194	54	100	4.2
Colombia	18	45–45–0	889	55	60	3.0

fertilizers and pest control, in combination with improved hybrids, yields per hectare could be doubled at least. The obstacles to this are, however, not of a technical nature but of an economic nature; in particular the existing facilities for crop marketing and fertilizer credit supply are inadequate and farmers have no incentive to apply modern means of production. This subject will be discussed more fully in the next part of this chapter.

17.3.5 Africa and Asia

– *Rhodesia*

In the northern part of Rhodesia, the results of 70 fertilizer experiments showed that substantial responses to nitrogen were obtained over a wide range of soils. The yield increases were very large, when heavy dressings of nitrogen were applied in conjunction with increased plant populations (3.0 to 4.5 plants/m^2). Phosphorus deficiencies were generally not encountered, and substantial responses were confined to one soil type, namely, loamy sands. No signs of potassium deficiency, at the existing intensity of cropping and yield levels, were found at the time *(Pawson [1957])*.

In this connection, it might be pointed out that already in the 1950's soils of the southern part of Rhodesia had begun to show potassium deficiencies after prolonged cropping, and that maize started responding to potassium fertilizer on certain soils *(Saunder [1954])* (cf. p. 120).

Since 1955, a number of important changes have occurred on farms cultivated according to modern methods, and average yields have doubled (from 1680 kg/ha in 1955 to 3300 kg/ha in 1968) *(FAO [1969])*.

In consequence of these developments, Rhodesia, which formely imported substantial quantities of maize, has now become an exporter of this commodity. These changes are attributed by *von Burkersroda [1965]* to the replacement of open-pollinated varieties by single and double hybrids, the adoption of higher plant population densities, earlier planting, improvements in pest control, and radical changes in methods of maintaining soil fertility, including the judicious use of fertilizers.

The rapid increase in the use of nitrogen fertilizers has reduced the acreage planted to green manures by nearly two-thirds. On the other hand, maize stover, which was previously removed for feeding to livestock, or burned *in situ*, is now turned under, increasing yields by an estimated 330 kg/ha.

Fertilizer use is increasingly based on soil testing correlated with the results of field trials.

Average nitrogen application to maize in the higher rainfall areas is approximately 90 kg N/ha. A yield increase of 200 to 400 kg can be expected from every 10 kg N applied, depending on weather and other conditions. Phosphate is applied regularly at rates of 22 to 44 kg P_2O_5/ha.

Many of the older maize lands have become critically depleted of potassium, particularly those with inherently low potassium reserves. The use of potassium fertilizers, either for corrective or maintenance purposes, is on the increase; the application of muriate of potash to maize more than doubled during the period 1960 to 1965, during which time the maize acreage increased by 7 per cent.

In Figure 89 (cf. p. 224) the effects of potassium fertilizer in conjunction with nitrogen and phosphorus, on yields of maize grown on a K-deficient soil, are shown.

Fertilizer recommendations for maize stress well-balanced combinations of NPK. The formulas 8–16–8 or 9–12–9 at the rates of 300 to 450 kg/ha are commonly used. Where K-deficiency is marked, an additional application of 50 to 110 kg/ha of muriate of potash is applied. Even on soils on which no response to K fertilizers is apparent, the Ministry of Agriculture recommends maintenance applications of 20–35 kg K_2O/ha *(von Burkersroda [1965])*.

– *Kenya*

Maize is the principal food crop of Kenya and also the most widely cultivated crop. In the course of a few years, yield levels have increased from 1200 kg to 5000–6000 kg/ha, as a result of the introduction of adapted varieties, the distribution of high-quality seed and improved agronomic practices *(FAO [1969])*. There is no doubt that amongst the latter, fertilization plays a leading role.

In Kenya, the results of numerous fertilizer trials on maize grown on two soil types were summarized as follows *(Weiss [1967])*.

1. Maize grown on soils derived from granite and gneiss required less phosphate in the seedbed and more nitrogen top-dressing for optimum yields than maize grown on soils derived from phonolites. The residual effect of annual applications of phosphates on both soil types was found to be high.
2. Nitrogen top-dressing of maize was found to be essential for maximum yields on both soil types, but the optimum amount required varied.
3. Potassium generally depressed yields.

In a large number of recent trials carried out by the *National Research Station* of

Kitale, in a region representative of the 80 000–120 000 ha of the main maize growing areas, the following results were obtained:

(a) On the red-brown and black clay soils of Mt. Elgon and Endebess, there were good responses to nitrogen, but no significant responses to phosphorus or potassium. The nitrogen response curves are shown in **Figure 192**, with indications of the economic optimum to be applied according to the relationships between price of maize and cost of fertilizer.

(b) On sandy clay soils very significant nitrogen and phosphorus responses were recorded. Due to the interactions between these two elements, fertilizer recommendations must consider both nutrients together. Recommendations based on the amount of money available to the farmer for fertilizers, are presented graphically in **Figure 193.**

(c) On soils derived from lower phonolite lava flows, there were very significant responses to phosphorus. Nitrogen generally tended to increase yields, but not always significantly. The recommendations for these soils are to apply at least 60 kg P_2O_5/ha and to top dress with about 50 kg N/ha.

A number of additional trials have indicated that there was a tendency for sulphur deficiencies to appear on land which had been broken from grass in the previous season, with a resultant reduction in the yields of maize *(Allan and Masyanga [1969])*. Recent recommendations for fertilizer application for maize in different areas in Kenya have been summarized by *Allan [1968]* (Table 108).

Table 108. Fertilizer recommendations for maize in Kenya *(Allan [1968])*

Area	Soil type	Phosphate status	Fertilizer (kg per ha) P_2O_5	Nitrogen
Busia	Silty loams	medium	22.5–33.5	56
Kakamega	Red-brown basaltic loams	low	67 –89.5	28–39
		high	33.5–45	28–39
Kisii	Red-brown loam	low	67 –89.5	none
		high	33.5–45	none
Trans Nzoia	Red and brown clays	low	78.5–112	up to 134.5
		high	45 –56	up to 134
Endebess	Dark brown alluvial and black clay soils	high	22.5–33.5	up to 112
Mt. Elgon	Black forest loam	high	22.5–28	none
Eldoret	Red brown lateritic clays	low	33.5–45	45–67
		high	22.5–33.5	45–67
Njoro	Brown to dark brown loams	low	33.5–45	28–39
		high	22.5–33.5	28–39
Central Kenya trial sites	Red and dark red friable clays	low	67 –89.5	none
		high	45 –56	none

– *Tanzania*

Maize is the most ubiquitous and probably the principal food crop of western Tanzania. Yields of maize obtained under traditional farming conditions average around 440 kg/ha. Low soil fertility and erratic rainfall are the major factors limiting crop yields throughout most of the zone.

A number of experiments have indicated that appropriate applications of fertilizers are probably the major factor for increasing maize yields. Following 132 fertilizer experiments (NP and NPK*) carried out over three years in this region, it was possible to define 16 response areas. In four of the 16 response areas, representing most of the southwestern half of the zone, threefold yield increases were obtained, on the average, from moderately heavy applications of nitrogen and phosphate. Throughout much

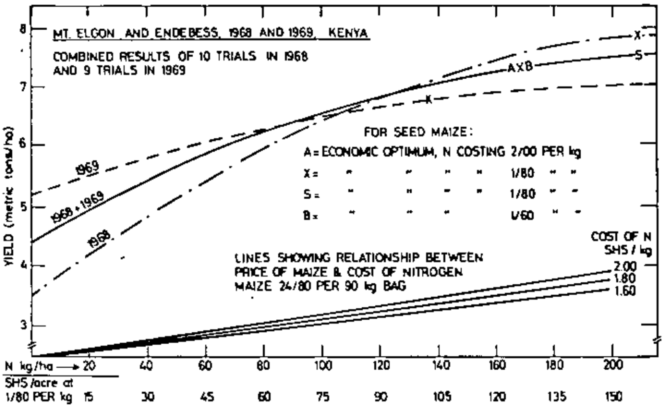

Fig. 192 Nitrogen responses on clay soils, in Kenya, in 1968 and 1969, showing economic optimum to be applied according to the relationships between price of maize and cost of fertilizer *(Allan and Masyanga [1969])*. By courtesy of the National Agricultural Research Station, Kitale, Kenya.

