International Potash Institute

Potassium in the Agricultural Systems of the Humid Tropics

Proceedings of the 19th Colloquium of the International
Potash Institute held in Bangkok/Thailand 1985

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Contents of the Proceedings of the 19th Colloquium of the International Potash Institute, Bangkok/Thailand *[1985]**

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Chairman of the Opening Session

Dr. *G. W. Cooke,* Honorary Scientist, Rothamsted Experimental Station, Harpenden, Herts/United Kingdom; member of the Scientific Board of the International Potash Institute; Chairman of the 19th IPI-Colloquium

Opening Session

Agriculture in S.E. Asia

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Summary

The geography, climate and agriculture of Thailand are discussed with comparative statistics from other S.E. Asian countries. Policies contained in the fifth National Economic and Social Development Plan (1982-1986) are outlined.

1. Introduction

Though there are variations, the countries of South East Asia (Table 1) all have a tropical climate, locally modified by altitude and proximity to the sea. The Indonesian and Philippine archipelagos consist of many islands, some very small and not inhabited, some like Java and Sumatra are large land masses. Indonesia and the Philippines have distinct dry and wet seasons; generally speaking, Malaysia (the Peninsula, Sabah and Sarawak) shows little seasonal change with temperatures fairly even through the year and no distinct dry season (north east and south west monsoons).
Table 2 lists for comparative purposes data relating to the principal arable crops grown in these countries, showing some contrasts in relative importance of the various crops and in average yield levels. Agriculture is the main source of employment in S.E. Asia; the percentages of the economically active population engaged in farming being: Bangladesh 84, Thailand 75, Indonesia 60, Malaysia and the Philippines 50. Throughout the area, the great majority of holdings are small. Access to the services and infrastructure which support agriculture is poor.
Year to year variations in yield and production are great, the main cause of such instability being climatic variation whose effects are greatest in areas without irrigation which account for some 80% of the cultivated area. Lack of control over water in areas without irrigation is the main factor limiting yield. Rainfall is variable in both time and space; even within one season crops may suffer from both excess and lack of rainfall. Four fifths of the rain falls in a 4-6 month period, the rest of the year being virtually dry. If the onset of the monsoon is delayed or the rains cease early, the whole year's farming programme is disturbed. The effects of climatic variation are much more severe than in temperate areas.

Table 1 Countries of South East Asia — extent and population

	Population (mio)	Area (km^2)
Indonesia	170	1904343
Malaysia	15	327910
Philippines	50	300000
Thailand	51	513120

Table 2. Main economic crops 1978-1982: 5 year average harvested area (1000 ha); 5 year average yield (A); highest (B) and lowest (C) annual yield (t/ha).

Crop	Indonesia				Malaysia				Philippines				Thailand			
	Area	A	B	C	Area	A	B	C	Area	A	B	C	Area	A	B	C
Rice	9027	3.26	3.75	2.86	697	2.79	2.88	2.55	3513	2.21	2.37	2.06	8967	1.89	1.94	1.80
Maize	2803	1.41	1.51	1.32	9	1.21	1.33	1.10	3319	0.95	1.04	0.88	1371	2.19	2.34	2.00
Cassava	1384	9.58	9.76	9.26	37	10.31	10.71	10.14	196	11.04	11.62	9.71	1059	14.86	16.23	13.86
Sugarcane	140	100.1	102.9	89.9	19	45.29	50.00	90.19	432	46.3	48.4	42.6	515	40.9	48.8	29.9
Sorghum													209	0.94	1.51	0.61
Soybeans	756	0.88	0.97	0.84					9	0.89	1.09	0.75	115	1.03	1.11	0.94
Groundnuts	502	1.55	1.64	1.44	6	3.68	3.83	3.50	49	0.86	0.92	0.76	105	1.24	1.28	1.18
Cotton	12	0.57	0.89	0.27					6	0.97	1.71	0.53	117	1.17	1.33	1.04

Sources: — *Office of Agricultural Economics MOAC*
— *FAO Production Yearbooks 1980-1982*

Such lack of stability means that new crop production technologies based on high yield and fertilizer responsive crop varieties have mainly benefitted those farmers with access to irrigation. This results in regional disparities and has tended to widen the gap between rich and poor farmers. At the same time, the increase in production from irrigated areas alone is not sufficient to meet the needs of the growing population. Production must be improved also in the rainfed areas.

While the overriding importance of water control is stressed, its effects are modified by soil type and particularly the soil's moisture retention and transmission properties. Choice of crop and cropping system thus depends on a combination of rainfall distribution and soil type.

2. The geography and agriculture of Thailand

2.1 Geography

Bounded on the north, northeast and east by Burma, Laos and Kampuchea and on the south by Malaysia, Thailand lies between 6 and 20° N and 97 and 105° E extending down the Malay Peninsula between the Andaman Sea and the Gulf of Thailand. There are four main regions: Northern, Northeastern, Central and Southern. These are divided into provinces (changwats). The core of the country is the Central Plain, a triangular delta composed of lowland and swamps where water is impounded for rice for 4-5 months of the year, with flat, fertile alluvial land watered by a network of canals. To east and west there are mountain ranges, rolling hills and lowland suitable only for upland crops. This Central Region accounts for 20% of the farming households.

The Northern region, including the upper Central Plain is the largest of the four regions but two thirds of the land is unsuitable for agriculture. Rice is grown in the valleys and flood plains in the wet season with upland rice, groundnuts, mung, soya, sesame and vegetables on the terraces; further south, maize and cotton are grown. Irrigation permits the growing of rice, soya, mung beans, groundnuts, sesame, tobacco and cool-season vegetables in the dry season. The region accounts for a quarter of the farming families of the nation.

Low soil fertility and water retention limit possibilities in the Northeastern Region. The rainy season lasts from April to October with annual rainfall about 1280 mm. Rainfed rice is the main crop but kenaf, cassava, maize, sorghum, sugarcane, beans, bananas, pineapple are also grown. There are areas of improved grassland.

The narrow Southern Region extending to the Malaysian border and only 20 km wide in parts is mountainous. Rubber is the main crop but rice, coconut and tropical fruits are also grown. 40% of the land is unfit for farming; 30% of usable land is used for paddy, the remainder mainly for tree crops.

2.2 Climate

The country generally is hot and humid with mean January temperature 22-26 °C and 28-32 °C in April. In the hot season (March to May) the temperature approaches 38 °C with high humidity; during the rains from June to October the temperature is quite low

Table 3. Characteristics of general soil grouping in Thailand

Mapping Unit Groups	Great Soil groups	Parent material	Drainage	Texture	Base status	Fertility status	Common crops	Region
II	Alluvial	Recent Alluvium	Poor	Fine	Variable	Moderate to high	Rice Irrigated Upland	Central, northeastern and eastern side of region
IV	Low-Humic Gley	Semirecent and Old Alluvium	Poor to Good	Medium	Low	Low to moderate	Rice Irrigated Upland	Central and northeastern region
V	Grumusols Rendzinas Brown Forest Non-calcic Brown Red Brown Earth	Residuum Collovium Alluvium	Good	Medium to Fine	High	High	Maize, Cotton, Sugarcane, Soybean	Central region
VI	Gray Podzolic	Old Alluvium	Excessive	Medium to coarse	Low	Low	Cassava, Kenaf Cotton, Sugarcane, Rubber	Widely spread through four regions
VII	Red-Yellow Podzolic	Residuum Colluvium Alluvium	Good	Medium to fine	Low	Low	Cassava, Kenaf, Sugarcane, Rubber	Scattered through four regions
VIII	Reddish-Brown Lateritic Reddish-Brown Latosol Red-Yellow Latosol	Residuum Colluvium Alluvium	Good	Medium to fine	Low	Low	Maize, Cotton, Soybean, Sugarcane, Pineapple, Cassava, Kenaf, Rubber	South to north of the western part and northeastern region

Source: Thailand Strategy for Fertilizer Development, October 1979.

due to cloud cover. The «cool» season from November to February, except in the northern mountains where it is very cool, is not exactly cool.
Rainfall over most of the country is 1000-1500 mm per year but parts of the southeast and south receive more than 3000 mm. In the far south weather conditions are governed by the northeast and southwest monsoons.

2.3 Soils

The soils of Thailand are dealt with in some detail in a later paper in this Colloquium. Here we include only the summary of the characteristics of general soil groupings in Table 3.

2.4 Agricultural production, domestic consumption and exports

The population of Thailand has increased from some 45 million in 1978 to the present 51 million and is expected to reach about 76 million by the year 2000.
The total land areas of Thailand is 51311501 ha with 15660000 forest, 19773887 farming land and 15877614 ha, unclassified (Table 4). Farming land increased by 1675965 ha, between 1976 and 1982. 84% of farming land is owner occupied. The average farm size is approximately 4.25 ha.
Trends in crop production are shown in Table 5 with data for 1974/5 and 1983/4. The greater part of the increase in crop production came from increased planted area; yield per unit area increased slightly.
Between 1974 and 1983, the total workforce increased from 21.9 to 29.5 million (by 34%) while the proportion engaged in agriculture fell from 68 to 61%. The ratio of farming to non-farming families has been fairly constant for the past ten years which may indicate a drift of single farm workers out of agriculture.

Table 4. Area under agriculture and forestry 1982.

	'000 ha.	Change 1976-1982
Total land	51311	–
Forest	15660	–4182
Agriculture	19774	+1676
Rice	11715	+ 305
Other arable crops	4686	+1268
Fruit and tree crops	1900	+ 254
Vegetables and flowers	55	– 2
Grassland	123	+ 57
Fallow	621	– 35
Unclassified	15878	+2506

Land Tenure: 82% of agricultural land in 1982 was owner-occupied.

Table 5. Areas planted to principal crops and total production 1974/5 and 1983/4.

Crop	Area '000 ha		Production '000 t.	
	1974/5	1983/4	1974/5	1983/4
Rice	7982	9925	13386	18730
Maize	1240	1688	2500	3552
Cassava	492	1404	6763	19985
Sugarcane	310	577	14592	21568
Soybeans	132	158	110	172
Cotton	52	102	56	202
Kenaf	884	202	384	222
Rubber	1406	1623*	382	594*
Mung Bean	207	491	188	300

* Estimated

Source: Ministry of Agriculture and Cooperatives Agricultural Statistics of Thailand

Gross domestic product has increased since 1974 from 271 368 to 928 548 million baht while the contribution of agriculture has fallen from 31 to 22% (Table 6). However productivity per worker in agriculture has risen from 5688 to 11 236 baht over the same interval but productivity in the non-agricultural sector is increasing at a faster rate (factor of 2.5 in the same period).

Table 7 shows the fate of agricultural produce. The increase in domestic consumption is due to population increase. The value of agricultural exports has increased appreciably witb the increase in planted area and modest yield increases.

Table 6. Domestic product and percent contribution of agriculture 1974-1983 (Unit: million baht)

Year	Gross domestic product in agriculture	Gross domestic product in non-agriculture	Gross domestic product	% of G.D.P. in agriculture
1974	84735	186633	271368	31.23
1975	94063	204753	298816	31.48
1976	104637	232978	337635	31.00
1977	110929	282101	393030	28.22
1978	129094	340858	469952	27.47
1979	147076	409164	556240	26.44
1980	173806	511124	684930	25.38
1981	187886	598280	786166	23.90
1982	188742	657394	846136	22.31
1983*	202797	725751	928548	21.84

Remarks: based on current prices
* primary data

Source: National Income of Thailand, 1978-1983

Table 7. Export and local consumption of crop products 1983.

Crop	Exports '000 t.	mio. baht	Av. growth rate %	Domestic consumption '000 t.	Av. growth rate %
Rice	3534	20100	15.20	12544	0.80
Maize	2646	8386	6.44	997	12.31
Sugar	1526	6325	6.11	643	5.09
Cassava	5196	15370	18.83	4009	17.93
Mung bean	85	870	17.91	91	0.09
Soybean	1	9	−20.82	150	5.63
Kenaf & jute	7	28	−33.94	191	4.96
Rubber	552	11739	12.33	34	10.22
Cotton				130	4.89
Coconut				1093	4.07

Sources: Selected Economic Indicators Relating to Agriculture Division of Agricultural Economic Research, Office of Agricultural Research.

2.5 Forestry

Our forests are an important natural resource and important also in maintaining environmental balance. They provide the habitat of our remaining wild animals and flowers; they provide raw material for industry and make available areas for recreation.

The area of forest is shrinking rapidly, from about 175000 km^2 in 1978 to less than 157000 in 1982 due to the demands for domestic consumption, the pressing demand for land for agriculture and other factors. Realising the importance of forest conservation, the Government has given this matter some priority in the current five year plan.

Domestic demand for timber for building, furniture and fuel is increasing with the increase in population. Estimates of consumption are given in Table 8 which also lists timber production, and import. Export has reduced over the past 5 years because of the increase in local demand.

Table 8. Production import and apparent consumption of timber.

1000 m^3

Year	Production	Timber Import	Export	Wood Domestic Apparent Consumption
1979	3100.7	1033.1	7.7	4141.5
1980	2544.2	434.3	1.5	2980.0
1981	1798.6	566.7	7.8	2357.5
1982	1769.4	488.5	1.5	2256.4
1983	1819.7	614.3	1.2	2432.8

Source: (1) Planning Division, Royal Forestry Department
(2) (3) Department of Customs.

3. Natural resources policy and development

3.1 General policy aims

The aims embodied in the fifth *National Economic and Social Development Plan (1982-1986)* are to:

1. Restructure the agricultural production process by shifting from «extensive agriculture» to «intensive agriculture» *i.e.* placing a heavier emphasis on yield improvement. This could be achieved by increasing the efficiency in the utilisation of land in both irrigated areas and non-irrigated areas, water resources and the conservation of natural resources to reduce their deterioration. Furthermore the government will promote the cropping pattern appropriate to soil quality and will provide necessary inputs like fertilizer, high yield seeds, and credit simultaneously with appropriate production technology in order to allow farmers to increase agricultural yield and rural labour utilisation.
2. Improve agricultural marketing, bettering farmers' bargaining power with special assistance to farmers in depressed rural areas.
3. Reform land tenure.
4. Provide the finance needed to expand credit to farmers and agricultural institutions and to harmonise conditions between the different agencies.
5. Encourage the merger of the various rural organisations (farmers cooperatives etc.), aiming for enhanced competitive ability and better channels of communication with the farmers, with farm business advice. Improvement of Government services in this area.

3.2 Development measures

3.2.1 Natural resources

a. Water

— Improvement of 2.56 mio ha existing irrigated areas especially for dry season cultivation.

— Development of neglected river basins especially Wang, Yom, Pasak, Sakaekrang, Banpakong, Rayong and Chanthaburi basins. Explore and develop a major scheme to take water from the Mekong for the Chao Phya river plain and the Northeast.

— Promotion of small scale irrigation schemes.
Introduction of water charges to improve utilisation efficiency and recover costs.

— Involvement of the private sector in land consolidation and irrigation works, water allocation and collection of water charges.

— Improvement of administration at all levels to coordinate development in different areas and decentralise control of small schemes.

b. Land and Forests

— Acceleration of land-use surveys upon which to base development policy, with precautions against the spread of urbanisation into farming areas.

- Priority for areas of good soil and where there has been investment in land improvement. Revision of the Law to enable Government to preserve such areas.
- Improvement of low fertility areas, especially acid sulphate soils in the Central region, saline soils in the Northeast, eroded soils in the North and mining-affected areas in the South. Mining operators to bear costs of restoration.
- Adoption of soil conservation techniques by farmers in erosion-prone highlands.
- Promotion of appropriate cropping systems.
- Speeding up of land tenure reform especially in Central and Lower Northern areas which have severe problems. Restriction of private holdings to 8 ha. Revision and enforcement of the *Farm Rent Control Act.*
- Prohibition of self-help land settlements in opening up new schemes but improvement of existing settlements with transfer of authority to the provinces.
- Survey to identify areas of deteriorated forest which might be released for farming or if unsuitable reforested. Reafforestation of 48 000 ha. annually by the private sector, the government providing technical assistance, including swamps with potential for coastal fishing.
- Promotion of the planting of fast growing trees for firewood and erosion control and for restoring 7000 ha. of watersheds in the North.
- Improvement and decentralisation of Government's staffing to obtain better control and prevention of forest destruction.
- Conserve the existing national park and expand wildlife conservation areas.