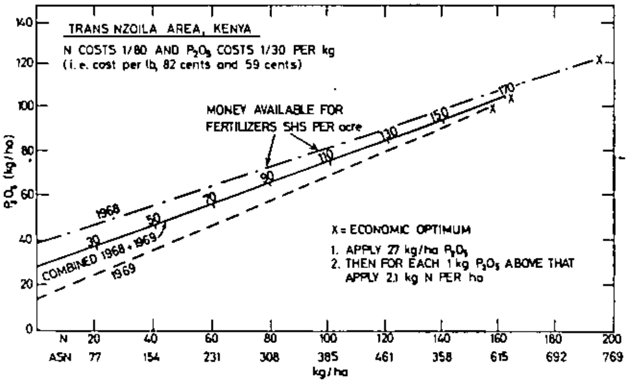

Fig. 193 Fertilizer recommendations for sandy clay soils in Trans Nzoie area, based on the amount of money available to the farmer for fertilizers *(Allan and Masyanga [1969])*. By courtesy of the National Agricultural Research Station, Kitale, Kenya.

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* 40 and 80 kg each of N, P_2O_5 and K_2O, compared with no fertilizers.

of the remainder of the zone, notably on the sandy granitic soils around the south of Lake Victoria, yields were found to be doubled by the use of nitrogen alone. In the drier areas, notably Shinyanga district, responses to both N and P were on the average very small. In the Karagwe district, on soils with a high Mg/K ratio, positive responses to potassium were obtained.

Timely planting, uniform stands and stalk-borer control are necessary in order to obtain the fertilizer responses mentioned above. The introduction of improved varieties may stimulate still better responses to fertilizers. In a subsidiary experiment it was found that Kenya hybrid 622 gave a response of 2500 kg/ha to an application of 176 kg N/ha, as compared with only 1700 kg/ha for Katumbidi *(Scaife [1968])*.

In a semi-arid part of Tanzania, yields of maize on a sandy loam, with near optimum fertilizer treatments, reached around 4400 kg/ha of grain, approximately tenfold the normal yield achieved under traditional farming conditions.

The main effect, over a five-year period, was obtained from combined N-P dressings. Annual dressings of 64 kg/ha N, together with initial applications of 51 kg/ha P_2O_5, produced a mean yield increase of 55 per cent over the unfertilized control. Potassium applications gave little yield increase during the first three years, but became more important thereafter, indicating progressive depletion of available K from the soil *(Anderson [1970])*.

Robinson [1969] studied the relationships between maize yield responses to two rates of nitrogen or phosphorus fertilizers, and soil pH values, on soil samples collected in fertilizer trials over western Tanzania. No relationship of practical significance was found for nitrogen fertilizer responses. The maize yield responses to phosphorus fertilizer decreased as the pH value of the topsoil approached neutrality (7.0). This relationship should be useful in interpreting soil phosphorus tests for advisory purposes in this region.

– *Zambia*

Both the climate and the soils of Zambia are well suited for maize production, although natural fertility of the soils is generally low. Average yields of rain-fed maize in 1968 were 1040 kg/ha *(FAO [1969])*. However, research work has shown that yields of 8 to 9 tons/ha can be obtained, even under rain-fed conditions by using hybrid seed, appropriate cultural practices, pest control and an adequate fertilizer programme. Nitrogen is deficient throughout the country; two-thirds of the maize growing areas are deficient in sulphur, which may limit growth to an even greater extent than nitrogen. Neither phosphorus nor potassium limits maize yields as a rule, though with very high levels of nitrogen and increasing maize yields the situation may eventually change. Commercial producers who achieve high yields use 90 kg N, 45 kg P_2O_5 and 22.5 kg K_2O per ha at sowing and a further 45 kg N/ha as top-dressing, with a plant population density of about 4.5 plants/m^2 *(Ballantyne [1965])*.

– *Malawi*

In Malawi, the main nutrient deficiency is a chronic lack of nitrogen, which is found in all soils, except for certain recent alluviums of heavy soil and red ferruginous clay loam soils, which have been maintained at a high level of fertility by good rotation practice and regular applications of farmyard manure. The recommendations for maize based on experimental evidence are as follows: to apply from 22 to 44 kg/ha N on fertile red ferruginous clay loam soils, and from 44 to 88 kg/ha N on other soils (except on recent alluvial soils, which do not require fertilizer applications).

For dressings of 66 kg/ha N or less, split applications were shown to have no marked effect. Nitrogen may become limiting after a relatively short period of cultivation. Responses to phosphorus were generally erratic and could not be closely related to laboratory determinations of soil P. However, threshold values could be determined below which a response could be expected and above which no economic response would be obtained. On soils low in P, the optimal general dressing recommended is 220 kg/ha of single superphosphate.

The soils are generally rich in potassium and so far there has been little or no response to K-fertilization. The yield levels to be expected with fertilizer dressings of up to 88 kg/ha of the limiting nutrients are from 3300 to 4400 kg/ha *(Brown [1966])*.

– *Nigeria*

As in many other African countries, many soils in Nigeria are deficient in phosphorus. In trials at Abeokuta, maize responsed to phosphorus (110 kg superphosphate per ha) with a 38 per cent increase in yields. The corresponding increases for nitrogen (110 kg ammonium sulphate per ha) and potassium (110 kg muriate of potash per ha) were 23 and 4 per cent, respectively *(Miracle [1966])*.

Long term trials were carried out at Samaru, in northern Nigeria, to determine which soil factors might become limiting to crop production under continuous cultivation. From these trials indications were obtained that soil acidity, and a deficiency of one or more trace elements were limiting factors with maize (as well as cotton). There was also some evidence of incipient potassium deficiency with these crops. The conclusion was drawn that in the short term, organic manures might be effective in maintaining fertility under continuous cultivation. Their favourable influence could be ascribed entirely to the provision of their plant nutrients, mainly phosphorus, and possibly also through its effect on soil acidity, as burning the organic matter prior to its incorporation in the soil was consistently superior to allowing it to decompose in the soil *(Heathcote [1970])*.

The trials were extended to embrace a wider range of soils and climate and were carried out at three sites, representing three soils in three climatic zones in northern Nigeria. The soil and climatic data for the three sites are given in Table 109:

Nitrogen gave large and significant increases in yield in all trials. *Lime* gave only small yield increases and responses to *trace elements* were not consistent; yields of maize were significantly increased at Samaru. *Potassium* gave marked increases in yield in 3 out of 5 trials, and showed some yield improvement in the others. This result is almost totally at variance with previous experience on the savannah areas of Nigeria and elsewhere in tropical Africa, but does bear out the possibility of incipient K deficiency noted in the earlier experiments by *Heathcote [1970[*. The authors attribute the discrepancy between their results and those obtained in earlier trials as following: (a) the soils on which the experiments were carried out have well-below optimum values for such criteria of fertility as organic carbon, nitrogen and CEC; (b) In the earlier trials, unimproved local varieties were used, with relatively low nutrient requirements; (c) the ability of the soil to buffer itself against an inba-

Table 109. Soil and climatic data on three experimental sites in Nigeria *(Heathcote and Stockinger [1970])*

Site	Latitude and longitude	Carbon (%)	Nitrogen (%)	pH in 2:1 m/100 $CaCl_2$	Cation exchange capacity (me/100 gm)	Exchangeable K (me/100 gm)	Exchangeable Ca (me/100 gm)	Mean annual rainfall (mm)	Duration of rains (days)
Kano	11°58'N 8°51'E	0.296	0.027	5.4	1.90	0.09	1.04	850	120–130
Samaru	11°11'N 7°17'E	0.580	0.040	5.2	2.96	0.20	1.89	1100	140–150
Mokwa	9°18'N 5°04'E	0.538	0.038	5.8	2.42	0.06	2.00	1100	165–175

The main treatment effects on maize for each treatment are shown in Table 110.

Table 110. Effects of treatments on grain yields of maize *(Heathcote and Stockinger [1970])*

Site	Year	Yield increments due to treatments*				S.E.	Control yields (kg/ha)
		N	K	L	T		
Kano	1968	+ 917	+539	+ 25	— 16	±154	247
	1969	+1099	+123	+125	+224	±121	144
Samaru	1968	+ 933	+ 75	+ 56	+473	± 84	1274
Mokwa	1968	+ 945	+304	+ 90	+240	±120	2122
Mokwa	1969	+1136	+419	+103	+ 33	± 93	1468

* N = 375 kg/ha nitrochalk (21 per cent N)
K = 88 kg/ha muriate of potash (50 per cent K)
L = Lime added at rate required to raise pH in surface soil horizon to 6.0
T = trace elements (B, Cu, Zn, Mo)

All plots received adequate amounts of phosphorus annually.

lance of ions brought about by heavy fertilizer applications may be limited; in the early trials, fertilizers were added at rates which would be considered low elsewhere, but which would not seriously upset this balance; (d) the likelihood of potassium response may have been further reduced by the use of ammonium sulphate in these trials, as one effect of this fertilizer was to reduce the levels of exchangeable calcium and magnesium in the soil, while hardly affecting that of potassium. In the trials of *Heathcote and Stockinger* described above, varieties of higher yield potential were used, rates of fertilizer application were relatively high, additions of calcium were much greater, especially as nitrochalk was used instead of ammonium sulphate. The additional Ca may have aggravated K deficiency.

The authors conclude that their results indicate that the accepted views on soil fertility and fertilizer usage in northern Nigeria, especially with regards to potassium, may have to be drastically altered in the light of changing farm practice.

In western Nigeria, applications of 94 kg N, 59 kg P_2O_5 and 44 kg K_2O produced grain yields of 6325 kg/ha at Ibadan, 5608 kg/ha at Fashola, and 6621 kg at A Kure. An investigation of maize production costs and returns indicated that applications of 450 kg of ammonium sulphate, 146 kg of triple superphosphate and 157 kg of muriate of potash per ha applied to a high-yielding, adapted variety, would generally prove to be profitable in most parts of western Nigeria *(de Geus [1970])*.

– *Union of South Africa*

The importance of maize in the economy of the Union of South Africa has been stressed in Chapter 1.

South African soils are notoriously poor in available phosphate. It is generally recommended that in areas with a rainfall of 375–500 mm phosphatic fertilizers should be broadcast at the rate of 24 to 40 kg P_2O_5/ha; and then ploughed under to a depth of at least 20 cm. Where rainfall is over 600 mm, from 40 to 60 kg P_2O_5 are usually applied, of which two-thirds are broadcast and the rest placed in the row at the time of sowing. Nitrogen, preferably in the forms of nitrates (because of the low pH of most South African soils) is applied at the rates of 20 to 30 kg N/ha. Potassium is required on the leached, worn-out and deep sandy soils of the high rainfall areas. With the heavy dressing of phosphorus fertilizer, potassium appears to become necessary on soils which were not originally deficient in this element *(Brevis [1955])*.

The extreme P-deficiency of these soils is demonstrated in a unique manner. In experiments with green manures ploughed under before maize, it was found that differences in the amounts of available nitrogen set free as a result of the decomposition of the green manures, could not be closely correlated with subsequent maize yields. On these highly P-deficient soils, the beneficial effects on maize due to green-manuring were largely attributable to the phosphate of the green manure, the latter serving as a 'catch crop' for phosphorus. Consequently it was found more economic and expedient to use adequate amounts of superphosphate, instead of resorting to green manures.

The levels of yield of maize in South Africa are still very low, with an average of 970 kg and 480 kg/ha, in 1968, for European and African Farms, respectively *(FAO [1969])*.

The low yields of maize in the Union of South Africa has been generally ascribed to the low, erratic and poorly distributed rainfall. As a result, recommendations have always stressed the need for a low plant population density, of about one/plant/m^2. With these low plant populations, response to nitrogen fertilizer is bound to be minimal, so that low yields are practically inevitable. Thus a vicious circle is created, whereby agronomic practices are adjusted to low yield levels, and low yield levels are thereby perpetuated.

These assumptions have been reevaluated in recent years, and almost identical results obtained in three separate investigations in different regions of the Union.

In experiments in Pretoria, with an average rainfall of 720 mm, of which 559 mm occur during the growing season (November to March inclusive) it was found possible to double the yields of maize by increasing plant density from 1.1 to 3.3 pl/m^2 and applying urea at the rate of 150 kg/ha. When nitrogen was applied to the widely spaced plants (1.1 pl/m^2) the effect on yield was either negligible or even negative.

Superphosphate, applied at the rate of 635 kg/ha superphosphate, increased yields by about 10 per cent, irrespective of plant density *(Human [1963])*.

In the Bergville District of Natal, with an annual rainfall of 605 mm, with good distribution over the growing period, the best grain yields were obtained from applying 106 kg N/ha to a plant population of 3.6 plants/m^2. At 1.1 plants/m^2 the same application of nitrogen increased yields by 652 kg/ha, whilst the corresponding increase at 2.2 plants/m^2 was 2600 kg/ha *(Mallett [1964])*.

In the Highveld Region, a relatively low-rainfall area of the Union of South Africa (average 439 mm during the growing period of maize), it was found that the lowest plant densities produced the highest yields when no nitrogen was applied; grain yield decreased by 17.7 per cent when the stand was increased from 1.1 to 2.2 plants/m^2, and by a further 14.1 per cent when the stand was increased to 3.3 pl/m^2, indicating that simply increasing plant density was not a means for improving yields. However, even under these conditions of fairly limited moisture, nitrogen slightly improved yields at all plant densities; the highest yield was obtained (2100 kg/ha) from 106 kg N/ha with a plant density of 2.2 pl/m^2 *(du Ploy and Roux [1968])*.

In brief, in contradiction to the older recommendations, a combination of higher plant densities and appropriate fertilizer applications, enables yield levels to be improved in different parts of the Union of South Africa.

Levels of nitrogen should of course be adjusted to rainfall conditions. The average optimum levels of nitrogen recommended for different maize growing areas in South Africa are given in Table 111 *(de Geus [1970])*.

Table 111. Recommended rates of nitrogen application for different areas in South Africa *(de Geus [1970])*

Area	Nitrogen (kg/ha)
Western Transvaal	37 –42
North-Western Orange Free State	37 –42
Northern Transvaal	37 –47.5
Eastern Transvaal	63.5–74
North-Eastern Orange Free State	63.5–69
Natal	90 –100

– *India*

Maize is an important crop in India, and is grown on an area of over 5 million ha. Yields per ha are however amongst the lowest in the world. *Relwani [1962]* attributes the poor yield performance to inadequate fertilization of the crop and lack of sufficient knowledge on important cultural practices such as optimum sowing date and plant population density.

Indian soils are highly deficient in nitrogen and most soils on which maize is grown are also deficient in phosphorus. Organic manures are generally reserved to cash crops, such as sugarcane, cotton, tobacco and vegetables, so that economic sources of fertilizers are essential for increasing the yields of maize.

In the Punjab, on a loamy soil deficient in nitrogen, with 9–12 kg available P_2O_5/ha and 313 kg available K_2O/ha, nitrogen applications were found to increase yields consistently. On an average of 3 years, 33 kg N/ha increased yield by 514 kg/ha; a second increment of 33 kg N gave an additional increase of 321 kg/ha. The net profits per rupee invested in the fertilizer were R 3.21 and 1.53 for the first and second increments, respectively. No response to phosphorus or potassium was recorded in these trials. Overall yield levels were however low *(Relwani /1962/)*.

The change-over from local open-pollinated varieties to improved hybrids, has, as elsewhere, had a marked bearing on fertilizer response. Though yields of local varieties can be increased considerably by fertilizers, hybrids are more than twice as responsive to fertilization than are the local varieties; the increase in net profit from fertilization has been found to be three times that from local maize. In certain trials, four hybrids receiving 112 kg N/ha showed an increase of at least 20 kg grain per kg of N, while only in a single case did a local variety show a similar response. At one centre the recommended hybrid produced as much as 49 kg grain per kg of N *(Engle /1962/)*.

In field trials in Rajasthan the highest yields of grain and stover were recorded for maize receiving 201.6 kg N/ha (which increased grain yields by 318 per cent over the control), phosphate at the rate of 67.2 P_2O_5/ha and potassium at the rate of 89.6 kg K_2O/ha *(Singh et al. /1965/)*.

The most recent fertilizer recommendations for maize have been summarized by *Shah /1969/*:

a) Nitrogen

In the western Gangetic plains, hybrid maize responds well to up to 150 to 250 kg N/ha. In Rajasthan also, favourable results were obtained with up to 240 kg N/ha. In the eastern Gangetic plains, maize grown under adverse conditions rarely responds to applications above 75 to 100 kg N/ha. Under favourable growing conditions, hybrid maize yields 5–6 tons/ha and responds economically up to 175 kg N/ha.