3.2.2 Research and extension

Improvement of water control, land utilisation and forests will not on their own be sufficient to achieve progress. It is essential at the same time to develop research and extension. The aims are to:

- Rationalise the national agricultural research plan and decide on priorities with reference to the problems of the various areas.
- There will be emphasis on yield improvement in rainfed areas, concentrating on major crops, *e.g.* paddy capable of withstanding drought and salinity, high yield cash crops and perennial crops.
- Diversification of cropping.
- Intensify extension with concentration on small farms to train farmers in modern technology, build up farmer groups with extensive use of small demonstration and trial plots.
- Promote the adoption of proper rotations with crops including castor, beans, cotton, sesame and wheat in irrigated areas in Central and Northern Regions.
- Promote the use of crops and systems to minimise water use such as beans, oilseeds, cotton with livestock and inland fisheries in the Northeast.
- Promote inland fishing in natural waters and reservoirs.
- Speed up production of improved planting material — target 5000 t. paddy seed and 4000 t. beans. Encourage farmers in seed production.
- Encourage participation by the private sector in seed production, the Government avoiding competition where commercial interests are already involved.
- Improve fertilizer supplies to reach a target of 30% of total demand. Emphasis on rice in rainfed areas. Encourage use of farm wastes in home produced manures.

- Encourage private industry to set up a fertilizer factory on the Eastern seabord, and to produce marl for tackling the acid sulphate soil problem.
- Diversify cropping. Diversification is needed to minimise risks from fluctuating prices and increase returns. This will involve the following:

  a) Double cropping of paddy with irrigation using fertilizers and the deep placement method with suitable short season varieties distributed by seed exchange.
  b) In addition to the present economic crops (rice, rubber, cassava, maize, sugarcane, vegetables, tobacco, groundnuts and soybeans) other crops should be introduced — temperate fruits, tea, coffee and wheat in the North; coffee, cacao, coconut and oil palm in the South; kenaf, perennial crops, lacq and silkworm in the Northeast.
  c) The *Agricultural Economic Zones Act* will be amended to demarcate zones on the basis of soil quality, market trends, farmer capability and income.
  d) Speeding the substitution of cassava by rubber in the Eastern Region to reduce cassava production to demand level.
  e) Promotion of the use of latex stimulations and high level tapping in rubber plantations in the South.

3.2.3 Credit

To profit from the new technology, farmers will need access to credit.

The *Bank of Thailand* will formulate policies for the allocation of agricultural credit, cooperating with the appropriate agencies. Capital of the *Bank of Agriculture and Agricultural Cooperatives (BAAC)* will be increased to 4000 million baht for provision of farmer credit particularly in depressed areas.

Farmers in an area with similar cropping systems will be encouraged to request credit, market their produce and purchase inputs jointly. Commercial banks and private institutions will be encouraged to provide farm credit under a government interest rate policy compatible with the risks involved.

Both short and long term credit will be required to suit the needs of each locality and its development plans.

3.2.4 Marketing

Improvement of marketing will involve the formulation of annual operational plans, needing the cooperation of the relevant agencies in the public and private sectors. It will also require review of Government intervention policies, particularly for rice. Taxes and commercial regulations which are burdensome to the export trade must be minimised. Marketing improvement will require:

- Provision of basic infrastructure — rural roads, warehouses, stores, communications in rural areas.
- Improving market information especially in remote areas to secure fair dealing for farmers by middlemen.
- Establishing Government procedures in central markets with control of the auction system and quality control of produce. Incentives to the private sector to establish central markets and to provide weights and measures services under government supervision.

- Formation of farmer cooperatives. Stress on quality standards to improve farmgate prices.
- Selective government price support according to government's financial resources.
- Study of the contract trading system to give fair contract arrangements between farmers and factories.

3.2.5 Special areas

Particular attention will be paid to development in three priority regions: The backward rural areas, the rainfed areas, the irrigated areas.

4. Conclusion

Both *Government* and the *Private Sector* have important roles to play in agricultural development. Government must accept responsibility for the overall infrastructure including roads, communications, irrigation. It must provide research and extension. Research priorities are the improvement of planting material, integrated pest control, soil and water management and fertilizer use. Government will aim to provide a climate in the market which through assuring fair and economic returns to the farmers will enable them to take up the improved practices and purchase the necessary inputs. Operations such as improved cultural practices are adopted only when market prices are high. Adoption of new production technology by farmers in Thailand (like farmers elsewhere) depends largely on economic incentives rather than on yield incentives alone. The level of basic knowledge and the economic status of the farmers are major constraints to the acceptance of technology and its application.

Potassium in the Agricultural Systems of the Humid Tropics

An Introduction to the Colloquium

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The humid tropics have a very great potential for agricultural production because the solar radiation received, and the high temperatures, promote good growth of all plants and particularly of those with the C_4 photosynthetic system. Rainfall is generally sufficient for rain-fed crops and also to maintain the reserves needed for irrigation systems. Therefore these regions have the potential to feed large local populations and to export food and products for industrial processing to other less-favoured regions. These potentials are achieved when all constraints to crop growth are identified and overcome by the use of inputs and/or management practices. In this Colloquium we are concerned with nutritional constraints, and particularly those imposed by potassium supplies, and with the use of fertilizers to overcome these constraints to achieve maximum economic yields. The nature of the problems we must consider in planning to make efficient use of fertilizers can be assessed by comparing the overall needs of crops for the nutrients which fertilizers supply, and the amounts of nutrients supplied by fertilizers to make good deficiencies in supplies.

1. Nutrients removed by crops

Table 1 shows that the weights of N and K taken up by most crops are comparable and the weights of P absorbed are much less. Root crops are notable in that they need to take up large amounts of K which are mostly contained in the tubers that are sold from the farm. Grain crops also take up much K; rice absorbs a larger weight of K than of N, at harvest most of this K is in the straw and if this is returned to the land either by being ploughed in, or made into compost or manure, the reserves of K in local soils will be replenished. This emphasises the need to consider the fate of crops and the use made of their residues when assessing the needs of farming systems for supplies of K (and P) fertilizers to replace the amounts removed in produce sold from the farm. Table 1 also shows the amounts of nutrients that are removed in typical yields of crops that are taken from the land either for industrial processing, or for direct export to cities or overseas. Oil palm, sugar cane, bananas, pineapples, and tobacco, are examples of the crops which remove large amounts of K (and much more K than N).

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Table 1. Amounts of nitrogen, phosphorus and potassium in tropical crops

	Yield t/ha	N	P kilogrammes/hectare	K
Cereals Rice				
Grain	9.8	143	26	26
Straw	8.2	75	5	232
Total		218	31	258
Maize				
Grain	9.5	150	27	37
Stover	11.0	110	19	135
Total		260	46	172
Wheat				
Grain	6.2	87	17	25
Straw	6.5	31	4	80
Total		118	21	105
Root crops, contents of tubers only				
Cassava	30.0	120	40	187
Yams	11.0	38	3	39
Potatoes	35.6	115	18	161
Forage crops, in yields of dry crop				
Lucerne (alfalfa)	10.0	200	20	170
Coastal Bermuda grass	20.0	340	35	250
Napier grass (elephant grass)	24.0	360	64	298
Fruit crops				
Bananas (in fruit)	45.0	78	22	224
Coconuts (dry copra)	1.4	62	17	56
Pineapple, in fruit	55.0	43	7	109
total in crop		205	25	326
Plantation crops, contents in harvested fraction				
Oil palm (yield of oil)	2.5	162	30	217
Sugar cane (cane yield)	88.0	45	25	121
Rubber (yield of dry rubber)	1.1	7	1	4
Coffee (made coffee)	1.0	38	8	50
Tea (dried leaves)	1.3	60	5	30
Tobacco (cured leaves)	1.0	116	14	202
Cotton seed and lint	1.7	45	11	14
stalks, leaves, and burs	2.2	39	5	33
Grain legumes				
Beans	1.0	31	3.5	6.6
Soybeans	1.0	49	7.2	21
Groundnuts (unhulled)	1.0	49	5.2	27

Note: The yields stated for cereals, forage crops and grain legumes are on the basis of dry weights; yields stated for root crops and fruits are on the fresh weight basis (with 15-20% dry matter); yields of plantation crops are of produce as marketed.

2. Fertilizers applied in regions

The use of fertilizers was established in the last century but the quantities then applied were small. Very large increases have occurred in the last 30 years and these are shown by Table 2 which gives *FAO [1984a]* data for the amounts used in two temperate regions and in three regions which encompass humid tropical countries. In the period from 1953 to 1983 the amount of N used in the world increased by about 12 times, but the K used increased by only 5 times. This raises the question of balance in the amounts of nutrients applied; this is examined in Table 2 by giving the ratios of N : P_2O_5 : K_2O. We see that only in South America are the weights of N and K_2O used roughly equal; the very low N : K_2O ratios for the fertilizers used in Asia and Africa are a cause for concern that we must discuss.

Table 2. Amounts of nutrients applied as fertilizers in several regions of the world in 1952/3 and 1982/3. *(FAO [1954 and 1984] data)*

	N	P_2O_5	K_2O	N : P_2O_5 : K_2O		
	thousands of tonnes used			ratio of amounts used		
1952/3						
Europe	2108	2658	2862	100	126	127
North and Central America	1738	2331	1688	100	134	97
South America	79	104	33	100	132	42
Asia	800	343	256	100	43	32
Africa	146	181	38	100	124	26
The world	4891	6107	4896	100	125	100
1982/3						
Europe	14767	8244	8508	100	56	58
N. and Central America	11140	5075	5110	100	46	46
South America	1108	1508	1036	100	136	94
Asia	22819	7689	2544	100	34	11
Africa	1865	1147	426	100	62	23
The world	61021	30833	22844	100	51	37
FAO's Classification of Regions for 1982/83						
All Developed countries				100	61	56
All Developing countries				100	37	14
Developing market economies in:						
Africa				100	71	41
Latin America				100	75	48
Near East				100	54	3
Far East				100	34	18

3. Changes in reserves of nutrients in soils.

All soils contain some reserves of plant nutrients and these maintain the natural vegetation, the growth of which is regulated by the amounts available. When man replaced this vegetation by food crops the nutrients present sufficed to grow the small yields that were sufficient for the subsistence of the local people; soil fertility was maintained by returning to the land nutrients in crop residues and in wastes from the human and animal populations. With expanding populations this situation changed; the majority of people now live in cities equipped with sewage disposal systems which pass the plant nutrients that were in human food to rivers which flow to the sea. Agricultural practices were intensified to produce higher yields which removed more nutrients from the soil. In addition many tropical countries established industries which processed agricultural products taken from the farms; this resulted in the removal of large amounts of plant nutrients as did the export of farm produce to other countries which is now a common practice in many tropical regions.

The effects of these changes in the amounts of produce grown, and the use that is made of the produce, on the nutrient reserves in the soils may be assessed by examining the results of experiments which measure the effects of fertilizers on crop yields and by chemical analyses of the soils. Unfortunately in many developing countries only short-term experiments have been made to examine the need for fertilizers and these have not revealed the effects of continued cropping on soil fertility. In most regions of the world the soils contain much less N than is needed for good crop yields; in early tests the application of more N in fertilizer gave impressive improvements in crop growth which quickly established this nutrient as a fertilizer and resulted in the great increases in the amounts used which are shown in Table 2. The soils examined in these early experiments often contained some reserve of K and the response to K-fertilizers were much smaller than the responses to N and this led to the general view that K-fertilizers were not important. These reserves of K are, however, quite small in most tropical soils and they are quickly exhausted by continuous cropping. This process of the depletion of reserves of soil K is intensified by applying N-fertilizers and planting high-yielding varieties of crops so that after a few years yields are limited by deficiency of K. This effect has been clearly shown in many tropical countries by experiments which have been under continuous cropping for a number of years; large responses to K-fertilizer have been recorded and the depletion of available K in the soils has been confirmed by analyses.

When considering the depletion of reserves of nutrients in soils two other processes must be mentioned. Leaching by water passing through the soil removes soluble nutrients and much potassium may be lost by this mechanism from light-textured soils with small cation exchange capacity. Secondly, erosion of cultivated soil removes large amounts of all plant nutrients. Both leaching and erosion losses should be minimised by the careful management of land use, cultivations and irrigation.

4. The need for balance in inputs to farming systems

When planning improvements to raise the productivity of agricultural systems we should not consider the factors affecting crop growth in isolation. This is because the factors *interact* so that when two or more inputs are applied together their combined effect on crop and yield is much greater than the sum of the effects of the inputs when each is tested alone. Nitrogen and potassium fertilizers illustrate this interaction well; much experimental work has shown that the full return from N-fertilizer cannot be achieved unless the supplies of K are adequate. On soils that have been cropped for a number of seasons and have become deficient in K some experiments have shown that N-fertilizer applied alone has had no effect on crop yield, but when K was applied together with the N there were large responses to the N and to the K. There is a serious risk that when N-fertilizer is applied where the K supply is not adequate there will be an economic loss to the farmer since any yield increase from N will not be sufficient to pay for the fertilizer.

Other inputs to farming systems interact with nutrients. An important example is that provided by irrigation; many experiments have shown large interactions between the supply of water and the application of N, P and K fertilizers, adequate nutrition increases the efficiency of the water used by the crop. This effect is particularly important with potassium since this nutrient is responsible for the regulation of the stomatal apertures in leaves which ensure efficient use of water and also provide for the entry of carbon dioxide into the leaf to initiate the photosynthesis which results in the yield that we require. Expenditure on new irrigation schemes, or the improvement of existing schemes, will not be repaid if nutrient supplies, and particularly the supplies of K, are deficient.

5. Improved agricultural systems.

Much of the agricultural improvement that has raised yields in recent years, and the continuation of which is so essential if the world's expanding population is to have enough food in future, is the result of work by plant breeders who have developed new plant material which has a greater potential for growth and yield, which gives larger responses to fertilizers, and which resists the attacks of pests and diseases. I do not need to emphasise in a meeting in this region the magnificient work done by the *International Rice Research Institute* in breeding improved varieties of rice. The greater potential that is possible from these new cultivars can only be achieved by ensuring that the supplies of nutrients are adequate to grow the larger crops. An example of the difference in nutrient contents between a high-yielding rice variety «TNl» and an old local variety which it replaced was reported by *Kemmler [1972]:*

	Grain yield t/ha	Nutrients taken up N	 P kg/ha	 K
Local variety	2.8	82	10	100
TNl	8.0	152	37	270

The normal practice in introducing a new variety would be to supply the extra N to achieve the larger yield but, in such circumstances, it must be recognised that the amount of K needed by the new cultivar approaches three times as much as was sufficient for the traditional variety. Therefore unless the soil reserves of K are carefully assessed and K-fertilizer is applied where these are insufficient the full return will not be obtained from the work of the plant breeders, or from the N-fertilizer that was applied. Similar considerations apply where chemicals are used to control pests and diseases. The full economic return from expenditure on pesticides is only obtained when nutrient supplies are sufficient to provide for the increased yield.

In making plans for greater production from existing cropped land by the improvement of agricultural systems it is essential to recognise that the plants will need to take up a larger quantity of K if the crops are to yield well enough to justify expenditure on new seed, on lime and other fertilizers (which may include sulfur and trace elements), on irrigation where needed, and on any chemicals which are considered necessary to control pests and disease.

6. Agricultural production for export

Exports of agricultural produce have large effects on national nutrient balances. It is relevant to discuss this here since our host country, Thailand has a very important industry in exporting food and other agricultural products. I shall return to this subject in our concluding session, but I will report here the result of calculations which I made of the nutrients leaving the country in exports of agricultural products in 1982:

	N	P_2O_5 tonnes	K_2O
Nutrients in produce exported	159788	72658	156498
Nutrients in fertilizers used in 1983/84	255000	135500	36800

The fertilizers applied in the year following the exports provided about 60% more N than was exported and nearly twice as much P_2O_5, but the K supplied by fertilizer was less than one-quarter of the amount exported. Of the total amount of K exported two-thirds was contained in tapioca products. It is clear that the exports from Thailand must be resulting in the depletion of soil potassium reserves to an extent that the yields of crops that follow these export crops will be seriously reduced.

Other countries of this region are also involved in considerable exports of agricultural produce. Some examples are given in Table 3, they are taken from the latest *FAO [1984b]* Report.

A new activity reported by *Palacpac [1985]* is a plan to export dried Napier grass (elephant grass — *Pennisetum purpureum)* worth $20 million each year from Philippines to Japan. The initial plan is to export 12000 tonnes per year of the dried grass and this would contain about 180 tonnes each of N and of K_2O and 74 tonnes of P_2O_5. The total Japanese requirement for this type of animal feed was stated as 400000 tonnes annually. Careful study of the plant nutrient background of such «agribusiness» activities will be necessary because herbage crops take up large amounts of potassium and other nutrients; when the crops are used by cattle on the same farm the greater part of the nutrients they contain are returned in excreta, but when forage is exported to another region of the same country or to another country, losses of all nutrients and particularly the K will have to be replaced to maintain the productivity of the soil to produce forage. Replacement of such exported K will be very important where a rotation is used and arable crops are grown after a period of producing the forage crop for sale off the farm.

As I stated above the climate of the humid tropics gives a large potential for plant growth and it is inveitable that countries will plan to improve their trade position by exporting part of their agricultural production. It is very important that both employment prospects, and foreign earnings, should be protected by adequate nutrition of the crops on which the trade will depend.