In the Southern zone, the optimum level for nitrogen is between 200 to 250 kg N/ha during kharif* and between 150 to 250 kg N/ha during the rabi** season.

The higher application during the kharif season is due to the leaching caused by heavy rains.

The response to nitrogen, when applied up to the optimum level is generally between 15 to 25 kg of grain per kg of N, and under unfavourable conditions, about 9–10 kg of grain per kg of N. At current prices, 4–5 kg of grain pays for 1 kg of nitrogen.

b) Phosphorus

The earlier open-pollinated varieties showed no response to phosphorus fertilization; the situation has changed with the advent of hybrids. Recently very marked responses to P applications have been recorded in a number of locations: linear response up to 60 kg P_2O_5/ha in the Kulu Valley of Himachal Pradesh; increases in yield of 2000 to 3000 kg/ha from fertilization with 60 kg P_2O_5/ha in hybrid maize grown on the red soils of Andhra Pradesh. In the maize-growing areas of Gujurat and Chindwara, many soils are very low in available P and maize yields very poor without P-fertilization.

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* Kharif: spring to autumn

** Rabi: autumn to spring

On soils low in available P, a response of 15 kg per kg of P_2O_5 applied, up to levels of 50 to 60 kg P_2O_5/ha has been recorded. At current prices, 3–4 kg of grain are equivalent in cost to 1 kg of P_2O_5.

c) Potassium

Response to potassium has been less general than to nitrogen or phosphorus. A significant response of 1300 kg/ha to an application of 50 kg K_2O/ha has been obtained in the Kulu Valley. Moderate responses have been observed at Delhi, in Bihar and at Karimmagar in Andhra Pradesh.

Potassium fertilizers are cheaper than those providing nitrogen and phosphorus: an additional yield of 2 kg of grain will pay for 1 kg of K_2O, so that any yield increase above 100 kg/ha will be profitable.

d) Secandary nutrients

The levels of calcium, magnesium and sulphur have been found to be generally adequate in most soils in which maize is grown.

e) Micronutrients

Zinc is the only micronutrient that has been found to limit maize yields at a number of locations. Yield increases of 500 to 1000 kg/ha have been obtained in such fields following applications of 5–10 kg zinc sulphate/ha. At Srinagar, and in the Punjab, maize has given a linear yield response up to 25, and occasionally up to 40 kg zinc sulphate per ha.

17.3.6 Australia

In fertilizer experiments on red loam soils in Queensland, applications of 44 to 88 kg/ha of nitrogen gave economic increases in yields, on land under continuous maize, provided seasonal conditions were favourable and that the crop was not heavily infested by tropical rust. In dry seasons, which are infrequent, no response to N can be expected. The nitrogen applications have been found to have little residual effect. Yield responses to phosphorus were obtained only when the available P in the soil was less than 56 ppm. On soils high in available P, a growth response to superphosphate was evident up to six weeks of age, but was not evidenced in the final yield, probably because phosphate uptake by the unfertilized plants during the long growing period of the crop was adequate. No evidence was obtained showing an effect of potassium on yield *(van Haeringen and van der List [1965])*.

17.4 Fertilizer use in developing countries

17.4.1 Importance

Much of the rise in crop yields in industrialised countries can be attributed to increased use of fertilizers. For example, it has been estimated that half of the rise in crop production per unit areas in the United States since 1930 has been due to additional fertilizers *(Durost and Barton [1960])*. Similar results have been recorded in developing countries that have started to use fertilizers. In India, increased fertilizer use was estimated to be responsible for 4.6 million tons out of the 11.2 million tons increase in food production during the second five-year plan *(FAO [1967])*. However, it is, difficult to separate out the effects of other improved practices which, in addition to making their own specific contribution to yield increases, greatly enhance the response of the crop to fertilizer applications.

Over all regions and countries of the fertilizer programme of the *FAO Freedom from Hunger Campaign*, nitrogen gave positive effects in 97 per cent of the locations, phosphorus in 90 per cent, and potassium in 85 per cent *(Couston [1967])*. The most successful fertilizer treatment increased yields by an average of 60 per cent, and was profitable in over 90 per cent of all locations. If the other production inputs had also been introduced, the overall effect on productivity would have been even greater *(Olson [1968])*. The value/cost ratio averaged 4 to 8, indicating that the investment in properly used fertilizers is highly profitable.

In the early stages of development of traditional farming, although plant nutrients are the major limiting factor (if water supply is adequate), the yield increases due to fertilizers are, of necessity, limited. Marginal productivity of fertilizer increments is low because other essential production factors that interact with fertilizers are not present.

Limited knowledge on the most effective way of using fertilizers may also reduce their impact. Factors such as optimal rates, best timing of application, most suitable nutrient carrier, combinations of fertilizers in the right proportion, are highly relevant to the overall effects obtained. Faulty or negligent application techniques, such as uneven distribution of the fertilizer, may also reduce their effectiveness.

All these problems fade as knowledge on fertilizer application increases as a result of research, and the farmers know-how improves through education and extension work *(Mellor [1962])*.

Increased use of fertilizers is already important in the early stages of development, for practical and for psychological reasons: (a) Practical; because the returns are quick and little capital is required. The use of fertilizers is probably the most responsive single factor for increased yields per hectare or per unit water.

Fertilizers also have the great advantage that they can be successfully applied by the individual farmer who has the necessary initiative, without his being dependent on his neighbours; by contrast, many other practices, such as insect and disease control, are almost certainly doomed to failure – for obvious reasons – unless organised collectively and carried out in a planned fashion over fairly large areas.

(b) Psychological; because few inputs have such strikingly visible effects on the crop. The fertilizer itself is a tangible input, so that the relation between cause and effect is most evident. For these reasons, fertilizer application is considered a 'lead' practice which predisposes the farmer to adopt other improved practices. Every improvement in varieties and in management practices that increases yields, also increases fertilizer requirements. Increased amounts are needed to enable the potential yield increase due to improved practices and to replace the additional nutrients removed from the soil.

Fertilizers bear such a highly complementary relationship to other yield-increasing practices that the amounts of fertilizer used per hectare of land have been found to be a reliable index of progress in the adoption of yield-increasing technologies in general. *Williams and Couston [1962]* report a 0.87 coefficient of correlation between fertilizer consumption and grain yields in 40 countries. Generally, the countries with low levels of fertilizer use and yield-value* of crop production are the relatively under-developed countries; high levels of fertilizer use and yield-value of crop production characterise countries with a modern highly productive agriculture and an efficient industrial sector.

17.4.2 Complemental nature of technological factors

Agricultural progress cannot, as a rule, be piecemeal. There is little point in introducing improved varieties or hybrids if they are unable to develop their potentialities due to lack of nutrients; there is no justification in fertilizing so as to produce what might become a bumper crop, if disease prevention and pest control are not carried out and part of the crop is thereby lost. Living standards will hardly rise if weed control is ineffective because it has to be carried out by back-breaking manual labour. For these reasons, single-practice programmes, such as introducing irrigation, applying fertilizers, using good seeds, controlling pests, etc., usually give poor results (*Kellogg [1962]*).

Kellogg provides an illustrative example of the inefficacity of fertilizers, when used on varieties not adapted to high levels of fertility, and conversely, of the need for fertilizer application before improved varieties can give highly increased yields. In fertilizer trials on maize in India, the increases obtained over unfertilized local varieties were 1290 kg/ha from hybrid seed alone, 1110 kg/ha from the application of fertilizer alone, and 3480 kg/ha from the combination of the two.

Certain techniques, when applied in combination, can give rapid and spectacular results in a very short time. A combination of improved variety, appropriate fertilization, adjusted plant population, efficient weed control and plant protection can give increases in yield that range up to several hundred per cent. The expenditure required from the farmer for inputs is very low in relation to the additional yield produced, provided the prices charged for fertilizers and pesticides are not inflated as a result of deliberate policy, dependence on unscrupulous middlemen, unrealistic distribution costs, or other man-made factors that disrupt the cost ratio of crop and input factors.

17.4.3 Economic constraints

Maize is particularly well suited for serving as the backbone of a programme designed to introduce improved practices. It responds spectacularly well to fertilizers, without any of the undesirable side-effects resulting from heavy fertilization rates that are

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* The yield-value index of crop production per hectare is obtained by multiplying the production of each recorded crop by its regional price-weight, aggregating these values, and then dividing by total hectares of crops (*Williams and Couston [1962]*).

usual in many other crops – such as lodging in the small grains, excessive vegetative growth in cotton, reduced sugar content in sugar crops etc. The main obstacle in encouraging the use of fertilizer on maize is economic. Maize is an important food crop in many developing countries, and an increase in production would have far-reaching effects on the nutrition of the populations of these countries. The subsistance farmers are faced with the paradoxical situation that in spite of undernutrition and even hunger, the prices he obtains for food products are extremely low, and even so they cannot always find buyers for a surplus they may have harvested over their own requirements:

Over 85 per cent of the population in most of the developing countries is engaged in agriculture, and the purchasing power of the vast majority is extremely low. Under these conditions, it are only export crops that can provide the cash needed to buy inputs such as fertilizers. Increased yields of food crops generally result in an immediate drop in their already low prices. Small wonder that it is difficult to induce the farmer, even after the spectacular effects of fertilizers on the crop are demonstrated to him, to spend part of his meagre cash income on fertilizers *(Bergmann [1970])*. Only an appropriate government policy, assuring a fair price for agricultural produce for the home market, and a supply of fertilizers at a fair price, can overcome this limitation to agricultural progress and increased productivity.

A very convincing example is provided by the campaign for increased fertilizer use by FAO in a number of countries of northern Latin America. By trials and demonstrations it was shown that the application of fertilizers to maize was economically justified, and that a doubling of yields could be achieved from the technical point of view. And yet farmers' response was most disappointing. For this reason, the FAO experts have come to the conclusion that future trial and demonstration work with fertilizers, and other improved practices, must proceed in close association with pilot-schemes on credit. Such a pilot-scheme involving 200 tons of fertilizers per year, provided by the FAO, was launched in El Salvador in 1964; most of the credits were for maize. The average credit was for 300 kg of fertilizer material, or dollars 33.60. About 50 per cent of the credit were already recouped by 1965.

In Nicaragua, a credit programme, involving 3000 tons of fertilizer is also underway. It is financed by government funds and executed by the National Bank.

In brief, it must be realized that however great the benefits to be derived from the use of fertilizers in developing countries, a rapid increase in their use cannot be expected unless essential social, economic and institutional changes are adopted.

17.5 Economics of fertilizer use

Determining the most economic combination and rate of fertilizers to use is the most important application of the results of fertilizer research. This requires taking into account two sets of factors – agronomic and economic.

Two types of information are needed from the agronomic point of view for making fertilizer recommendations for specific producing conditions: (a) the general yield equation for the crop, with yield expressed as a function of applied fertilizer variables and the productivity factors; and (b) the levels of the productivity levels for the specific conditions for which a fertilizer recommendation is to be made.

Unfortunately, there are as yet no well defined procedures to follow in formulating a general yield equation and in characterizing the productivity factors. Consequently, the results obtained in field experiments are usually averaged over broad geographical areas from which only very general fertilizer recommendations can be formulated *(Laird et al. [1969])*.

The amounts of fertilizer that a farmer should use does not depend only on the anticipated yield response under specific producing conditions, but must take into account a number of economic factors, such as the ratio between the cost of the fertilizer and the probable price of the product, the availability of cash on the cost of credit, the degree of risk and uncertainty involved, and the ability of the farmer to absorb these risks; conditions of land tenure, etc.

17.5.1 Law of diminishing returns

Applying fertilizers to crops is generally one of the easiest and most profitable ways of eliminating an important limiting factor in crop production. However, the fertilizer rates that give the highest yields are not necessarily the most profitable ones. The response to increasing amounts of fertilizer follows the law of diminishing returns, and a point is invariably reached at which an increment of fertilizer will increase costs more than it does returns. Where a nutrient deficiency is severe, the first units of nutrient added may cause a very small yield response; with additional increments the rate of response increases until an inflection point is reached; this is followed by a maximum after which yields decrease with additional fertilizer increments. In this case the overall yield-response curve is sigmoid-shaped.

In long-term investigations on two soil types in Missouri *(Colyer and Kroth [1968])* it was found that *maximum yields* were only slightly higher than those which would result in *maximum profits*. However, the quantity of nitrogen fertilizer required to obtain the maximum yield was generally substantially greater than that required for economically optimal yield.

An example of how the law of diminishing returns operates in the case of nitrogen application to maize is shown in Table 112.

Table 112. Response of maize in Illinois to increasing amounts of nitrogen *(Anon. [1967])*

Added nitrogen (kg/ha)	Maize yield (kg/ha)	Additional yield from additional Nitrogen (kg/ha)
—	4328	—
1st 10	4636	308
2nd 10	4938	302
3rd 10	5187	249
4th 10	5409	222
5th 10	5590	181
6th 10	5725	135
7th 10	5846	121
8th 10	5946	100
9th 10	5993	47
10th 10	6027	34

The results of an investigation by *Barber [1964]* on the profitability of potassium application to maize in Indiana, are shown in **Figure 194**. Crop yield was found to increase in typical curvilinear fashion with increasing amounts of potassium, and total dollar returns were highest at the highest potassium rate applied (132 kg K/ha). However, the most economical return was obtained at about 66 kg K/ha.

17.5.2 Determining optimum economic rates of fertilization

Many methods have been devised to analyse the results of fertilizers experiments from the point of view of maximum economic return.

Where the fertilizer experiments have been planned in such a way, that a response curve can be drawn, the point of maximum return from the fertilizer can be determined graphically, as in **Figure 195** *(Stritzel [1963])*.

All this appears at first sight fairly simple and straightforward; in practice, however, supplying fertilizers in the most economical way is a complicated problem, and fertilizer practice is still highly empirical. The following are some of the difficulties encountered by the farmer in an economic analysis of fertilizer profitability.

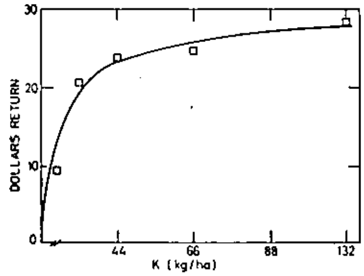

Fig. 194 Profitability of potassium application to maize in Indiana *(Barber [1964])*. Dollar returns climbed up to the highest rates 132 kg K per ha. About 66 kg K per ha per year gave the most economical return in this maize-soybean-wheat-hay rotation. By courtesy of the American Potash Institute.

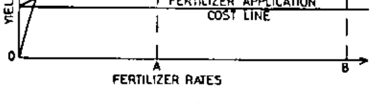

Fig. 195 Generalised crop response curve with associated cost lines shown in terms of quantity of crop increase required to pay for the fertilizer *(Stritzel [1963])*. Maximum total profit occurs at point A, where returns minus costs are highest. Point B is a break-even point, where the value of the yield increases just equals the cost of fertilizer and its application. By courtesy of Iowa State University.

(a) The most important are the uncertainties regarding yields and prices involved in his calculations; (b) the profitability of fertilizing depends on the overall level of management; (c) the residual effects of the fertilizer must be considered; and (d) a decision usually has to be taken on the most profitable combination of nutrients and not on the level of a single nutrient.

17.5.3 The role of prices

Three relationships are important in considering the role of prices in determining fertilizer use: the cost of the fertilizers, the cost of other inputs, and the price of the agricultural product.

An example of the effect of the cost/price ratio between nutrient and maize is shown in **Figure 196** *(Brown et al. [1956])*. To determine the optimum input of either nitrogen or potassium* for maize, the cost of the nutrient was divided by the price of maize. Selection of the appropriate ratio from one of the two graphs in Figure 210 provides the optimum input for this particular soil type.

Two examples of fertilizer recommendations made to Kenya farmers, presented in a graphical form, and showing the economic optimum to be applied according to the price ratio between nitrogen and maize, is given in Figures 206 and 207.

Heady and Haroldsen [1965] have estimated that a 1 per cent decrease in fertilizer price would increase fertilizer purchase by 1.4 to 1.8 per cent. Similarly, a 1 per cent increase in crop prices would be expected to increase fertilizer purchases by about 0.5 per cent.

The prices paid by farmers in the United States for fertilizers have decreased in relation to the costs of other inputs such as farm machinery, wages and land. *Heady and*

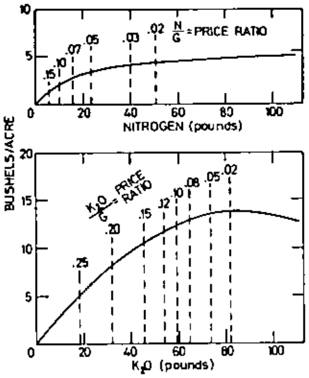

Fig. 196 Example of effect of the price ratio between nutrient and product. Added bushels from K_2O and N and optimum rates for specified price ratios of fertilizer nutrients and corn, Carrington soil *(Brown et al. [1956])*. By courtesy of Iowa Agricultural Experiment Station.