Table 3. Exports of some agricultural products from selected countries in south-east Asia in 1983. Data from *FAO [1984b]* Trade Yearbook

	Value of agricultural products exported $\$ \times 10^4$	Weights of agricultural products exported in 1983; thousands of tonnes							
		Rice	Maize	Bananas	Pineapple (canned)	Tea	Coffee (green and roasted)	Tobacco (unmanufactured)	Rubber (natural)
Burma	23170	842	38	—	—	—	—	—	14
China	369261	1087	67	121	9.7	92	10	33	1
India	234958	165	—	—	—	209	70	83	—
Indonesia	195281	—	1.7	—	—	69	241	23	942
Japan	87016	329	—	—	—	2.1	0.2	2.8	—
Korea DPR	10255	200	—	—	—	—	—	8.5	—
Korea Rep.	56093	—	—	—	—	0.3	—	32	1.8
Malaysia	357947	—	2	25	43	0.3	4.2	—	1560
Pakistan	79701	904	1.3	4.6	—	0.4	—	—	—
Philippines	140353	40	—	612	146	—	22	23	9
Thailand	333219	3534	2646	12	136	0.5	12	35	554
Vietnam	10285	1.5	20	12	—	10	2	—	33

7. The way forward

It is certain that most countries of the humid tropics will have to consider how to expand production to feed their increasing populations and/or to strengthen their export positions. In many areas there are only very limited opportunities for bringing new lands into cultivation so much of the increase will have to come from increased production from land that is now under cultivation. This will require the use of modern technological packages involving improved varieties of crops, new cropping systems (with more frequent cropping and also intercropping), pest and disease control, and other inputs such as irrigation, as well as very considerable increases in the amounts of fertilizers used. Such packages will involve much extra cost and it will essential to consider the balance between inputs so that by interaction with other inputs, and with resources in the soil, yields may be raised to the economic maximum. It is important to remember that high yields minimise the effects of total costs on cost per unit of produce. Maximum economic yield therefore provides the ability to grow food or products for industry at minimum cost per tonne which aids the consumer by keeping prices down, and also places the exporter in a strong position. As has been stated above the larger yields will require increased amounts of plant nutrients and, in the present context, it is important to ensure that potassium deficiency, which experiments show is quickly caused by intensive cropping without adequate replacement of the K removed, does not become a constraint to crop growth. If this occurs the economic return from other costly inputs, such as N-fertilizer, irrigation, or pesticides, will be reduced or will become negative, and the cost of the food will be increased.

Correct balance in the use of fertilizers will lead to greater production and to the conservation of soil fertility, and it will ensure the stability and profitability of agricultural systems and so lead to national prosperity. Therefore it is appropriate for us to spend this week in considering the scientific background of this topic. We will first consider the potentials of the crops of these regions and the nutrients they require. The ability of soils to supply the potassium required will be discussed in the second session while the third session will discuss the maintenance of soil fertility in upland farming systems with special reference to potassium. The fourth session will review the research and development work done in south-east Asia to define the needs for potassium. We will plan to define the research that must be done, and the extension of the results in providing information for farmers, with the object of ensuring that sufficient potassium is applied where it is needed and that the amounts applied are used efficiently by the crops. In our discussions we should identify both strong and weak points in the present use of K-fertilizers so that we can indicate what further work is required to lead to recommendations that will ensure the balanced use of the plant nutrients which are applied in the fertilizers which give us the power to prevent nutrient deficiencies in plants resulting in deficiencies of food for the human population of the world.

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1st Session

Yield Potentials and Nutrient Requirements of Crops

Physical Resources of the Humid Tropics and their Relation to Yield Potentials of Food Crops

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Summary

The analysis presented in this contribution has shown that the physical resources of the humid tropics permit high agricultural production levels. However, in extensive areas temporary water shortage presents a serious constraint, so that the potential set by crop characteristics, radiation and temperature is not reached. Development of reliable irrigation facilities could alleviate that problem, as has been shown in various places.

Nutrient shortage to the vegetation forms an even more serious problem, especially because many tropical soils are seriously depleted due to their old age. In addition many soils show phosphorus fixing properties limiting the effectiviness of phosphorus fertilizer application. Finally the high temperatures and humidity favour the decomposition of organic material and limit the buffering capacity of the soils for nutrients. However, judicious application of fertilizers could improve that situation.

In any case, sustained high production requires input of materials from outside the agricultural community, at a reasonable cost. In analysing the present situation in many parts of the world, it appears that not so much the physical resources are the limiting factor for agricultural production, but that the economic environment in which the farming community is operating, is a serious limitation to crop production. Such a conclusion may on one hand seem disappointing for agronomists, since it could imply that their possible contribution to alleviation of the problem of hunger and malnutrition is very limited, on the other hand it does require continuous emphasis on the fact that agricultural science can provide solutions, if the economic incentives are strong enough.

1. Introduction

The humid tropical region, as defined by *Blumenstock and Thornthwaite [1941]* comprises about 25% of the land surface of the earth. In terms of total population the humid tropics contain some of the most densely populated areas of the world (the Indonesian island of Java for instance has a population density of over 600 persons per km^2), due in part to the favourable environment that ensures a relatively stable food production over the years. The rapidly expanding population of these regions requires, however, a steady expansion of food production to satisfy the requirements also in the future.

In principle, increased food production can be achieved by two means. One is increasing the acreage under food crops, through reclamation of land currently under natural vege-

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tation or not used due to unfavourable environmental conditions, or through transfer of land from cash crops to food crops. The other one is increasing the yield per unit area, either through extension of the period of crop growth, such as multiple cropping, or by increasing the yield per «field day» of the crop.

Reclamation of new land, however, generally meets with difficulties, because the land that could easily be reclaimed is used for cultivation already, thus reclamation in the present situation requires substantial efforts that cannot be provided by individual farmers or local communities, but must be brought about by large-scale government-sponsored operations requiring high investments. In many instances the economics of such operations are doubtful, because price policies for agricultural products are not conducive for production increases. Moreover, transformation of soils presently under natural vegetation into agricultural land often leads to a rapid decline in the nutrient-supplying capacity of the land, through leaching, loss of top soil through erosion and exploitation. This results in disappointingly low yields at relatively short term, that makes the effort of farming hardly worthwhile.

More promising therefore seems the venue of increasing the yield per unit area. In this contribution the physical resources of the humid tropics will be discussed, their relation to the yield potential of some major food crops of the region, and the constraints that may be operative in determining the present yield levels. Some conclusions will be drawn as to the possibilities of alleviating these constraints and increase the yields.

2. The physical resources

2.1 The climatic resource

The geographical zone referred to as the humid tropics is located roughly between 20° north and 20° south of the equator. The climatic environment of the region is in part conditioned by its proximity to the equator, which for instance is responsible for the absence of large temperature fluctuations throughout the year. However, locally, the climate may be modified by the influence of specific topographical and geographical features, such as mountains and proximity to the sea. It is outside the scope of this paper to go into the processes underlying the climatic variation throughout the year, such as the general air circulation over different parts of the world *(Williams and Joseph [1970]).* For the present purpose, only the consequences for the relevant climatic variables will be discussed, and their effects on crop growth and yield.

2.1.1 Radiation

The energy of the sun is a major resource in the agricultural production process in which this energy is converted into edible organic material by means of plants and animals. Outside the atmosphere of the earth, a surface kept at a right angle to the rays of the sun receives energy at an average rate of 1360 W m^{-2}, a value known as the solar constant. However, the earth's surface is generally not perpendicular to the rays of the sun, and the lower the sun angle, the lower the energy intensity received on a horizontal plane. The variation in this geometrical factor is relatively small in tropical regions, compared to the temperate regions, as illustrated in Figure 1, derived from the *Smithsonian Meteorological Tables (Monteith [1972]).*

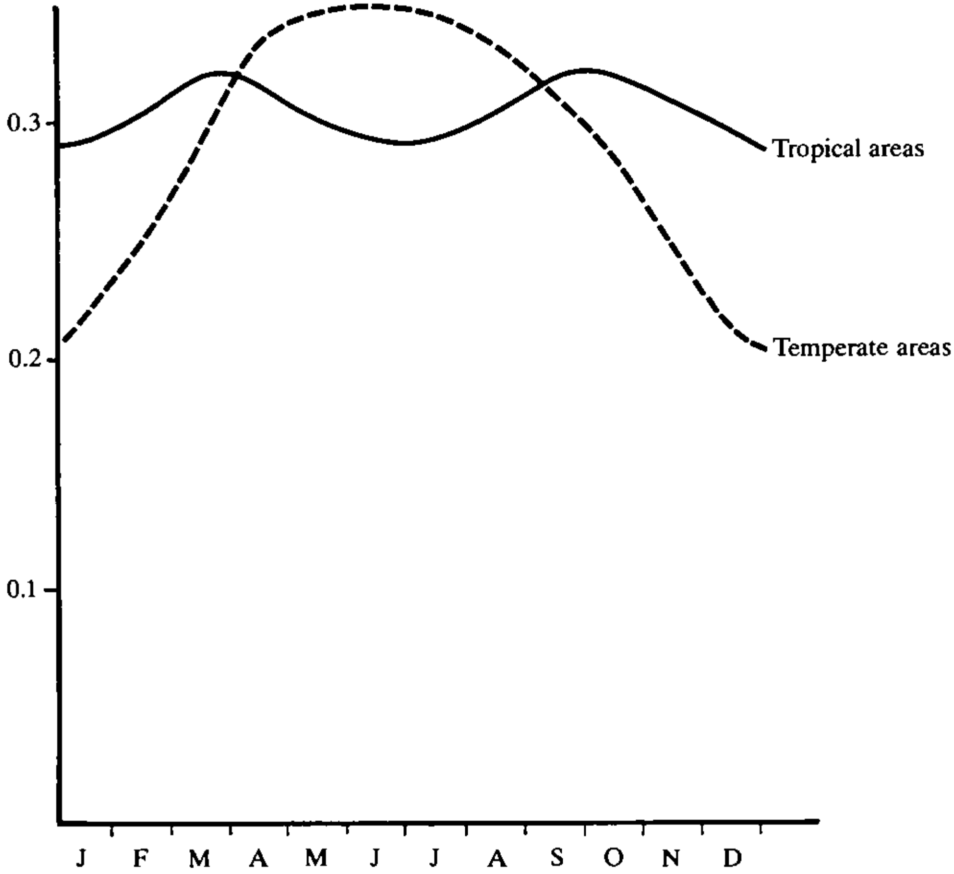

Fig. 1 Ratio of radiation received on a horizontal plane outside the atmosphere and the solar constant.

Moreover, in passing through the atmosphere part of the radiation is absorbed and scattered by clouds, by gases and by solid particles in the atmosphere, such as dust and salt. The actual radiation intensity received on a horizontal plane at the earth's surface is thus appreciably lower than the extra-terrestrial radiation intensity. In Figure 2 radiation data from some stations in the humid tropics are given. These data clearly show that considerable differences among the locations exist. In Dacca, the highest value occurs in May at slightly over 2.4×10^7 J m^{-2} d^{-1}, dropping to a low of 1.6×10^7 J m^{-2} d^{-1} in January. The pattern for Los Baños, the Philippines is very similar, with the highest value measured in April and the lowest in December, although with about 1.2×10^7 J m^{-2} d^{-1} still 25% lower than in Dacca.

The pattern for San Ramon on the South-American continent is distinctly different, with the maximum occuring in November, but with 1.9×10^7 J m^{-2} d^{-1} substantially lower than in the Southeast Asian region. The amplitude is also lower, as the minimum in June is almost 1.5×10^7 J m^{-2} d^{-1}.

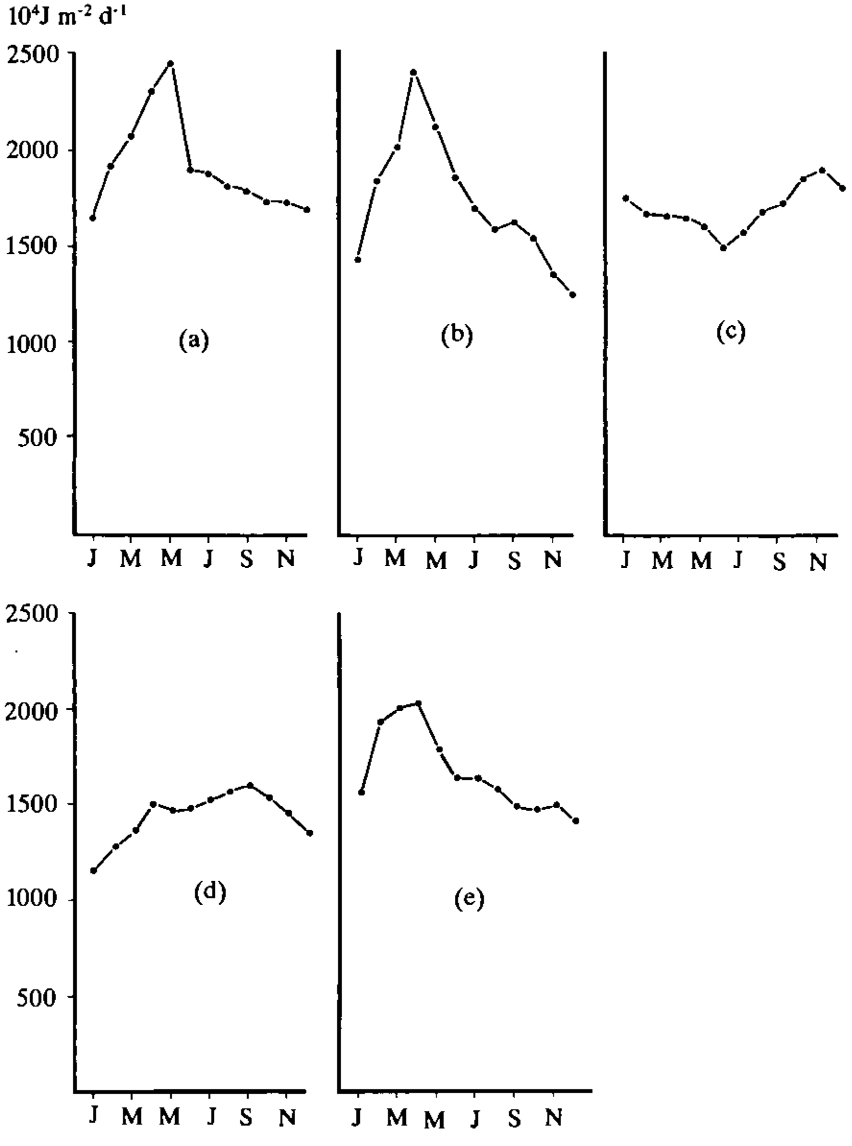

Fig. 2 Monthly average total global radiation for five locations in the humid tropics. a) Dacca, 23°43' NL, 90°26' EL; b) Los Baños, 14°25' NL, 121°20' EL; c) San Ramon, 11°08' SL, 75°18' WL; d) Bogor, 6°45' SL, 107°01' EL; e) Lampang, 18°17' NL, 99°31' EL.

The pattern for Bogor, on the island of Java shows about the same fluctuation as San Ramon, the maximum value not exceeding 1.6×10^7 J m^{-2} d^{-1}, and the minimum at 1.15×10^7 J m^{-2} d^{-1}. The timing is again different however, the maximum being observed in September, and the minimum in January.

The radiation pattern for Lampang in Thailand is again very similar to those for the first two locations, but the maximum is substantially lower (slightly over 2×10^7 J m^{-2} d^{-1}), with about a similar minimum.

Such differences are partly related to the geographical position of the locations: Bogor is located 250 m above sea level in a mountainous area, where cloudiness is generally high, whereas Los Baños and Dacca are both located at sea level, with a much longer duration of bright sunshine. San Ramon is located in the Andes at an altitude of 800 m, where cloudiness is also rather high, and the mirrored pattern reflects the position with respect to the thermal equator.

2.1.2 Temperature

A general feature of the humid tropics is, that temperature fluctuations throughout the year are as a rule relatively small. However, temperature is affected by the prevailing air streams, the duration of bright sunshine, and the geographical position in which latitude, altitude and distance to the sea play a role (Figure 3). The «ideal» picture is most closely approached by the temperature regime at Bogor, where average temperature fluctuates only slightly over one °C over the year. The temperature pattern in this case is affected by the altitude of 250 m at which the station is located. The other extreme in the examples is Dacca where the average temperature differs more than 10 °C between winter and summer. Dacca is an inland station, lacking the modifying influence of the sea and located almost at sea level. Los Baños and San Ramon are intermediate cases, with respect to temperature, showing variations of 4 and 2.5 °C, respectively.