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* In this experiment, N and K effects were found to be independent, so that the optimum rate for each nutrient could be selected without regard to the level of the other.

Haroldsen [1965] estimate that a 1 per cent increase in land price will increase fertilizer use by 0.4 per cent.

The reduction in the cost of fertilizers, the increased cost of the other inputs involved in agricultural production and the higher prices paid for grain, have all contributed to a general increase in the use of fertilizers in maize production, in developed countries. The increase has been far smaller in the developing countries, mainly because of the tendency for fertilizer costs to increase in relation to grain prices for reasons explained above (cf. p. 435).

17.5.4 Uncertainty and fertilizer use

In making decisions on the use of fertilizers the farmer is faced with a number of factors whose values cannot be predicted with certainty at the time the decision must be made. These are mainly biological and physical factors which determine the yield that will be harvested, and economic factors which determine the price the farmer will obtain for his crop.

The calculation of the most profitable rate of fertilization is based on data obtained from field experiments; these results need not necessarily apply during the following season, when the same crop is grown on a different field or a different crop is grown on the same field. The response of the crop to fertilization is dependent on many environmental factors which cannot be forecast and on agronomic practices which may differ from farm to farm: such as varieties, plant population, maintenance of fertility level, etc. A difference in the amount of rain-fall or in its distribution, the incidence of diseases or pests or other similar factors make all the difference in the response of the crop to fertilizers. As a general rule the lower the amounts of available nutrients, the greater the response and the more profitable are higher rates of application (**Figure 197**, *Dumenil et al. [1959]*).

The cost to the farmer of making mistakes in his decisions regarding fertilization of maize has been estimated by *Havlicek and Seagraves [1962]*. The costs* of wrong decisions on the application of nitrogen to maize were calculated from 37 experiments over a 3-year period. Weather conditions, in particular droughts, were included in the analysis. These workers found that the loss resulting from a wrong decision on fertilizer use, based on wrong assumptions regarding the price of maize at the time of harvest, has relatively little effect on profits. For example, if the farmer assumed that the price of maize would be dollars 1.25/bu and applied nitrogen at the most profitable rate, and the price turned out to be only dollars 0.75/bu, his net loss would be dollars 0.58/acre; if the price turned out to be dollars 1.75/bu, he would lose only dollars 0.28/acre. The highest loss from a wrong decision was found to occur when the farmer plans for a low price and applies fertilizers accordingly. If he planned for dollars 0.75/bu maize and the price actually turns out to be dollars 1.75/bu, his net loss will be dollars 2.90/per acre. Wrong decisions based on uncertainty due to weather have a greater impact on the potential losses to farmers than the price of maize.

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* The examples that follow, though they illustrate general principles, refer to specific situations; therefore the units of measurement have been left in their original form and not recalculated in metric units as elsewhere in this book.

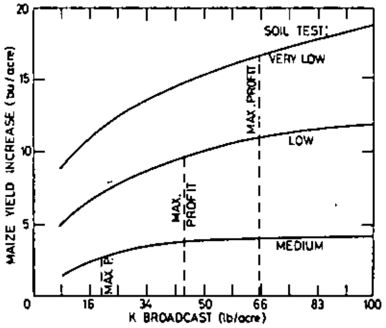

Fig. 197 Rate of application of potassium for maximum profit on maize as related to soil-test level in Iowa *(Dumenil et al. [1959])*. By courtesy of the Iowa State University.

If a farmer applied fertilizer on the assumption that 'average' weather conditions would prevail, he would lose dollars 6.63/acre in the case of insufficient rainfall and dollars 7.16/acre if conditions were unusually favourable. This illustrates the economic significance of irrigation, not only as a means of increasing yields, but also of increasing profitablity, by eliminating an important component of uncertainty in the decision process.

For the farmer in a developed country in the temperate regions, using advanced agricultural technology, the inability to predict accurately the most profitable rate of fertilizer application is not a serious handicap in the use of fertilizers. Fertilizers are cheap, and do not generally represent more than 5–10 % of the cost of production *(Bublot [1967])*. High yields are obtained as a result of costly inputs in labour, mechanisation and pest, weed and disease control, but are also dependent on adequate and high levels of fertilizer application. Even if the farmer applied amounts in excess of immediate requirements, this is not money lost, but will be mostly retrieved by increased yields of subsequent crops.

The situation is entirely different for a farmer in a developing country. Fertilizer application is usually the first step taken to increase yields, whilst agricultural technology is still backward, varieties primitive and yields generally low. Fertilizers are relatively expensive, because they usually have to be imported. Even a low rate of fertilization may account for a relatively high proportion of the total costs of production. The risk of no response, or even a negative response if rainfall is insufficient or badly distributed, is great. Even when rainfall is satisfactory, a yield increase of even 30 % in relation to the unfertilized crop, may still be insufficient to cover the cost of fertilization. Small wonder, therefore, that under these circumstances, even farmers who wish to improve their production methods adopt a very cautious approach to fertilizer application and apply only moderate amounts. Here again, there is a great difference between the farmer in a developed country and his counterpart in a developing country. The former can afford to take greater risks. He knows that he stands to lose more by producing low yields in a good season than from relative lack of response to fertilizer in a poor season. He also knows that most of the fertilizer will not be lost, and the carry-over effect will be greater, the lower the yield during the current season. The subsistence farmer, who literally lives from hand to mouth, cannot afford to take such risks on the basis of such calculations.

The prospects for profit from fertilizer use must be sufficiently great to outweigh the investment risk, and the marginal return to marginal cost ratio must be considerably higher in developing countries than in those with advanced agriculture. Because of the overall cost structure and levels of technology, the opposite is generally the case under existing circumstances.

Fertilizer use is, however, an essential ingredient of increased productivity: the financial risks involved can be reduced provided the other essential factors of production are adopted, such as an improved rotation for increasing soil fertility, and improving moisture regime, soil and water conservation methods, disease, pest and weed control, as well as improved varieties.

As the farmers gain experience in the use of fertilizers and in applying improved technology, they gain confidence and are more likely to adopt the recommendations of the advisory services. They can be encouraged to do so if the depressing influence of risks is at least partially offset by creating a more favourable cost/price relationship through equitable price support and/or fertilizer subsidy programmes *(FAO [1967])*.

Extensive fertilizer trials in developing countries have shown that it is generally profitable for traditional farmers in developing countries to use fertilizers, in particular on a responsive crop like maize. In Table 113, are shown the results of fertilizer trials and demonstrations on maize in several developing countries.

Table 113. Results of fertilizer trials and demonstrations plots on maize in a number of selected countries *(FAO [1967])*

Country, region, variety, etc.	Fertilizer treatment (kg/ha)	Yield (kg/ha)		Yield increase		Net return from fertilizer		Output (kg/grain) per kg of nutrients
		Control	Fertilized	kg/ha	Percentage	$/ha	Per $ of fertil.	
El Salvador-central	90-90-0	2420	4146	1726	71	93	3.1	9.6
Ghana								
Forest	22.4-0-22.4	1419	2287	868	61	47	4.6	19.3
Savanna	44.8-0-0	1159	2022	863	74	41	3.2	19.3
Honduras								
Hybrid-north	90-90-90	4788	9801	5013	105	272	5.3	18.6
Local	45-45-45	1674	3110	1436	86	64	3.0	10.6
Morocco-north								
Irrigated	40-40-0	1436	2395	959	67	31	2.9	12.0
Non-irrigated	0-40-0	648	1053	405	62	13	2.8	10.1
Morocco-south								
Non-irrigated	20-40-0	723	1139	416	58	9	1.7	6.9
Nigeria								
Forest	0-0-22.4	1521	1861	340	22	11	4.2	15.2
Savanna	0-0-22.4	1262	1559	297	24	9	3.7	13.3
Turkey								
Marmara	40-40-0	2246	3194	948	42	50	3.0	11.8
Black Sea	40-40-0	2072	3788	1716	83	111	5.4	21.4

The fertilizer applications shown are those which reported the largest net return per ha above the control plots. The data show that considerable yield increases were obtained, ranging from 22 to 105 per cent and from 297 to 5013 kg/ha. In all cases, the value of the increased production was greater than the cost of the fertilizer used. The net returns per dollar invested in fertilizers generally ranged from about dollars 3 to 5 (The one exception was under particularly unfavourable conditions of rain-fed maize, producing only 723 kg/ha without fertilizers). Not surprisingly, the highest net return from fertilizers (dollars 272 per ha; dollars 5.3 per dollar of fertilizer invested), was obtained (in Honduras) with a hybrid, producing up to 9800 kg/ha and to which the highest fertilizer rate in these trials was applied (90–90–90).

17.5.5 Capital and credit

The optimum economic level as determined in **Figure 195** corresponds to the point at which the cost of the last increment equals the additional value of the crop in question. This assumes that the farmer has sufficient capital to exploit all profitable investment potentialities available, a situation that is indeed rare in agricultural enterprises, particularly in developing countries where capital scarcity is the rule.

An example of the kind of choice a farmer is faced with when he does not have all the capital available to make maximum profits, is given in Table 114 *(Jensen and Williams [1963])*. In this example, it is assumed that a farmer managing a farm of 100 acres, has half his land on Skyberg soil and half on Floyd soil.

Table 114. Yields, costs and returns from application of potassium to maize on Floyd silt loam (1958) and on Skyberg silt loam (1957), Dodge County, Minn. *(Jensen and Williams [1963])*

Amount of K	Added K	Cost of added K at 6 cents /lb	Corn yield	Added yield	Value of yield at $ 1.00/bu	Returns per $ 1.00 invested in K
lb K/acre	lb K/acre	$/acre	bu/acre	bu/acre	$/acre	$
			Skyberg silt loam			
0	—	—	93	—	—	—
25	25	1.50	104	11	11	7.33
50	25	1.50	110	6	6	4.00
75	25	1.50	115	5	5	3.33
100	25	1.50	118	3	3	2.00
125	25	1.50	120	2	2	1.33
			Floyd silt loaO			
0	—	—	50	—	—	—
25	25	1.50	72	22	22	14.67
50	25	1.50	83	11	11	7.33
75	25	1.50	90	7	7	4.67
100	25	1.50	97	7	7	4.67
125	25	1.50	102	5	5	3.33

* No starter fertilizer applied, but 80 lb. N and 52 lb. P per acre were broadcast prior to planting.

A glance at Table 114 shows that it is profitable to apply potassium at the highest rates tested (125 lb K/acre on the Floyd soil, and at 100 lb K/acre on the Skyberg soil); in other words, the farmer should apply 11 250 lbs of potassium. However, suppose our hypothetical farmer is short of capital and can only afford to purchase 5000 lbs of potassium. From Table 114 we see that the highest return from fertilizers is obtained from 25 lbs/acre of K applied to the Floyd soil. The next highest returns are from 25 lbs/acre on the Skyberg and from an additional 25 lbs/acre on the Floyd soil.

Therefore, in order to invest the sum available to him, so as to make the maximum profit from his investment in fertilizers, the farmer should apply 3700 lbs of K on the Floyd soil, at the rate of 75 lbs/acre, and the remaining 1250 to the Skyberg soil, at the rate of 25 lbs/acre. This will give him an added yield value of:

On the Floyd soil: $50 \times (22+11+7) =$ dollars 2000
On the Skyberg soil: $50 \times 11 =$ dollars 550
Total = dollars 2550

When operating capital or credit at reasonable cost are not available to the farmer, he may be unable to use the most profitable rates of application of fertilizer or – in extreme cases such as those that arise in developing countries, he cannot afford fertilizer use at all.

The return per unit money invested in fertilizer is highest at the lower rates of fertilizer use, because of the diminishing yield responses with increased rates of application. Therefore, the farmer who is unable to obtain money for the purchase of fertilizers at a low cost will adopt lower levels of fertilization than he would if capital was not the limiting resource.

One important application of this situation is concerned with the *minimum economic rate of application*, ec. the rate associated with the lowest cost per kilogram of maize permitted by all other conditions. This rate depends on the level of other variable costs of production, excluding the cost of the land, which remains unchanged whether a crop is grown on it or not. The higher these costs the higher the minimum economic rate *(Ibach and Mahan [1968])*. The principle is illustrated by **Figure 198**.

An example of fertilizer recommendations, to Kenyan farmers, presented graphically and based on field experiments, and taking into account the amount of money available to the farmer for the purchase of fertilizers, is given in **Figure 192**.

The economic minimum rate is of particular importance when capital available to the farmer is limited, a situation extremely prevalent in developing countries and particularly in subsistence farming. This rate makes possible a higher net return from specified amounts of capital than at any other rate. If capital is limited, it is more economical to apply the economic minimum rate to part of the land and to leave the rest idle.

An economic analysis by linear programming showed that in Iowa, it would be more profitable for a beginning farmer to farm 32 ha with a maize-maize-soybean rotations fertilized at an intermediate level rather than to farm 74 ha, without fertilization *(Heady [1956])*.

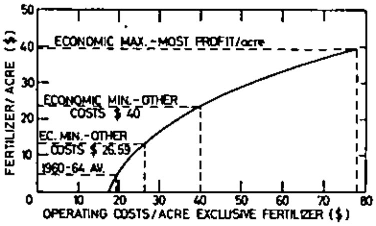

Fig. 198 Economic minimum and maximum expenditures for fertilizer. By courtesy U.S. Department of Agriculture.

17.5.6 Substitution relationships

Fertilizer-yield relationships can serve as a guide for making various combinations of inputs in maize production, the choices being based on estimates of probable gains from making substitutions.

– *Land*

Fertilizers can substitute for land, since a given production can be achieved from a smaller area by using fertilizers. The less fertilizers previously used, the larger the area of land which can be substituted for a given amount of fertilizer. In traditional farming, fertilizers can therefore substitute for large areas, provided that appropriate varieties and cultural methods are adopted simultaneously. In the USA, it is estimated that one ton of NPK can substitute for 3.76 ha of land (at 1960–64 average crop and fertilizer prices and fertilizer use). If no fertilizer is used, one ton of NPK would substitute for 5.38 ha, whilst if fertilizer is already used at the economic maximum, one ton of fertilizers would substitute for only 0.76 ha. For maize produced without fertilizers, on land yielding 5400 kg/ha, it was estimated that one ton of fertilizers could substitute for 2.28 ha, whilst on land on which 88 kg/ha of fertilizer were applied, it would substitute for only 1.16 ha *(Heady and Haroldsen [1965])*.

In Louisiana, a study carried out in 1960 showed that the same production level of maize could be obtained from less than half the acreage devoted to corn, if fertilizers were substituted for land at the economically optimum rate *(Sullivan and Wiegmann [1960])*.

It has been mentioned that 40 to 70 per cent of the increase in yields in the United States is the result of greater fertilizer use. It has been suggested that on the average, each additional ton of fertilizer in 1951–55 gave returns equivalent to 7.5 ha of cropland *(Christensen et al. [1962])*.

In view of the generally low cost of fertilizers and the very substantial yield increases that their rational use makes possible, the tendency in countries with a modern agriculture is to substitute fertilizers for more expensive inputs, such as labour and machinery.

Normally, in a modern agricultural economy, a farmer will not reduce the area of his own land which he is cultivating, because he can produce more by using fertilizers. He will simply increase production on the whole area available to him. The situation is different in regards to rented land, and he will then consider how best to use his capital – by increasing the area he intends to farm, or by intensifying production on a more limited area.

– *Labour*

Fertilizers can increase yields per unit of land with relatively small increases in labour. It is therefore possible to produce a given output with less labour. In Iowa, it has been estimated that one ton of fertilizer can substitute for 600 hours of labour in the production of maize when no fertilizers are used, and for 120 hours of labour if 33 kg/ha of fertilizers are applied *(Heady and Haroldsen [1965])*. This aspect is becoming of increasing importance in industrialized countries with chronic shortages of labour for agriculture.

17.5.7 Effects of management level

A fundamental economic rule is that the productivity of any one resource depends on the quantity and quality of other resources with which it is combined. The interaction of fertilizer use with other production factors has been discussed in chapter 15. It is obvious that adapting fertilizer use to other production factors and vice-versa, is a basic test of managerial ability.