There is some danger in considering average air temperature in connection with crop growth, as the same mean temperature may result from different values for minimum and maximum temperature. Especially at higher altitudes the daily amplitude may be considerable. Assimilation is mainly affected by day-time temperature, whereas growth and respiration are much more sensitive to night-time temperatures. Hence, average 24-hour temperatures may mask important differences in crop performance.

2.1.3 Air humidity

The major effect of air humidity on crop performance is through its influence on the evaporative demand of the atmosphere, which is one of the main determinants of crop transpiration. In this respect it is not so much the absolute humidity of the air that counts, but rather the difference between the saturated humidity at the prevailing air temperature and the actual humidity. For Dacca (Figure 4a) the vapour pressure varies between about 14 mbar in January and about 34 mbar in June/July. That, however, coincides with a temperature fluctuation between 18.5 °C and 29 °C, corresponding to saturated vapour pressure values of about 21.4 and 40.3 mbar, respectively. The difference in vapour pressure deficit is thus only very small, varying from about 7 mbar in January to about 6 mbar in June/July. The relative humidity, another measure of air humidity fluctuates between 65% in the dry season and 85% in the middle of the wet season. However, in terms of evaporative demand, the absolute difference between saturated vapour pressure and actual vapour pressure is the driving force, hence there is very little variation over the year.

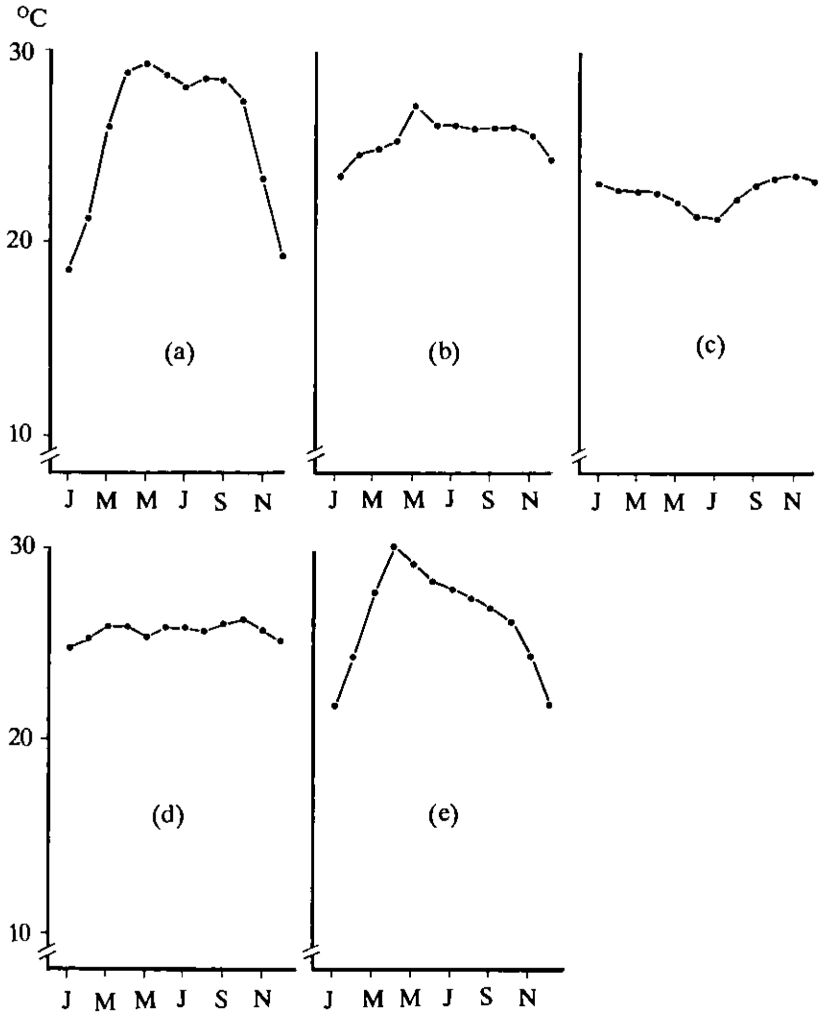

Fig. 3 Monthly mean daily temperature for five locations in the humid tropics (for details see caption Figure 2).

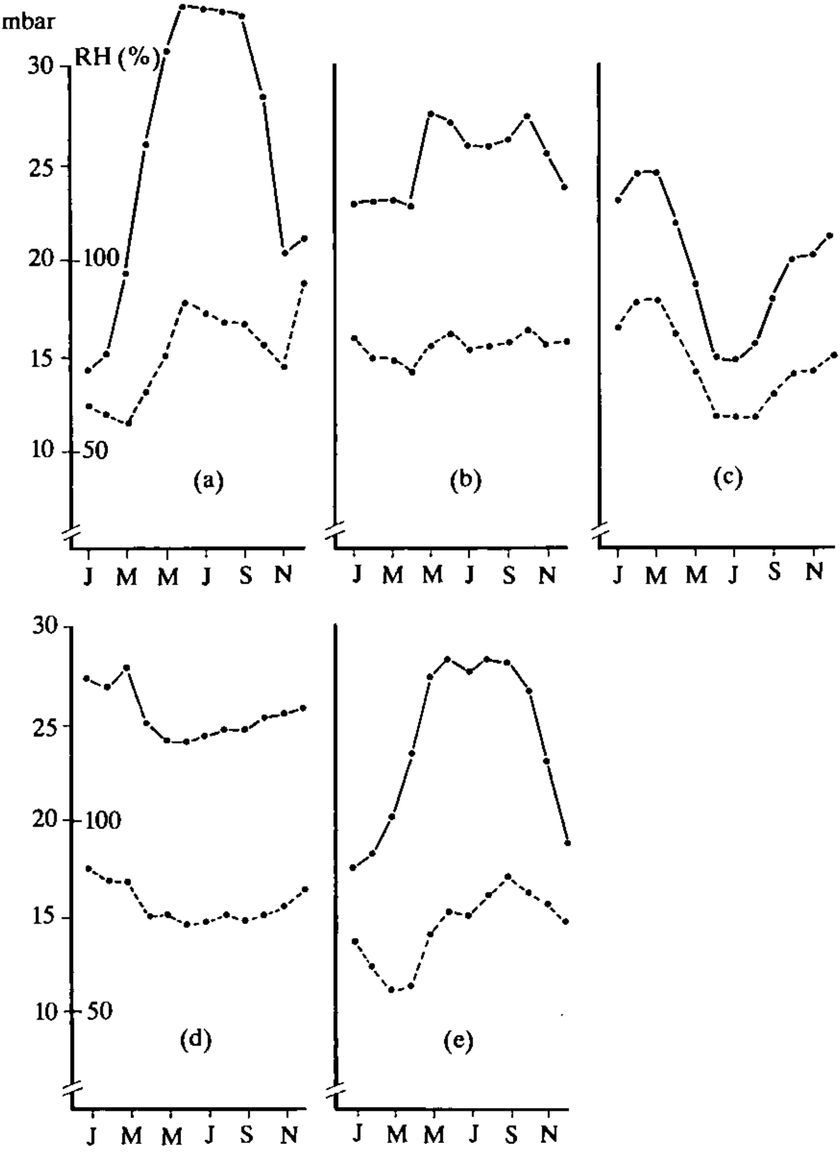

Fig. 4 Monthly mean vapour pressure (—) and monthly mean relative humidity (---) for five locations in the humid tropics (for details see caption Figure 2).

The situation is different in San Ramon, where in the dry season (June/July) the actual vapour pressure is around 15 mbar, at a temperature of 21 °C, corresponding to a saturated vapour pressure of about 25 mbar. Relative humidity is thus about 0.6, and the vapour pressure deficit 10 mbar. In the wet season (January/February) the actual vapour pressure is around 25 mbar, at a temperature of 22.5 °C, hence a saturated vapour pressure of 27.5 mbar. Relative humidity is then 0.9, and the vapour pressure deficit only 2.5 mbar. The contribution of the «drying power» term in the evaporative demand is thus substantially higher in the dry season than in the wet season for this location.

2.1.4 Potential evapotranspiration

In Figure 5 the evaporative demand of the atmosphere, expressed as potential evapotranspiration is shown for the various locations.

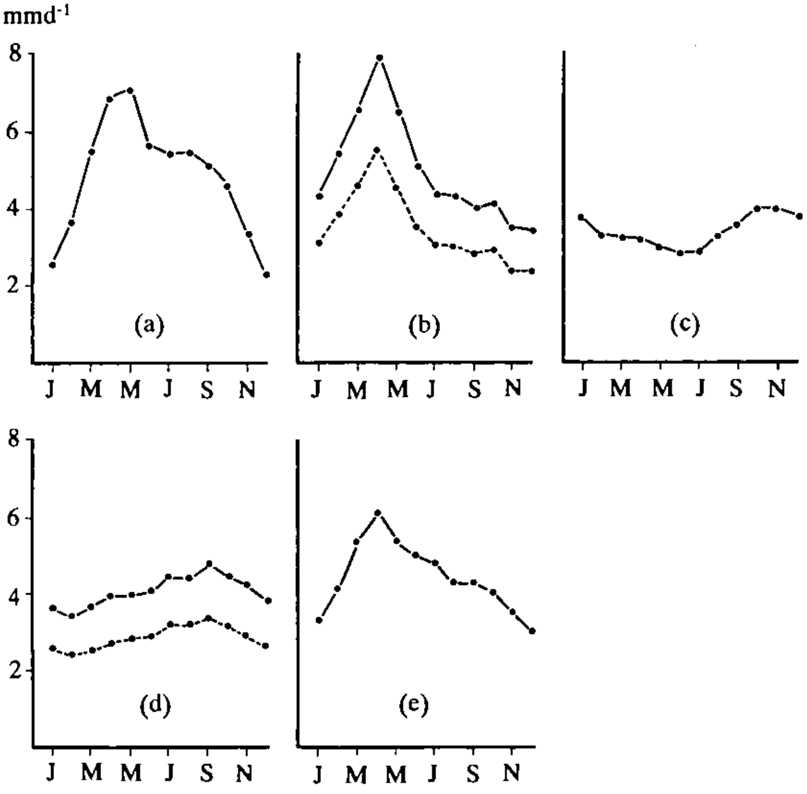

Fig. 5 Monthly mean potential evapotranspiration for five locations in the humid tropics. Dotted lines are calculated from class A pan measurements (for details see caption Figure 2).

For Dacca (a), San Ramon (c) and Lampang (e), the values are those calculated according to the method of *Penman,* while for Los Baños and Bogor Class-A pan values are given. It would be possible to devote an entire lecture to the relation between the two values, including a treatise on the question to what extent either of the values is representative for the actual water requirement of a crop surface. There seems to be little point in starting that discussion in the framework of this presentation, hence, as a rule of thumb, a conversion factor of 0.7 has been assumed to convert Class-A pan data into crop water requirements (Figure 5, dotted line).

Comparison of Figure 5 and Figure 2 shows the strong positive correlation between the level of radiation and the evaporative demand for each of the locations. That correlation is of course not surprising because most of the energy absorbed by the vegetation must be dissipated in the form of transpiration, since the photosynthetic process utilizes only a negligible part of that energy. When comparing different locations the correlation is less strong, because other factors such as air humidity and wind speed are co-determining factors for the evaporative demand. Nevertheless, the correlation still holds to a considerable degree as witnessed by the highest value of 8 mm d^{-1} (Los Baños, April) and the lowest value of 2.6 mm d^{-1} (Bogor, December), coinciding with practically the highest (2.45×10^7 J m^{-2} d^{-1}) and the lowest (1.3×10^7 J m^{-2} d^{-1}) average radiation intensity. These values also illustrate the substantial variation in crop water requirements both throughout the year and between various locations in the humid tropical region. These variations are of direct consequence for crop production, because the availability of sufficient moisture to satisfy the demand as dictated by environmental conditions, is a prerequisite for unrestricted growth of the crop.

2.1.5 Precipitation

The other weather variable that is of importance for the availability of moisture for the vegetation is the amount of precipitation. The designation «humid tropics» could suggest that precipitation is always plentiful, but the data in Figure 6 show that a large variability exists, both within the year and from location to location: monthly rainfall varies from almost 440 mm (Bogor, October) to 5 mm (Dacca and Lampang, January/February). The rainfall amount and rainfall pattern is primarily determined by the general air circulation, but may be modified by the geographical position, including proximity to the sea, and position with respect to nearby mountains, both relative to the main wind direction. Where air streams hit land masses after passing over water bodies for prolonged periods of time, precipitation is generally high, whereas further inland precipitation tends to be lower. Also locations on the windward side of mountains (such as Bogor, Figure 6d) are wet (orographic rains), while locations on the leeward side tend to be much drier. In Southeast Asia (Figures 6a, 6b, 6d and 6e) rainfall is mainly determined by the location of the intertropical convergence zone (ITCZ, *Oldeman and Frère [1982]).* In the northern hemisphere winter period, the ITCZ is located south of the equator, while high pressure areas are located over the Northasian continent and over the North Pacific, separated by a low pressure area off the coast of Japan. The consequence of this air pressure distribution is that northerly winds prevail in Bangladesh and Thailand, bringing cool and dry air after passing over the Indo-Chinese continent. This period is therefore dry to extremely dry in this region (Figures 6a and 6e). In the Philippines northeasterly winds from the Pacific prevail during this period, but the mountain chain present over most of

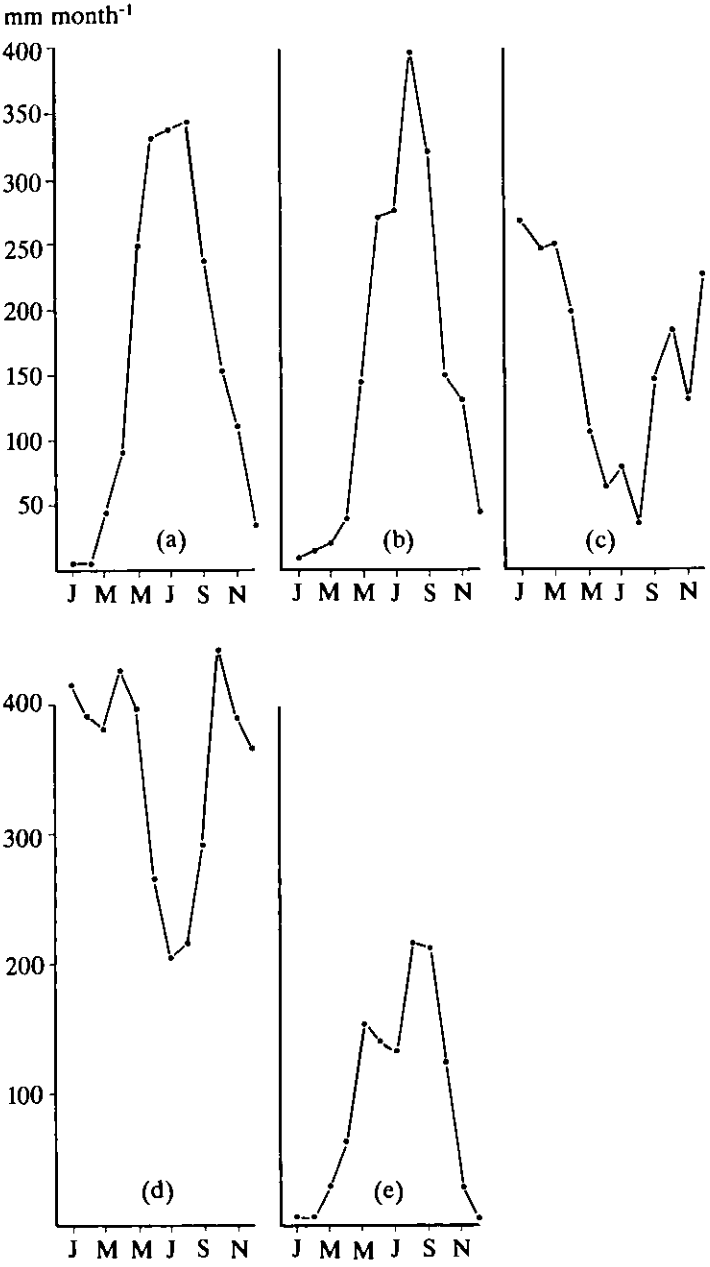

Fig. 6 Monthly rainfall for five locations in the humid tropics (for details see caption Figure 2).

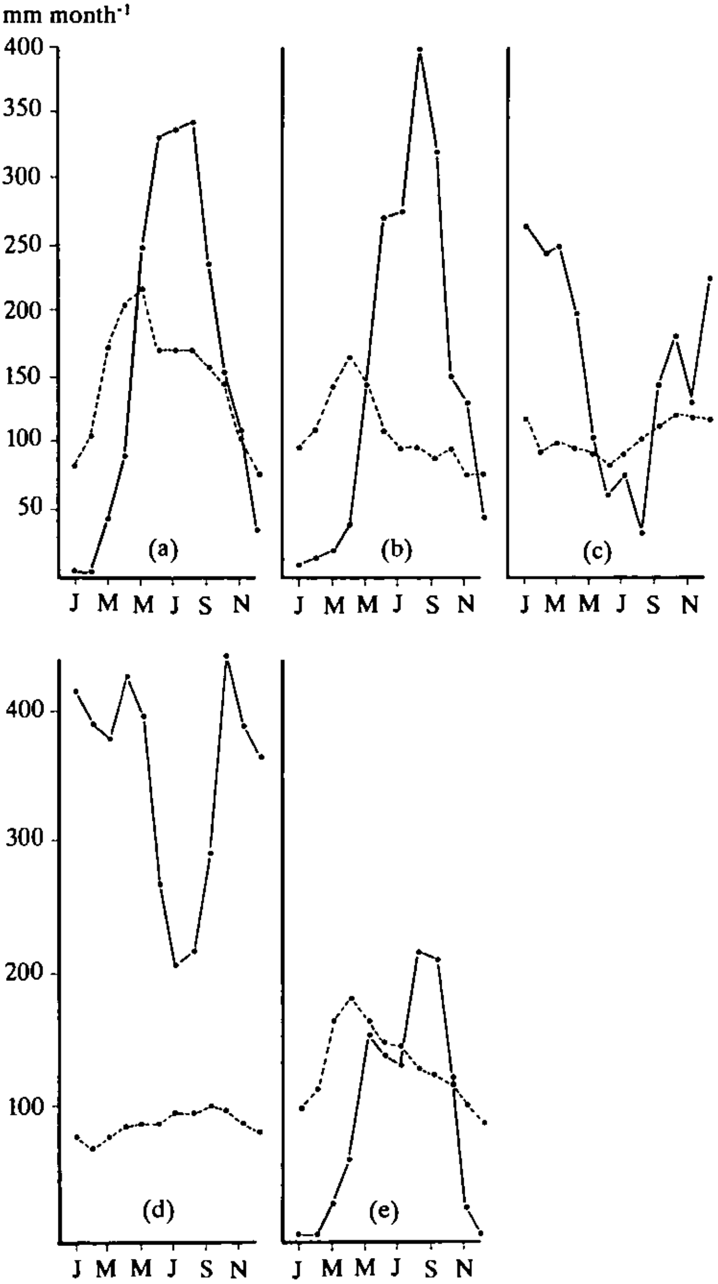

Fig. 7 Mean monthly water balance for five locations in the humid tropics (for details see caption Figure 2).

the country prevents far penetration so that Los Baños is very dry during that period (Figure 6b). Indonesia, particularly the southern part is subject to northwesterly winds that bring moist air to the western part of Java, where rainfall is intensified by the east-west chain of volcanoes on the island (Figure 6d).

In the northern hemisphere summer period the situation changes dramatically. The Eurasian continent is heated substantially in this period, creating a cell of low pressure over the Indian subcontinent, accompanied by high pressure regions over the Australian continent, just off the east coast of South Africa, and in the Pacific Ocean on both sides of the equator. The consequence is that in Thailand and Bangladesh southwesterly winds now prevail, bringing air that has picked up moisture passing over the Indian Ocean, so that rainfall is high to very high during that period.

Easterly to northeasterly winds, originating in the Pacific, reach the Philippines bringing also there abundant rainfall. Occasionally these easterly waves develop into cyclonic disturbances that reach the islands in various stages of development, up to tropical typhoons.

Indonesia is during that period subject to southeasterly winds originating from the Australian continent. In the southeastern part of the country that leads to relatively dry periods, but in the western part rainfall is still very substantial, even though relatively it is the driest period (Figure 6d).

In terms of crop production it is the balance between evaporative demand (Figure 5) and precipitation (Figure 6) that determines to what extent unrestricted crop growth can be expected. If the evaporative demand exceeds precipitation for a prolonged period of time, temporary water shortage for a crop may develop, leading to closure of the stomata in an attempt to restrict water loss to the atmosphere with the consequence that exchange of CO_2 is reduced proportionally *(de Wit [1958])*. As a result growth and production will also be reduced. To illustrate that effect more clearly, the data of Figure 5 (on a monthly basis now) and Figure 6 have been combined in Figure 7, according to the method proposed by *Thornthwaite [1948]*.

Figure 7 shows that Bogor (Figure 7d) is the only location where rainfall at all times exceeds potential evapotranspiration, so that continuous cropping is possible without the risk of water shortage. For all other locations there are periods of variable length (3 months for San Ramon, to 7 months for Lampang) where potential evapotranspiration exceeds precipitation to some extent. Especially when the period is prolonged and the deficit substantial, water shortage may easily develop since the capacity of the soil to store such quantities is seldom sufficient.

It appears thus that in the humid tropics extensive areas exist where during part of the year water supply is a serious limitation to crop production.

2.2 The soil resource

In addition to climatic factors, soil properties play an important role in determining the yield capacity of a certain crop in a given environment. On the one hand the physical properties of the soil are of importance, which determine its suitability as a rooting medium, *i.e.* the presence of hardpans, the mechanical resistance to penetration etc., its characteristics with respect to the water balance, such as infiltration capacity, water holding capacity, drainage characteristics. On the other hand the chemical properties of the soil play a role, in which its capacity to retain and supply essential nutrients to the vegetation is of major concern. In addition, unfavourable characteristics such as high salinity, high concentrations of certain elements, such as aluminium or iron or a low pH may play a role, but such conditions, although sometimes affecting considerable areas, are only of local importance and can be left out of consideration in a generalized treatment.

2.2.1 Soil physical properties

The most important physical characteristics of soils in relation to crop productivity are related to the relative proportion in which the three soil phases: solid material of organic or mineral nature, soil water and soil air occur at a given moment. The distribution of the three phases is to a large extent governed by the particle size distribution of the solid phase. In soil science the particles are generally divided into three classes: those smaller than 0.002 mm, the clay fraction, those between 0.002 mm and 0.05 mm, the silt or loam fraction, and those between 0.05 and 2.0 mm, the sand fraction. Particles exceeding 2.0 mm are called stones and are removed before the particle size distribution is determined. Soils can be classified on the basis of the relative proportion of these three particle size classes and a standardized system has been developed for the nomenclature into clay soils, loam soils, sandy soils and an extensive system of intermediates.

The importance of particle size distribution for the distribution of the three phases can be illustrated by the graphs in Figure 8, giving the relation between the fraction moisture in the soil (on a volumetric basis) and the suction applied to that soil, for three contrasting soil types. The moisture content at zero suction representing the total air space of the soil or the pore volume, is substantially higher for the heavy clay soil than for the sandy soil, with the loam soil having an intermediate position. That value is, however, not very interesting from an agronomic point of view since complete saturation hardly occurs in nature, except of course in bunded rice cultivation where it is a condition aimed for. A more interesting point is that at a suction of about 300 cm of water (at a pF value of about 2.5, pF being defined as the log (suction)), a value commonly referred to as «field capacity». It is rather loosely defined from a pure soil physical point of view as «the moisture content resulting when drainage has virtually ceased after application of excess water». It must be clear that on one hand the «virtually ceased» leaves ample space for subjective interpretation, while on the other hand that phenomenon is affected by the existing boundary conditions, such as the depth of a groundwater table or the presence of a compacted layer. Despite these reservations, however, it has long shown its merits in describing the soil water balance with respect to crop production. It is the moisture content that the soil will attain in an equilibrium situation after excessive rainfall and represents the upper limit of moisture available for uptake by plant roots. The difference among the three soil types is very pronounced here: the heavy clay can store more than 0.5 $cm^3\ cm^{-3}$ of water, whereas the sandy soil contains less than 0.05 $cm^3\ cm^{-3}$. Sandy soils such as some latosols under a heavy rainfall regime are subject therefore to excessive leaching, which is a disadvantage, because with the water also plant nutrients are washed out of the rootable profile. In addition the storage capacity for water is very low so that during a dry spell or a dry season very little moisture is available for plants from such a profile.

The lower boundary for plant available water is, in the same terminology, referred to as the «permanent wilting point», defined as that moisture content at which plants do not recover from temporary wilting and eventually die. Differences between species have been established with respect to this characteristic but a generally accepted convention

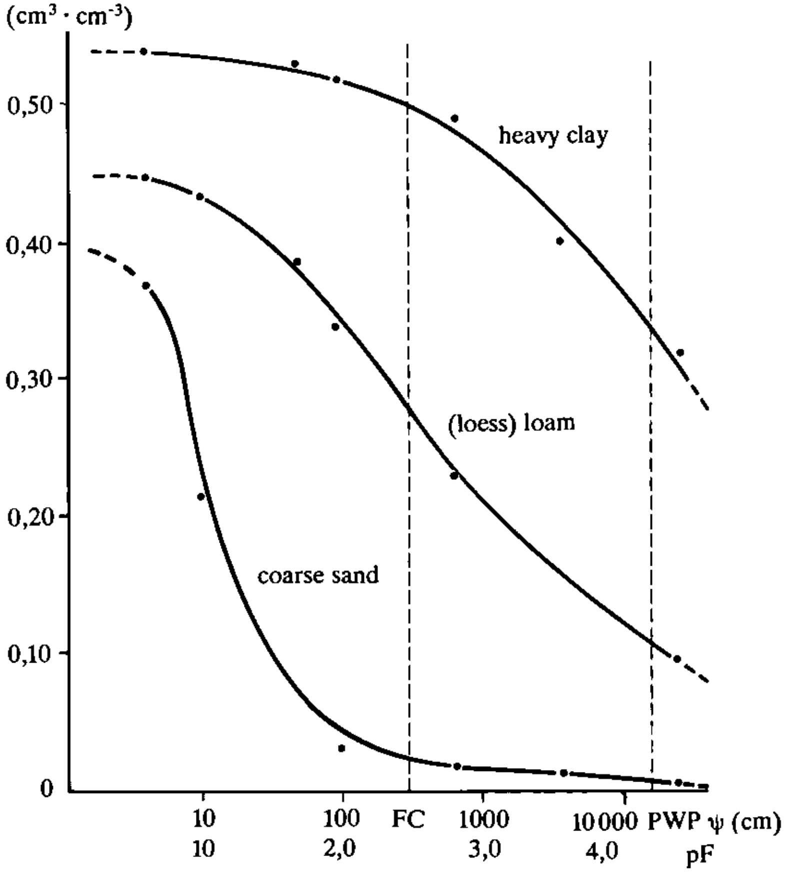

Fig. 8 Soil moisture retention curves for three different soil types. FC is field capacity; PWP is permanent wilting point.

places it at a suction of 16 000 cm or pF = 4.2 (Figure 8). At that suction value the sandy soil is practically depleted (0.02 cm^3 cm^{-3}), the loam soil still contains 0.11 cm^3 cm^{-3}, whereas the clay soil retains still 0.33 cm^3 cm^{-3}.

The differences among the various soil types can be explained on the basis of the physical laws governing soil moisture dynamics. The pores in the sandy soil, consisting for the larger part of large particles have a much greater diameter than the pores in the clay soil, where the particles are smaller and thence the smaller voids between them.

With respect to crop production, where moisture supply to the crop can be a major determinant for yield, especially during periods of low rainfall, the range between field capacity and permanent wilting point is of importance. In that respect the heavy clay soil presented here and the loamy soil differ very little, the first one having an available moisture range of 0.161 cm^3 cm^{-3} and the latter of 0.166 cm^3 cm^{-3}, whereas the sandy soil only has a range of 0.02 cm^3 cm^{-3}. As already hinted at earlier, sandy soils are very unfavourable during dry spells, as for instance with a rooting depth of 120 cm, the total soil-moisture store is only 36 mm, hence with an evaporative demand of 3 mm d^{-1}, a very modest value, just enough for 12 days. The loam soil on the other hand contains in the same zone almost 200 mm of available water, which could carry a crop through a rainless period of more than two months. The heavy clay soil in this case can supply practically the same amount of water as the loamy soil, however after a prolonged period of drought in which the soil has dried out to much lower moisture contents due to evaporation from the soil surface, much more water is needed to restore the soil to a moisture content suitable for plant growth.

Moreover, clay soils are much more difficult to work, hence with a given amount of available labour a smaller acreage of a clay soil can be prepared for crop growth than of a loamy soil, reason that loamy soils are much preferred in agricultural practice.

2.2.2 Soil chemical properties

The chemical properties of the soil that are of greatest interest with respect to crop production are those that determine the ability of the soil to supply the crop with the necessary nutrients. That capacity is co-determined by a complex of different factors, that act independently or interact with each other.

Although crops need many elements for unrestricted growth and production, many of these are required in such small quantities that practically always the supply from natural sources is sufficient to reach potential production. However, the macro-elements nitrogen, phosphorus and potassium are required in such large quantities that the actual production level is often determined by the amount of these elements supplied from these natural sources. In tropical soils a number of specific processes is prominent that affect this property.

In general, the warm and humid environment of the humid tropics is conducive to rapid decomposition of organic material. In the natural situation, *i.e.* under tropical forest, or perennial grass, the supply of organic matter to the soil is also high, so that an equilibrium situation at a reasonable level exists. However, under agricultural use, where a major part of the organic matter produced is harvested and removed from the field, the levels of organic matter in the soil decline very rapidly and with it its capacity to supply nitrogen *(Nye and Greenland [1960])*. After a number of crop cycles the nitrogen-limited yield may therefore reach such low levels that the efforts of farming are hardly worthwhile. Any management or cultural practice that aims at maintaining the level of organic matter in the soil (green manuring, inter-cropping, etc.) is therefore helpful in ensuring a continuous yield at a reasonable level.

Next to nitrogen, phosphorus is the single most important element in plant nutrition in the humid tropical zone. In many cases the level of total phosphorus in the soil is low, and moreover the availability for the vegetation is restricted. That is due to the phenomenon of phosphorus fixation that is widespread in these soils. That phenomenon is characterized by a parallel series of processes of absorption and precipitation in which phosphorus is effectively removed from the soil solution by the formation of insoluble phosphorus compounds such as aluminium and calcium phosphates. The concentration of inorganic phosphorus components, the only ones that can be taken up by the vegetation, remains therefore low in the soil solution and its availability is restricted. Even application of fertilizer phosphorus in such cases is of only limited value, because the recovery is generally low and the residual effects are limited. The exact quantitative relationships that govern these processes are still to a large extent unknown, and even though considerable progress has been made in recent years, it still appears impossible to predict the supply of phosphorus from natural sources even in well-defined environments, as well as the effects of application of fertilizers.

Also in the phosphorus supplying capacity of the soils, organic matter cycling and decomposition play an important role, as especially in tropical soils, low in total phosphorus, the organic component may constitute a substantial proportion of the total phosphorus supply to the vegetation.

3. Physical resources and crop production

Agriculture was defined earlier as the human activity that transforms the energy of the sun into edible organic material through manipulation of plants and animals. In principle, the number of resources that is needed is only small: a piece of land, some sun and rain, and a little bit of human physical effort. In subsistence farming these limited resources will often suffice to provide a supply of food and shelter to the farmer and his family, without too much inputs from outside. However, an ever increasing proportion of the population lives in such high concentrations that it is impossible to produce the bare necessities for life. That situation puts a heavy burden on the agricultural community that is expected to supply the requirements for living to the urban part of the population. It appears, and will be further elaborated in the remainder of this presentation, that, from a resource point of view, this requirement can only be satisfied, if sufficient means of production are put at the disposal of the farming community. And that at an economic exchange rate, that makes application of these means attractive.

3.1 Potential production

Potential production is defined in our context as the production of a certain crop, characterized by its genetic and physiological properties, growing under a given temperature and radiation regime, in a situation where all other constraints, that could feasibly be eliminated, have been removed. Such conditions imply optimum supply of water and nutrients, complete weed control and the absence of pests and diseases.

Under such conditions crop production is determined by the growth rate, *i.e.* the daily rate of dry matter accumulation on the one hand, and the duration of the growth period on the other hand.

The growth rate is determined by the amount of solar energy that can be utilized by the vegetation, which is a function of energy availability (intensity and duration of sunshine) and the capacity of the vegetation to absorb that energy, which is mainly a function of the absorbing green (leaf) area. In general, a crop growing under optimum conditions develops quickly sufficient leaf area to intercept all available energy so that after a short initial period, the crop maintains a radiation-determined linear growth rate. The total amount of dry matter accumulated depends then primarily on the length of the period that this growth rate can be maintained. The length of that period is governed by genetic crop characteristics (short-duration *vs.* long-duration cultivars) and the prevailing temperature. At higher temperatures the phenological development, that is the rate at which a crop goes through the various phenological stages, such as leaf formation, ear initiation, flowering and maturity, proceeds at a higher rate, and consequently the crop cycle shortens, resulting generally in lower total dry matter production. The yield, which only comprises the economically relevant plant parts, or the marketable product, and is thus only a fraction of the total dry matter produced, is co-determined by the distribution of dry matter over the various plant parts. Plant breeding over the past decades has for many species resulted in cultivars that invest a higher proportion of their total biomass in the economic plant parts. For such cultivars, the ratio of economic yield to total dry matter production, or the harvest index, is superior to that of the traditional cultivars, hence even with a shorter growth period, yields may be higher. An interesting observation in this respect is, that if traditional cultivars and modern (so called high-yielding) cultivars are grown under the same conditions and present day management techniques their total dry matter yields are very similar. (Of course care should be taken that the traditional cultivars growing under the high nitrogen supply common in modern agriculture, are not lodging). This result illustrates that plant breeding has hardly influenced the basic biochemistry and physiology of the plant.