Higher yields are one of the main factors for reducing costs of production per ton of maize produced. Certain costs remain unaffected by the yield level, such as land, buildings, equipment, seed, and weed, disease, and pest control etc. In the United States, it is estimated that with maize costs at dollars 40 per ton, 3 to 3.8 tons/ha of maize must be produced to pay for fixed costs, exclusive of fertilizers *(Tisdale and Nelson [1966])*.

The effect of superior management in raising the level of profitability of fertilizer use is shown in **Figure 199** *(Stritzel [1963])*. Clearly, the more efficient the management, the higher the amounts of fertilizer that can be applied profitably.

– *Fertilizer rates*

One aspect of good management is of course to make a correct estimate of the amounts of fertilizer to apply. In chapter 11 we have seen how soil tests can aid in assessing potassium requirements. *Dumenil et al. [1959]* give an example, based on 144 field

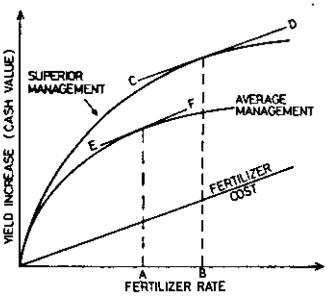

Fig. 199 Effect of management level on maximum profit rates of fertilizer application. The vertical lines from the points A and B to the fertilizer rate line indicate the points that give maximum profit for each management level. Clearly, the more efficient the management, the higher the amounts of fertilizer that can be profitably applied. (From *Stritzel* (1963): by courtesy of Iowa State University.)

trials in Iowa, how profitability of applying potassium to maize depends on adjusting rates to K-levels in the soil, as shown by soil tests (see Figure 197).

17.5.8 Irrigation

The principal limiting factor affecting fertilizer use on maize is moisture supply. With irrigation, the farmer has potential control of one of the main production factors – water, and the cost of fertilizers accounts for a much smaller fraction of the total production costs, as compared with rain-fed maize. The rates that have to be applied are high, but the risk of their not being profitable is much smaller than the potential losses due to low yields if nutrients are limiting. Under these circumstances, fertilizer application may be considered as an insurance measure. In view of the high costs involved in irrigation farming high yields are an economic necessity and the farmer actually cannot afford *not* to apply high rates of fertilizers.

– *Management*
In Kansas it has been shown that superior management including high rates of lime and fertilizer, increased yields of irrigated maize from 5700 kg/ha to 9500 kg/ha. At the higher levels, the cost of production were reduced from dollars 34/ton to dollars 27 *(Garman [1963])*.

17.5.9 Effects of fertilizer on quality

In chapter 9 we have discussed the effects of fertilizers on quality. In particular, the possibility of increasing protein content of maize by fertilization was documented. These effects may have considerable economic value, and, logically, should be taken into account when calculating economic returns from fertilization. Unfortunately, the price of the grain is not generally adjusted to its quality; however, farmers using the product for livestock feeding on their own farms, should certainly not disregard protein content when evaluating the most economic rate of fertilizer application.

17.5.10 Residual effects

The determination of profitability of fertilizers as described in **Figure 195** takes into account only the effect of the fertilizer on the yield of the crop to which it is applied. There are many supplementary effects that are not taken into consideration, among these residual effects on soil and subsequent crops. These have been discussed in Chapter 15.

Generally, the entire cost of the fertilizers is charged to the crop to which they are applied, and yet, as a rule, carry-over effects may be considerable, as much as 40–50 per cent and more for phosphorus, 25–60 per cent for potassium, and even 25 per cent for nitrogen. Frequently, the carry-over effects on the following crop(s) may be sufficient to pay the entire cost of the fertilizers applied. In trials in Nebraska, on irrigated maize, nitrogen applied at the rate of 88 kg N/ha increased yields by 3430 kg/ha in the year of application and increased the yield of the following maize crop by 700 kg/ha; the latter increase alone was sufficient to pay for the fertilizer applied during the preceding year *(Pumphrey and Harris [1966])*.

The residual effect may actually be greater than the direct effect: in Indiana, potassium applied to a rain-grown maize crop, at the rate of 55 kg K/ha, increased the yield of the crop to which it was applied by 546 kg/ha, but over four years gave a total yield response of 1400 kg/ha *(Robbins [1962])*.

Another example is given in Table 115, showing the residual effects of fertilizer applied to clover in a two-year rotation of red-clover seed and maize in Minnesota *(University of Minnesota [1961])*. At first sight, the fertilizer applied to the clover would appear unprofitable, but when the carry-over effect of P + K on the next season's maize is considered, it is seen to have been sufficiently great to make the fertilizer application profitable for both crops.

Table 115. Residual effects of fertilization in a two-year rotation, red clover seed and corn, Minnesota, 1959-60* *(Univ. of Minnesota [1961])*

Rate of Fertilizer*	Fertilizer cost**	First-year increase in red clover seed ***		First-year increase in returns over fertilizer from seed	Second-year increase in corn		Increase in total crop value for 2 years	2-year profits over fertilizer costs
		lb./acre	Value		bu/acre	Discounted value ****		
lb N+P +K/acre	$/acre		$/acre	$/acre		$/acre	$/acre	$/acre
0+44+ 0	10	-4	-1.04	-11.04	3.4	2.81	1.77	-8.33
0+44+ 83	15	9	2.34	-12.66	31.5	26.02	28.36	13.36
0+44+166	20	10	2.60	-17.40	33.4	27.59	30.19	10.19

* All the fertilizer were applied to the first-year crop. Yields are expressed as increases over check plots. Check plots yields were 84 lb. of seed and 52.9 bu. of corn/acre.

** Costs of P and K based on 23/lb P (10/lb P_2O_5) and 6/lb K (5 cents/lb K_2O).

*** Inadequate pollination and first crop clipped too late for good seed set. Clover seed valued at 26 cents/lb.

**** Discounted at interest rate of 10%/year. Corn valued at $1.00/bu.

Clearly, to disregard residual effects when these are expected, to be substantial, will lead to wrong decisions in the use of fertilizers.

Where a subsistence type of farming prevails, the farmer is concerned mainly with his immediate needs, and hence it will be difficult to persuade him to take into account residual effects when making his decisions on fertilizer use. Where farmers' incomes are higher and more secure, there is no justification in ignoring residual effects when deciding on an appropriate fertilization programme.

17.5.11 Optimal combination of fertilizers

Generally, the problem is not to decide on the optimum rate of a single nutrient to apply, but to chose the optimum combination of fertilizers to use. This requires information not only on the effects to be expected from increasing rates of each nutrient separately, but also of the interactions between them. These interactions between different nutrients may give a higher crop response than the sum of responses to each nutrient applied separately.

In Table 116 *(Arnon et al. [1962])* are summarized the results of a maize fertilizer experiment on an irrigated terra rossa soil, at Newe Yaar, Israel.

Table 116. Response of irrigated maize to fertilizers on a terra rossa soil *(Arnon et al. [1962])*

Rates of nutrients applied (kg/ha)			Yield increment**	Cost of fertilizer in terms of maize***	Net increment of yield
N	P	K*	(kg/ha)	(kg)	(kg/ha)
80	—	—	930	200	730
160	—	—	1360	400	960
240	—	—	1130	600	530
—	35	—	930	120	810
—	70	—	500	240	260
—	105	—	660	360	300
80	35	—	1710	320	1390
80	70	—	1200	440	760
80	105	—	1680	560	1120
160	35	—	1690	520	1170
160	70	—	1550	640	910
160	105	—	1530	760	770
240	35	—	2110	720	1390
240	105	—	1760	960	800
240	70	120	1900	1190	710

* Soil tests indicated high K, hence lack of response to K fertilizer.

** Yield without fertilizers was 6330 kg/ha.

*** The amount of maize required to pay for the cost of the fertilizer, at contemporary market prices.

The data in Table 116 illustrate the kind of information required to make a decision on the optimum combination of fertilizers required in a given situation. In this particular case, in view of the high K level of the soil, a factorial experiment was carried out with N and P only. It will be observed that the highest point of the response curve was apparently not reached in this trial, and yet the economic returns do not justify the highest levels of fertilizer application on this soil with a high level of fertility, as indicated by the yields obtained without fertilizer. It will be further observed that the highest yield increment was obtained at the 240–70-0 rate, whilst the highest net increment (yield increment less amount of grain required to cover the cost of the fertilizer) was obtained with 80–35–0 and 240–35–0. Though both these rates gave equal net increments, it is obvious that in this case, it is the lower rate which should be chosen by the farmer.

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