The effects of environmental conditions (or the physical resources) on crop production and yield have been studied ever since the beginning of agricultural research. However, the variability and unpredictability of especially weather conditions, and the interaction between its various components, make execution and interpretation of field experiments often very difficult. A convenient way to avoid (at least part of) those problems is the use of simulation models, where crop performance is predicted on the basis of knowledge of the basic physical, physiological and biochemical processes relevant for the production process *(Penning de Vries [1984]; de Wit [1970])*. At present many of such models, with different purposes and varying in their degree of detailedness and complexity are available *(van Keulen [1983])*. In such models crop growth rates are calculated from the assimilation rate, taking into account the respiratory losses involved in maintenance and growth, the distribution of dry matter over the various plant organs, typically in dependence of the phenological state of the crop. The phenological state in turn is determined by genetic factors, and the influence of environmental factors like temperature and daylength. A relatively simple model, containing these elements *(van Keulen et al. [1982])* has been used to analyze the effects of physical resources on production and yield of some important food crops grown in the humid tropics.

3.1.1 Radiation

The radiant energy emitted by the sun is in part, *i.e.* the wavelength region of 400-700 nm (visible light) absorbed by the green pigments of the plants and used for the reduction of carbon dioxide. Typically therefore at low levels of irradiance the rate of carbon dioxide reduction is proportional to the level of irradiance *i.e.* energy availability determines the rate of assimilation. At higher levels of irradiance the assimilation rate reaches a constant level irrespective of energy availability (Figure 9), *i.e.* the rate of assimilation is determined by the rate of transport of CO_2 from the ambient air to the active sites. However, especially at higher leaf area indices, part of the green area is in the energy-dependent part of the photosynthesis-light response curve and at the beginning and end of the day all leaves may be at that level. Crop assimilation rate on a daily basis increases therefore with increasing energy availability. The quantitative relations between these variables, in dependence of crop characteristics, geographical position and time of the year have been established with the use of computer models *(Goudriaan and van Laar [1978]; de Wit [1965])*.

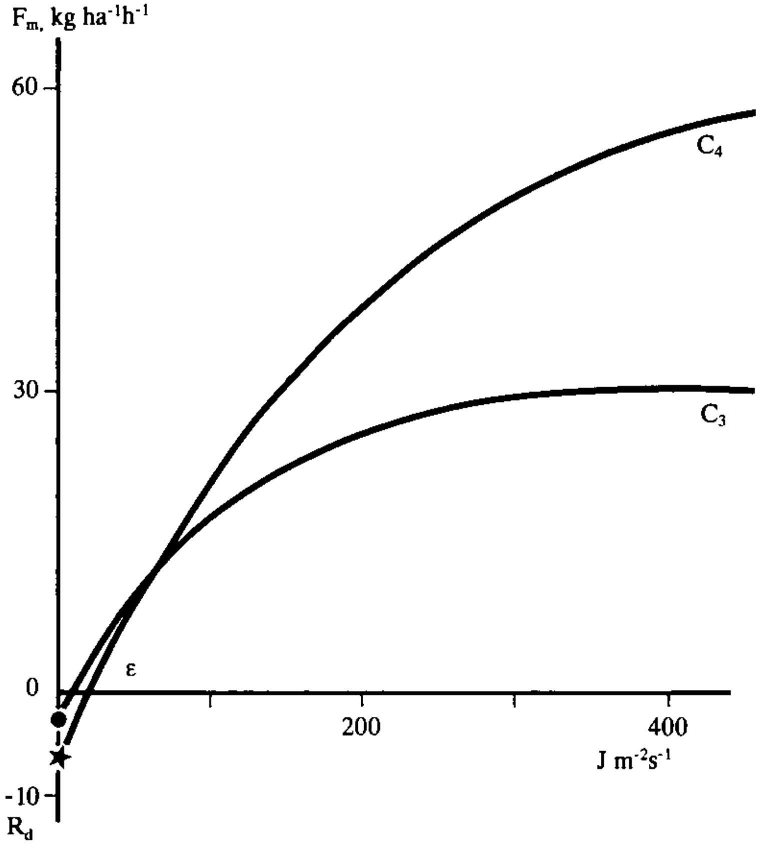

Fig. 9 The relation between absorbed radiation and the assimilation rate for individual leaves of plants of the C_3 and the C_4 type.

The effect of radiation level on the yield potential for a rice crop is illustrated in Table 1, where the calculated yield is given for a non-photosensitive short-duration rice variety. At each location the transplanting date was chosen in such a way, irrespective of other weather characteristics that grain filling took place either in the period with the highest radiation level, or in the period with the lowest radiation level. These results hint already at one of the difficulties involved in the analysis of the effect of one single climatic factor on production and yield. The weather characteristics change simultaneously and therefore interact.

However, as shown in Figure 10, a reasonable correlation exists between absorbed photosynthetically active radiation in the post-anthesis phase and grain yield. The scatter around the regression line may be due to different reasons. For Dacca both crops absorb the same amount of PAR (due to the fact that the crop maturing in the low-radiation period is in the field for two more weeks), but the yield differs 2000 kg ha^{-1}. Two processes contribute to this yield difference. Firstly, witnessed by the harvest index, the crop maturing in the low-radiation period has a higher energy availability in the pre-anthesis period and produced more vegetative material. Secondly, the longer growth duration reflects the lower temperatures during the growing period. As a result of both, the maintenance respiration requirements for the «low-radiation» crop are higher than for the «high-radiation» crop and consequently assimilate availability for grain growth is lower.

Table 1. The effect of radiation level on the yield of a short-duration rice cultivar.

Location	Transplanting date	Absorbed radiation post-anthesis (10^8 J m^{-2})	Yield (t ba^{-1})	Harvest index	Total growth period (d)
Dacca	Sept. 27	3.24	9.3	0.56	105
	Feb. 15	3.24	7.3	0.47	91
Los Baños	Aug. 28	2.05	5.6	0.45	94
	Jan. 15	3.52	8.7	0.52	98
San Ramon	Feb. 25	2.78	7.7	0.47	109
	July 13	3.18	8.5	0.49	106
Bogor	Sept. 27	2.02	6.2	0.48	95
	June 15	2.32	6.5	0.49	94
Lampang	Sept. 12	2.36	6.8	0.51	98
	Jan. 15	2.75	6.4	0.44	94

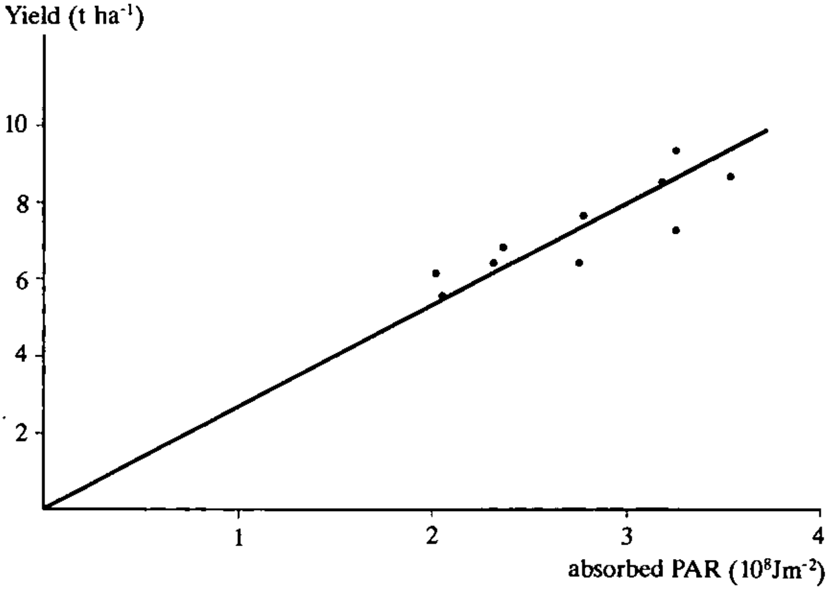

Fig. 10 The relation between absorbed photosynthetically active radiation in the post-anthesis phase and grain yield for a short duration rice cultivar (simulated).

A similar situation exists in Lampang, although there the effect is less pronounced. Particularly for Los Baños the difference between the two crops is striking: almost 3 t ha^{-1} more for the «high-radiation» crop. These results are in good agreement with those presented by *Yoshida and Parao [1976]* from a shading experiment and by *Yoshida et al. [1972]* from a maximum annual production trial. It is interesting to note that simulation of the latter trial, which involved continuous cropping of four rice crops within one year, resulted in a total yield of 33 000 kg ha^{-1} *(van Keulen [1986])*, illustrating that very high production levels are possible in the humid tropics, provided that possible unfavourable effects of water or nutrient shortage and weeds, pests and diseases can be avoided.

3.1.2 Temperature

Many of the plant physiological processes are enzymatic processes which are temperature-dependent. However, not all processes are affected in the same way, nor with the same intensity, and sometimes the effects work in opposite direction, so that the overall result is very difficult to predict.

Temperature affects the rate of assimilation as witnessed by the results of many experiments. In most cases, however, these results refer to plants grown under controlled conditions (a.o. constant temperature) and subsequently measured at various temperatures. In the field situation plants may adapt to fluctuating and suboptimum temperature conditions *(de Wit et al. [1978])* so that in fact the temperature effect is much less pronounced and a rather flat optimum exists.

A second process that is affected by temperature is the conversion of primary photosynthetic products into structural plant material, *i.e.* growth. That process takes place especially during the night and is therefore much more affected by minimum temperatures than by the average 24-hour temperature. This phenomenon plays especially a role in situations where low night temperatures coincide with relatively favourable day-time temperatures and high radiation levels. Plant species belonging to the C_4 type are much more sensitive to this phenomenon than species belonging to the C_3 type, because the limiting temperatures for the first group are around 10 °C, in comparison to 3-5 °C for the second group. Especially therefore for crops like maize, sorghum and tropical grasses this process should be taken into account.

A distinction should be made between growth, *i.e.* the increase in size, weight etc. of the biomass and development, the rate and order of appearance of vegetative and reproductive plant organs.

The order of appearance of the organs is species-characteristic, genetically determined and hardly subject to influence of external factors. The rate of development, however, in addition to being genetically determined, is strongly influenced by environmental factors, notably temperature and day length. Within the scope of this contribution the effects of day length will not be discussed, mainly because the quantitative relationships are not very well understood. It should, however, be realized that the choice for a day length intensitive cultivar may carry great risk, because it may result in untimely flowering or maturation of the crop (consider for instance maturity of a cultivar in the middle of the rainy season, when the field cannot be drained and the ears will not dry because of abundant rainfall).

The effect of temperature, however, is well-documented and it appears that the duration of a given phenological period declines with an increase in average temperature *(Robertson [1982]; van Dobben [1962])*. When the inverse of the duration of a certain phenological period («the development rate») is plotted *versus* average temperature, it appears that in many cases a straight line results, over a wide range of temperatures. This straight line may for some crops (or crop cultivars) cross the temperature axis at a non-zero value, the so-called threshold value below which development comes to a standstill. At high temperatures (above 30° C) the proportionality between development rate and temperature disappears. There is conflicting evidence about the relation above that point, in some cases the development rate appears to remain constant, in others there seems to be again a decline in the development rate. For most practical purposes, however, only the linear part of the relation is of importance. The linearity of the relation between development rate and average temperature is equivalent with the notion that for completion of a phenological phase a constant «heat sum» expressed in d °C is required. The consequences of this property are already visible in Table 1, where it is shown that the growth duration of the same variety that requires 1600 d °C from transplanting to anthesis and an additional 800 d °C from anthesis to maturity varies between 91 and 109 days depending on environmental conditions. The effect of temperature *per se* on yield is, however, difficult to deduce from these data, because temperature differences interact here with differences in radiation level.

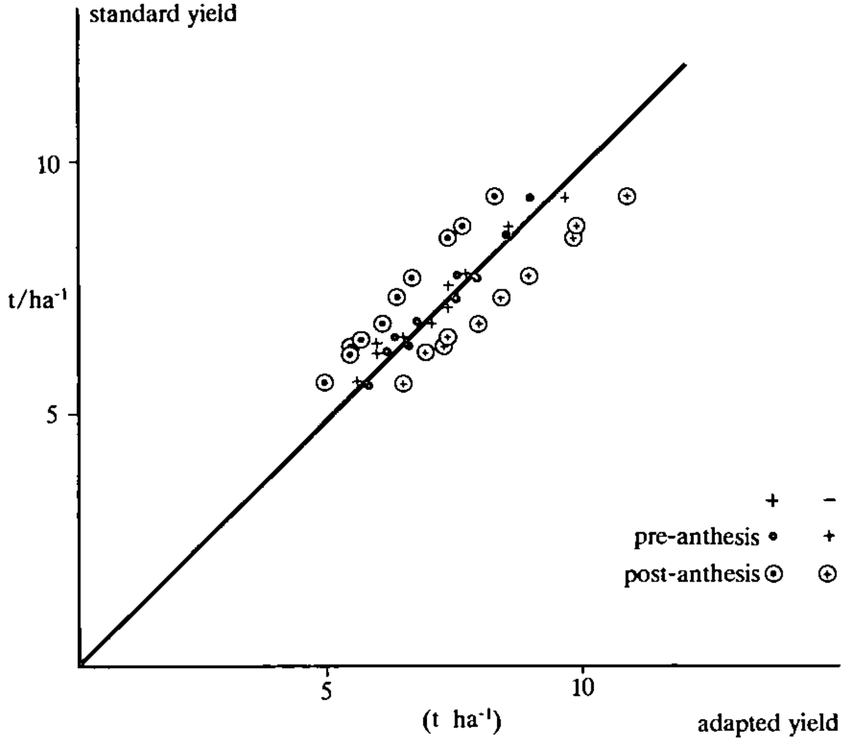

Fig. 11 The effect of temperature on calculated grain yield of a short-duration rice cultivar, standard yields calculated with data of Figure 3, adapted yields by assuming 2.5 °C temperature difference.

A more direct method is therefore applied by assuming that the average temperatures are either 2.5 °C higher or 2.5 °C lower, for both the pre-anthesis and the post-anthesis period. The results, presented in Figure 11 as the relation between the «standard» yield and the «adapted» yield, show that the greatest effects occur from temperature differences during the post-anthesis phase. Temperatures in the pre-anthesis phase also have some effects, but these are smaller and not consistent. Higher temperatures during the post-anthesis phase result in shorter periods of grain filling and accelerated senescence of the leaves. Moreover, the maintenance requirement of the existing biomass is higher, hence the overall effect is lower grain yields, as illustrated in Figure 11. Similar observations have been made in temperate regions, showing that bright warm summers generally result in lower grain yields than dull and cooler summers *(Monteith [1981])*.

It may be concluded from the — limited — evidence presented in this subsection that the relatively high temperatures prevailing in the humid tropical region are on the one hand an advantage, because they permit year-round growth of crops. On the other hand they may be disadvantageous, since they induce rapid phenological development of the crop, and hence a limited period of active growth and a restricted time span for growth of the reproductive plant organs.

3.2. Water-limited production

As was shown in Figure 7 there are considerable periods in some regions of the humid tropics where the evaporative demand of the atmosphere exceeds precipitation. Under such conditions it is likely that moisture availability for the crop becomes a factor constraining crop production. If rain does not replenish the moisture withdrawn by the crop from the soil profile, the soil dries out, hence the water remaining in the soil has an ever-decreasing potential, thus hampering uptake by the root system. As a consequence, the vegetation loses turgor, the stomata start to close, thus offering higher resistance to water loss, but at the same time obstructing entrance of CO_2, hence decreased assimilation rates and lower production. Eventually the plant will shed its leaves, dessicate and ultimately die.

To estimate the quantitative consequences of a certain rainfall pattern on crop production the soil-water balance must be considered. As discussed in Section 2.2 considerable differences exist among soil types with respect to soil physical characteristics associated with the water balance, such as infiltration capacity, storage capacity, etc. Moreover, geomorphological characteristics play a role such as the vicinity of a river and height above sea level. Water-limited production should therefore always be considered by combining climatic resources with soil resources.

That point is illustrated in Figure 12, where calculated grain yields for Dacca are presented for a medium duration maize cultivar, requiring 850 d °C above a treshold value of 10 °C from emergence to silking and 650 d °C from silking to maturity. Three situations are considered: first potential production as a reference point, varying between 7.5 t h^{-1} for crops emerging in the middle of the year (June/July) and 10.5 t ha^{-1} for a crop emerging in the middle of October. These differences are due to the combined effect of radiation and temperature as outlined in the previous section. The crops emerging in the middle of the year grow in a period with relatively high temperatures (the total post-silking period for instance is only about 40 days) and low radiation, whereas the crop emerging in October is subject to the reverse conditions (the post-silking period is more than 60 days in that case).

Fig. 12 Calculated potential grain yield (----), and water-limited grain yield on a loam soil (x—x) or a clay soil (....) for a maize crop sown at twelve dates throughout the year in Dacca.

In the context of this section, however, the other two lines in Figure 12 are of more interest: under rainfed conditions, the yield potential is only fully expressed for crops emerging in the period mid-May till mid-September. Crops emerging outside that period suffer from water stress during some stage in the growing season, which results in lower yields, or even complete crop failure, *i.e.* for crops emerging between the middle of November and the middle of December, if grown on a clay soil. It is clear that the sandy loam soil is more favourable in terms of water supply for the crop than the clay soil. For instance the crop emerging in the middle of February still yields 4 t ha^{-1} of grain when grown on a loamy soil and only 750 kg ha^{-1} when grown on the clay soil. This difference is related to the much higher storage capacity of the loamy soil, *i.e.* the difference between field capacity and permanent wilting point: 0.11 cm^3 cm^{-3} for the clay soil *versus* 0.18 cm^3 cm^{-3} for the loamy soil. Of course, in discussing such yields in general terms there is always a certain degree of arbitrariness involved, because the moisture conditions in the soil at the time of emergence have to be specified. And these conditions depend on the preceding use of the field and the boundary conditions. For the data presented in Figure 12 it was assumed that at emergence the profile was at field capacity in all cases, irrespective of preceding weather or other conditions. Such a situation would presumably only be commensurate with reality if the field had been fallow for some time preceding the assumed seeding date, and rainfall in that period was abundant. It is, however, difficult to treat this point in more detail in a general way.

Another aspect of the water-limited production is illustrated in Figure 13a, where the relation is given between calculated grain yield and total crop transpiration. Obviously a positive correlation exists, but the variability is quite high. Part of the reason for this variability is the fact that the harvest index, *i.e.* the ratio between grain weight and total dry weight depends to a large extent on the distribution of moisture availability. For the twelve emergence dates illustrated in Figure 12, the harvest index varies between 0.4

(emergence on day 319, *i.e.* the middle of November) and 0.5 (emergence on day 258, the middle of September). Obviously for the first emergence date, moisture availability during the pre-silking period was still reasonable, whereas after silking rainfall is very low and hence moisture supply to the crop is seriously limiting. On the other hand, the crop emerging in mid-September has a sufficient water supply throughout the growing cycle, and matures during a period of high energy availability.

When total dry matter production is related to total transpiration, the variability decreases markedly (Figure 13b). This illustrates that the processes of CO_2 exchange and water vapour exchange are closely related, because they are governed by the same physical principles. Thus a reduction in transpiration, due to insufficient moisture availability in the soil is accompanied by an approximately proportional reduction in dry matter production. Three points clearly deviate form the eye-fitted line in Figure 13b, which is due to the fact that the three crops concerned are growing in a period where the evaporative demand of the atmosphere is low compared to the remainder of the year. For the three encircled points the average «*Penman*» evaporation over the growing period is 2.7, 3.1 and 3.2 mm d^{-1}, respectively, compared to an average of 4.6 mm d^{-1}, for the other simulated crops.

The slope of the line in Figure 13b is 0.0054 kg dry matter per kg water or equivalent to a transpiration coefficient *(Tanner and Sinclair [1983]; de Wit [1958])* of 185 kg water transpired per kg of dry matter produced, which is a very reasonable value for a C_4 crop growing under intermediate evaporative demand. Of course, the overall water use efficiency expressed as kg dry matter produced per unit of moisture input in the system is much lower, because part of the rainfall evaporates directly from the soil surface and does not contribute to production, whereas amother part, especially in the rainy season is lost through drainage beyond the potential rooting zone.

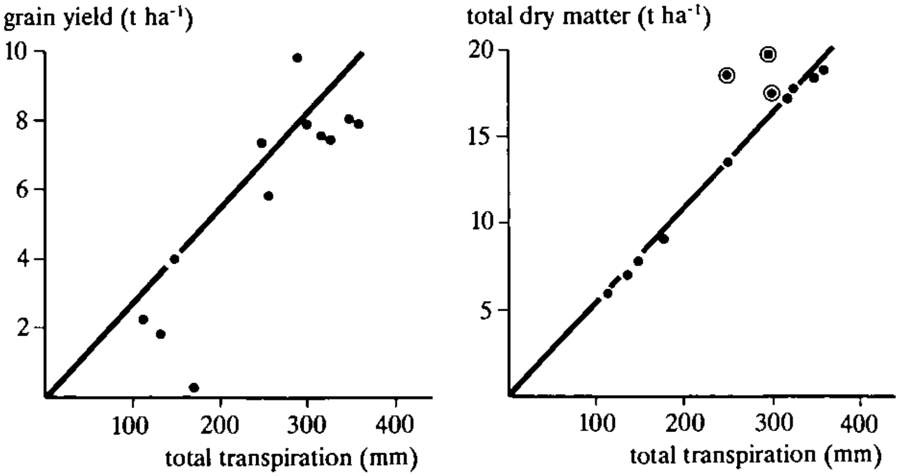

Fig. 13 The relation between grain yield and total transpiration (a) and that between total dry matter production and total transpiration (b) for a maize crop sown at twelve dates throughout the year in Dacca.

As indicate before, the initial conditions, that is the situation at the start of crop growth has a marked influence on crop performance, but also the boundary conditions. Taking again Dacca as an example, two contrasting situations are considered: one a sandy loam located in a river valley, where the groundwater table is at a depth of about 2 m below soil surface, and the other where the same soil type is situated at a much more elevated location, with a water table at a depth of at least 10 m. The initial conditions in both cases are the equilibrium moisture profiles associated with the assumed depth of the groundwater table. The crop in this case emerged on November 14th and, as shown in Figure 14, took 132 days to maturity. The crop growing in the low-lying area produces 20000 kg ha^{-1} of dry matter and yields 5500 kg ha^{-1} of grain (The potential production for this situation was calculated as 9300 kg ha^{-1}). The harvest index of this crop is 0.27 which is very unfavourable for a maize crop, but that is due to the fact that moisture shortage occurs from about day 105 onwards, *i.e.* during the grain filling stage. Hence, stover yield is virtually unaffected by drought, but grain yield suffers dramatically. This effect is even much stronger if the crop is cultivated at a site without influence of a groundwater table (Figure 14). Under those conditions production virtually ceases after silking and just enough moisture is available to allow assimilation at a rate equal to the maintenance requirements of the vegetation. With the groundwater table at 2 m depth, 137 mm of water is supplied by capillary rise out of a total transpiration requirement of 325 mm over the total growth cycle. Hence, the presence of a real, or a pseudo-groundwater table originating from an impervious layer somewhere in the profile, may be of crucial importance for crop production during a period of low rainfall.

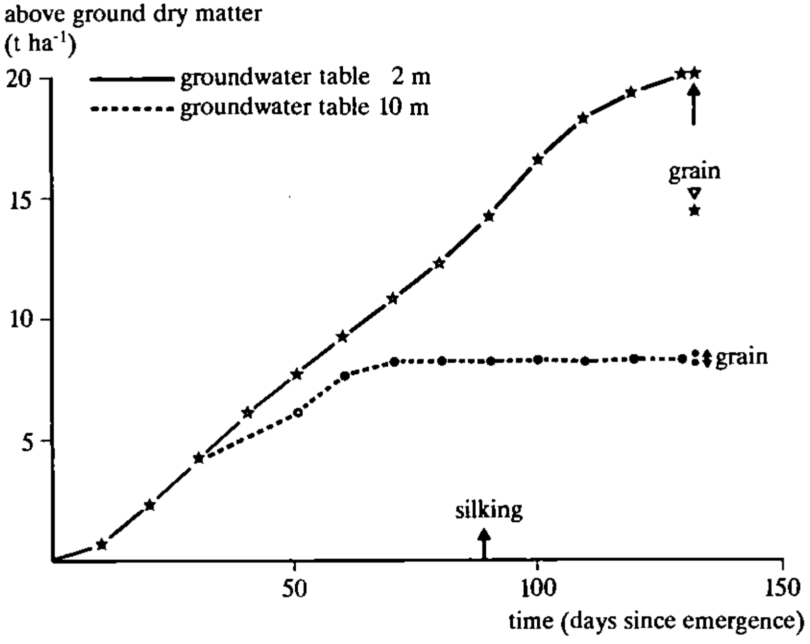

Fig. 14 Calculated growth curve for a maize crop emerging on November 14 in Dacca in either a low-lying or an elevated location.

In the situation with the groundwater table at a depth of 2 m the total transpiration deficit, *i.e.* the difference between actual transpiration and potential transpiration is about 50 mm over a period of a month. To achieve potential production under these conditions it would thus be necessary to ensure availability of that amount to the crop during the grain filling phase. If that would be supplied by irrigation, it is to be expected that losses will be incurred, their magnitude depending on the mode of irrigation and the quality of the irrigation system. Moreover, some irrigation applications will increase soil surface evaporation, which must be compensated also. A reasonable estimate would therefore be that 100 mm or 1000 m^3 ha^{-1} of water would have to be available to reach potential production.

From the five situations given as examples of the humid tropics in Figures 2-7, Dacca occupies an intermediate position in terms of moisture availability for crop production. Rainfall in Bogor is so high throughout the year that continuous cropping is possible without the risk of moisture shortage, *i.e.* moisture determined production equals potential production for any sowing date. On the other side of the spectrum is Lampang where only crops emerging between the middle of April and the middle of August attain potential yield under rainfed conditions. Crops emerging outside that period suffer from water shortage during part of their growth cycle, resulting in yield reductions. For twelve emergence dates, each time in the middle of a month, the relative transpiration, *i.e.* the ratio of actual transpiration to potential transpiration varies between 0.23, for the crop emerging in the middle of December, and 1.0 for the crops emerging in the middle of the year. In line with those observations is the fact that also the harvest index varies dramatically. It is about 0.01 for the crops emerging at the end of the year so that with a growth period of about 115 days grain filling takes place in the months January through March, by far the driest period of the year. On the other hand, the crop emerging mid-March suffers from water shortage at the beginning of the growth cycle, but is exposed to gradually improving conditions during the grain filling stage, which results in a harvest index of

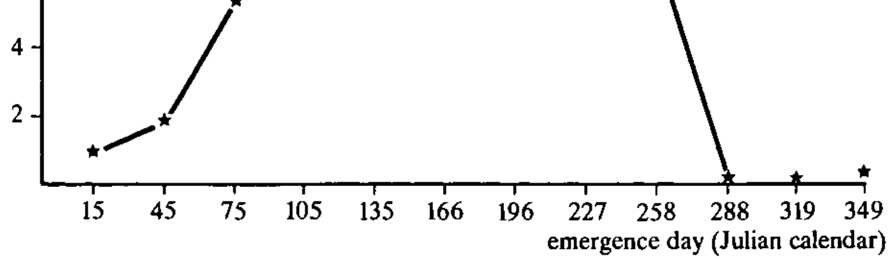

Fig. 15 Calculated potential grain yield (· --- ·) and water-limited grain yield (x—x) for a maize crop sown at twelve dates throughout the year in Lampang.

0.58, even though the yield falls considerably short of the potential, set by radiation and temperature.

Considering the results presented in this section, it may thus be concluded that watere shortage is a serious limitation for crop production in considerable parts of the humid tropics. The somewhat ironical situation exists, that the yield potential set by genetic crop properties, radiation and temperature is generally highest in the period that water supply is low and uncertain (Figure 15). Development of reliable and efficient irrigation systems could therefore provide a substantial contribution to increased food production in the humid tropics.

3.3 Nutrient-limited production

The subject of nutrient limitation and nutrient requirements will be treated in detail in another presentation in this colloquium, so there is no need to discuss it here extensively. However, in discussing the physical resources of the humid tropics, the impact of soil fertility cannot be completely neglected. As explained in the preceding section, the supply of nutrients from natural sources is relatively low in many soils in the humid tropics. Exceptions do exist, for instance in places where the soil originates from relatively young volcanic material, that due to continued weathering still supplies reasonable amounts of nutrients.

However, the more common situation is that, where the «base uptake», that is the uptake of nutrients in the absence of fertilizer application, is low. Under such conditions, where nutrient supply is the constraining factor for crop production, plants will tend to maximize the efficiency of utilization of the limiting element by diluting its concentration in the tissue to a minimum value. For cereals like maize and rice those values are around 0.01 kg N kg^{-1} dry matter and 0.001 kg P kg^{-1} dry matter in the grains, and 0.004 kg N kg^{-1} dry matter and 0.0005 kg P kg^{-1} dry matter in the straw or stover, respectively *(van Keulen and van Heemst [1982]; van Keulen [1977])*. If a harvest index of 0.5 is assumed, that means that about 70 kg of grain can be produced for each kg of N taken up by the crop, and about 625 kg grain per kg P absorbed. This implies that under natural conditions in countries like Thailand and Bangladesh, where typically 15-20 kg N ha^{-1} is supplied from natural sources, the yield varies between 1000 and 1500 kg ha^{-1} for cereals *(Wolf et al. [1986]; van Keulen et al. [1983])*. On the island of Java in Indonesia, consisting for a large part of more fertile soils, the N supply is of the order of 30 kg ha^{-1} during a rice growing cycle and yields reach values of about 2000 kg ha^{-1}.

The associated P requirements are of the order of 2-4 kg ha^{-1}, which is generally available from natural sources, However, the moment that nitrogenous fertilizers are introduced in the system and the N determined yields increase, P soon becomes a limiting factor and application of phosphorus fertilizers should be considered.

In the Southamerican part of the humid tropics often phosphorus is the most limiting element, as the soils have strongly phosphorus fixing properties. P-limited grain yields are often of the order of 600-1000 kg ha^{-1}. Improvement of that situation, however, requires in general application of substantial quantities of phosphorus fertilizers, as the recovery, again due to to fixation, is extremely low.

It must thus be concluded that in addition to water, soil fertility is a constraint for crop production in the humid tropics, and that application of fertilizer is a prerequisite for attaining yield potentials, set by the inherent physiological and biochemical properties of the plants.

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Yield Potentials of Plantation Crops

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Summary

Crop production can be considered in terms of interception of solar radiation, conversion of the intercepted radiation to plant dry matter, and partitioning of dry matter between harvested and non-harvested plant parts. Tropical perennial crops achieve much higher light interception than annual crops, and some have partition ratios comparable to annuals. They therefore give greater yields than annuals, despite relatively inefficient conversion of intercepted radiation to dry matter.

Possible reasons for the low conversion efficiency include high respiratory losses, because of the large proportion of non-photosynthetic tissues in perennial crops, and reduced photosynthetic rates because of excessively high leaf temperatures. Water stress may also be a limiting factor. Although partition ratios are high for some crops, they tend to be reduced at the planting densities necessary to give maximum light interception. There is some possibility of improving this by selection.

The main effect of nitrogen and potassium fertiliser application is to increase the efficiency of conversion of intercepted radiation, but small increases in light interception and in partition ratio may also occur.

1. Introduction

Perennial crops in a tropical environment have a large biological advantage over other cropping systems, because the growing season lasts for 12 months a year, and perennials maintain a complete leaf canopy throughout the year. This maximises interception of solar radiation, upon which plant growth depends. This advantage of tropical perennials is exemplified in Table 1, which shows that oil palm greatly outyields other oil crops, despite having been subject to much less research than some crops.

The crops considered in this review are listed in Table 2, together with the main economic products, and typical yields achieved with good management in favourable environments. When comparing yields from these crops with annual crops, we must remember that the perennial crops have an immature period, often of several years, before harvesting starts. The immature periods and economic lives of the crops are given in Table 2.

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I have elsewhere estimated theoretical potential yields for these crops *(Corley [1983a])*. These are shown in Table 3, together with the best actual yields known to me. For most crops the theoretical potential is approximately twice the record yield obtained so far. These theoretical potential yields provide targets for research workers, but their achievement is a very distant prospect. In this paper I shall discuss some of the constraints on achievement of the full genetic potential of existing material, and possible approaches to improving this potential.

Table 1. Approximate record yields from several oil crops

Crop	Yield (t.ha^{-1}.yr^{-1})
Oil palm	10.0
Sunflower	4.0
Olive	3.0
Oil-seed rape	3.0
Soyabean	2.0

Table 2. Details of the crops reviewed, their main products, typical annual yields achieved in favourable environments with good management, and economic lives and immature periods*.

Crop	Main product	Yield t.ha^{-1}	Immature period (y)	Economic life (y)
Oil palm	Oil	5-6	2.5	25-30
Coconut	Copra	2-3	2.5-7	up to 70
Cocoa	Beans	1-2.5	1.5	30-70
Rubber	Rubber	2	5	25-30
Cassava	Starch	10	–	0.5-2

* The immature period and economic life are given in years after planting in the field. There may be a nursery period of up to 1 year before field planting.

Table 3. Theoretical potential yields (from *Corley [1983a]*) and approximate record yields.

Crop	Total dry matter production (t.ha^{-1}.y^{-1})	Yield of economic product (t.ha^{-1}.y^{-1})	Best actual yield (t.ha^{-1}.y^{-1})
Oil palm	44	17	10
Coconut	51	13	6.3
Rubber	46	15	5.0
Cocoa	56	11	6.1
Cassava	64	40	25

2. Method of analysis

The yield of a crop can be considered in terms of the efficiency of successive stages in the conversion of solar energy to the economic product *(Monteith [1972, 1977], Squire [1984])*. In the simplest terms, only four parameters need to be considered:

S = the total solar energy received at the surface of the crop.

f = the fraction of this energy which is intercepted by the leaf canopy.

e = the efficiency for conversion of intercepted energy to plant dry matter.

Harvest index = the ratio of dry matter, or more correctly energy, in the economic product to total dry matter or energy fixed by the crop.

Total solar radiation in the tropics is considered eleswhere in this symposium. *Squire [1984]* showed that total radiation ranged from 6.1 to 6.5 $GJ.m^{-2}$ in oil palm growing areas in Malaysia. For simplicity in this review I have assumed a figure of $S = 6.3$ $GJ.m^{-2}$ per year, where no relevant radiation data were available.

3. Light interception

The fraction of total radiation which penetrates the leaf canopy ($1-f$) depend on the leaf area index, L (the ratio of total leaf area to unit ground area). In most crops the relationship has the following form:

$$\text{Ln}\,(1-f) = -kL$$

where k is the «extinction coefficient» *(Saeki [1963])*. The value of k usually depends mainly on leaf or leaflet angle to the vertical, with near vertical leaflets allowing greater light penetration.

Squire [1984] showed that for oil palm the light penetration through the canopy was better described by the following equation:

$$\text{Ln}\,(1-f) = a - kL$$

where a is a constant. The occurrence of a positive intercept on the L axis, in contrast to most species where the regression line passes through the origin, is probably because the leaves in an oil palm crown are not randomly distributed, but clumped around few, widely spaced growing points. This non-random distribution will also lead to a low extinction coefficient. *Acock et al [1970]* and *Squire [1984]* found a value of 0.34 for oil palm. Many crops have much higher coefficients; for example, *Cock [1983]* quotes figures of 0.7 to 0.86 for cassava. Leaves transmit less photosynthetically active radiation (PAR) than total radiation, and Squire found an extinction coefficient for PAR of 0.47 for oil palm, 1.4 times that for total radiation.

Figure 1 shows data from a coconut thinning trial in the Solomon Islands. The measurements here were of PAR, so the extinction coefficient of 0.65 may be equivalent to a coefficient of about 0.45 for total radiation. This suggests that coconuts have a rather more horizontal leaflet distribution than oil palms. The intercept on the L axis is much greater than that observed in oil palm by *Squire [1984]*. This probably reflects the fact that variation in leaf area index was obtained by thinning an initially regular stand, leaving large gaps in the canopy. Palms do not grow asymmetrically to fill such gaps, so light penetration is very irregular in thinned stands.

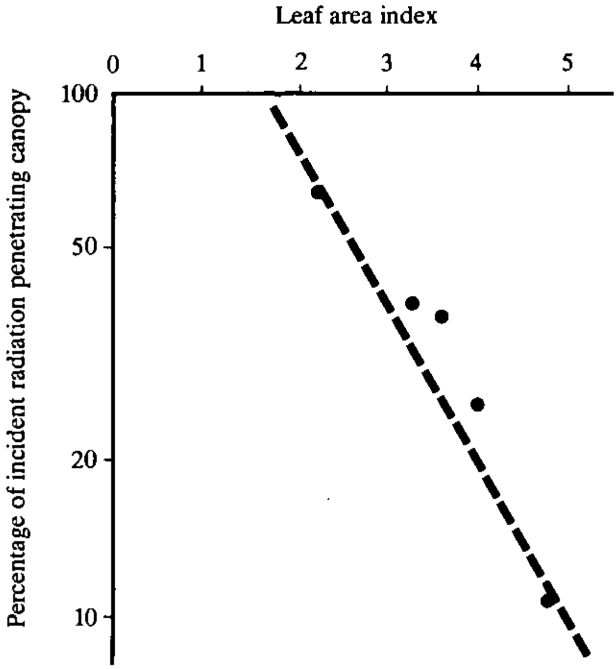

Figure 1 Relation between leaf area index and light penetration in a coconut thinning trial in the Solomon Islands. The regression line has the equation: $\mathrm{Ln}\ (1 - f) = -0.65\ L + 1.15$

To maximise total dry matter production, we must aim to maximise interception of solar radiation. For oil palm and coconuts it appears that leaf area indices of nearly 7 are necessary to achieve 95 percent interception of PAR, and between 8 and 10 to achieve 99 percent interception. In cassava, with a much higher extinction coefficient, 95 percent light interception would be obtained with L equal to about 4.

Hutcheon [1977a] quoted extinction coefficients of from 0.69 to 0.84 for cocoa, and stated that a leaf area index of 3 to 4 appeared average. *Thong and Ng [1980]* found L values of up to 10, but even at $L = 4$, 94 percent of radiation would be intercepted with an extinction coefficient of 0.69. Thus it appears that light interception by the cocoa canopy is relatively efficient. In practice, cocoa is often grown under shade provided by coconuts or leguminous tree species. *Yegappan* (personal communication) found that L for the leguminous shade trees could be over 4, and Lim (1980) showed light interception by *Gliricidia* shade could be as high as 88 percent, with figures of 50 percent being common. Coconuts planted at 120 palms per hectare will have an L of approximately 2.5, giving light interception of 50 percent. When cocoa is grown under shade, therefore, the light available to and intercepted by the cocoa canopy may commonly be less than 50 percent of the total incident radiation.

In practice, it is desirable to maximise light interception over the entire economic life of the plantation, but the above estimates were for single years only. When planted at normal densities, ground cover and light interception by these crops are incomplete for the first few years. With oil palm, for example, leaf area continues to increase until the palms are 8 to 10 years old, and the plant density required to give any particular value of L will change from year to year. Palms planted at a density to maximise light interception at 10 years old will intercept less light in the early years. *Squire [1984]* estimated that for a plantation intercepting 96 percent of total radiation at maturity, interception over a 25 year economic life would be 88 percent. For a stand intercepting 85 percent at maturity, total interception over the life of the planting would be 75 percent.

For these estimates, *Squire* assumed that light interception remains constant after maximum leaf area is reached at 8 to 10 years. However, recent work in Papua New Guinea by *Breure* (personal communication *[1985]*) shows that, after reaching a maximum at 8 to 10 years, light interception then decreases again. This appears to be associated with changes in canopy structure in older palms, including an increase in canopy depth due to variation in tree height, allowing greater light penetration at the same leaf area index. In practice, therefore, fractional interception over the life of the planting will be lower than estimated by *Squire*. *Breure* suggests that it might be possible to modify the relationship between canopy structure and age by selection, to improve utilisation of radiation. If variable height is important, planting of mixtures of clones differing in height might also be useful.

Ideally, complete ground cover and maximum light interception should be achieved as early as possible in the life of the planting. Obviously, earlier ground cover can be achieved by increasing the planting density, but this will result in very high leaf area indices later on. At high leaf area indices assimilate partitioning is unfavourably affected (see below), and yield is reduced. In practice, therefore, planting density has to be a compromise between maximising early ground cover and early yield, and minimising inter-palm competition to avoid a later yield decline. Increasing planting density is not, therefore, a practical way of increasing total light interception.

An alternative approach is to try to identify palms in which leaf area expands more rapidly than normal, and reaches a maximum earlier than the usual 8 to 10 years after planting. The choice of planting density might then be less of a compromise between early and later optimal densities. *Breure [1985]* studied the pattern of leaf area expansion in individual palms, and was able to identify palms showing a rapid increase in leaf area with age, but a relatively low mature leaf size. As expected, such palms gave a higher total dry matter production during the stage of leaf area increase, but also a more favourable partition of assimilates between vegetative and reproductive growth after canopy closure.

There are possibilities for increasing the fractional light interception by crops such as oil palm, therefore, but interception is already much greater than in annual crops, and accounts for the high productivity of the tropical perennials. *Monteith [1972]* estimated a value of $f = 0.33$ for temperate arable crops, and $f = 0.2$ for tropical annual crops, and pointed out that differences in f account for major differences in productivity between different conditions of climate and management.

4. Conversion efficiency

The efficiency of the canopy in converting intercepted radiation to dry matter can be expressed in terms of the total weight of dry matter produced per unit solar energy intercepted, or, more precisely, the energy fixed per unit energy intercepted. To get realistic figures for oil crops, we must take account of the much higher energy content of oil, relative to other plant tissues *(Corley [1973a], Squire [1984])*. Assuming energy contents of oil of 39.8 kJ.g^{-1} and for other plant material of 18.8 kJ.g^{-1}, *Squire [1984]* adopted the simple expedient of multiplying the oil weight by 2.1, the ratio of these energy contents. This gives an adjusted figure for dry matter production which can be directly compared with dry matter production by non-oil producing species.

For oil palm in Malaysia, *Squire [1984]* estimated conversion efficiencies ranging from 1 to 1.6 g.MJ^{-1} PAR intercepted, after allowing for the energy content of oil. The highest total dry matter production figure quoted by *Corley [1983a]* was equivalent to a conversion efficiency of 1.53 g.MJ^{-1}.

The highest efficiency observed in the coconut thinning trial mentioned above was 1.2 g.MJ^{-1} PAR. The maximum rate of dry matter production estimated for coconut by *Corley [1983a]* was also equivalent to a conversion efficiency of 1.2 g.MJ^{-1}. This dry matter production was a composite estimate from data of *Ouvrier and Ochs [1980], Vanialingam et al [1980]* and *Friend* (personal communication).

The maximum dry matter production for cocoa *(Corley [1983a]*, again a composite estimate from data of *Lim [1980]* and *Thong and Ng [1980]*, was equivalent to a conversion efficiency of 1.06 g.MJ^{-1} PAR, for cocoa grown without overhead shade. The best cocoa clone described by *Chan and Lim [1984]* gave an average yield of dry cocoa beans over four years of 6.1 t.ha^{-1}.y^{-1}. If we assume the same rate of vegetative dry matter production as for other cocoa material (a dubious assumption; the higher yield may well have resulted from a higher partition ratio), a conversion efficiency of 1.2 g.MJ^{-1} is indicated.

The maximum dry matter production data presented by *Cock [1983]* for cassava indicate a conversion efficiency of just under 1.1 g.MJ^{-1}. From the maximum dry matter production given for rubber by *Templeton [1968]*, an e of 1.5 g.MJ^{-1} is obtained, if the rubber canopy is assumed to intercept 95 percent of PAR for 11 months per year.

Gallacher and Biscoe [1978] found conversion efficiencies for well managed wheat and barley crops of about 2.7 g.MJ^{-1} PAR intercepted. *Milford et al [1980]* showed a value equivalent to 3.4 g.MJ^{-1} PAR for sugar beet. These efficiencies are appreciably higher than those estimated above for tropical crops. (The tropical crops achieve higher productivities, though, because fractional light interception is much higher — see above.) It is worthwhile exploring possible reasons for the relatively low values of e for the tropical crops. The conversion efficiency depends on the balance between photosynthesis and respiration. Of the total sugar produced in photosynthesis, a fraction is converted into the many organic compounds making up plant tissues. The remainder is used in respiration to provide the energy both for these conversions, and for maintenance of existing plant tissue. Any factor which affects the rate of either photosynthesis or respiration may alter the conversion efficiency.

4.1 Demand for assimilates

The first point to be determined is whether the net rate of dry matter production is actually limiting. In some crops, such as tea *(Tanton [1979])*, the ability of the storage organs to accept assimilates from the leaves, the «sink» activity, is the main limitation to yield, rather than the rate of photosynthetic production, or «source» activity. The crops reviewed here appear to be source limited, though. *Cock et al [1979]* showed that removal of a portion of cassava roots did not limit yield; the remaining roots grew larger to compensate. Corley *(1976a)* found that when a proportion of oil palm inflorescences were removed, the weight of the remaining fruit bunches was considerably increased. In cocoa, 80 percent of pods normally fail to develop, apparently because assimilate supply is inadequate *(Alvim [1977])*.

4.2 Leaf photosynthetic rates

The crops considered here use the C3 photosynthetic pathway. Photosynthesis of individual leaves of C3 species typically reaches a maximum at about 30 percent of full sunlight. In species using the C4 pathway, such as maize, sugar cane and sorghum, this light saturation does not occur, and they may have conversion efficiencies appreciably greater than the best figures for C3 species. However, the temperate crops mentioned above are C3 species, so this does not explain the discrepancies between those crops and the tropical crops reviewed here.

For most of these crops, it appears that maximum light saturated photosynthetic rates are within the normal range for C3 species. *Ceulemans et al [1984]* found an average rate for 20 rubber clones of 3 g CO_2 $m^{-2}.h^{-1}$, with a maximum value of 4.1 $g.m^{-2}.h^{-1}$ for the best clone. These rates for field-grown rubber trees were higher than those observed by *Samsuddin and Impens [1979]* for plants grown in controlled environment chambers.

For cassava, the highest figure observed by *El-Sharkawy et al [1984a]* was 4.4 g CO_2 $m^{-2}.h^{-1}$, and all the varieties studied gave figures of above 3.5 $g.m^{-2}.h^{-1}$.

Light saturated photosynthetic rates of about 3 g CO_2 $m^{-2}.h^{-1}$ have been observed for oil palm *(Corley et al [1973], Corley [1983b])*. In these studies photosynthesis was measured by uptake of $^{14}CO_2$, but this technique may give biased results *(Kemp and Blacklow [1984])*. Using an infra-red gas analyser, *W. Peace* (personal communication) has found rates of 1.6 $g.m^{-2}.h^{-1}$ for nursery plants in a controlled environment; as with rubber, field grown plants might well have higher rates.

For cocoa, maximum rates of CO_2 uptake are only 0.6 to 0.7 $g.m^{-2}.h^{-1}$ *(Hutcheon [1977b], Raja Harun and Hardwick [1984])*, with 85 percent of the maximum rate being obtained under as little as 5 percent of full sunlight. *Guers and Mousseau [1979]* observed similar maximum rates for intact leaves. With leaf discs floated on water, they recorded higher values, and suggested that a rate of 1.5 to 2 $g.m^{-2}.h^{-1}$ might be possible. None the less, the results obtained for cocoa are typical for leaves of shade species, with a low maximum, and light saturation at a very low light intensity. Cocoa is originally an understorey species, and is commonly grown under overhead shade, so these results are to be expected. However, the highest cocoa yields have been obtained without overhead shade, and photosynthetic rate in such conditions should be studied.

4.3 Light interception and canopy structure

Conversion efficiency may depend partly on canopy structure. For most C3 species, where photosynthesis is saturated at only 30 percent of full sunlight, conversion will certainly be inefficient if leaves receive intensities much greater than this. A continuous layer of horizontal leaves could give complete light interception with a leaf area index little above 1, but conversion efficiency would be poor, because all leaves would be illuminated well above the saturation level.

With the sun at high angles to the horizon for much of the day in the tropics, a canopy of vertically orientated leaves would give relatively low light interception, but as the leaves would be at acute angles to the sun, they would receive effectively low light intensities, and hence would make better use of intercepted radiation. Such an «erectophile» canopy *(de Wit [1965])* could have a high conversion efficiency, but would only give good light interception at a high leaf area index.

Squire [1984] states that «the canopy of oil palm does not provide an effective intercepting surface considering the amount of foliage it contains». This is partly true, in that it results partly from non-random distribution of leaflets (see above), but to the extent that it is related to leaflet angles it should perhaps be considered more as an indication of good light penetration than of poor interception. The leaf canopy of a young oil palm seedling nursery is strongly erectophile, with more than 70 percent of the leaves at angles exceeding 45° to the horizontal *(Hong [1979])*. The canopy of young palms in the field *(Corley [1976a])* and 10 year old palms *(Breure,* personal communication) is not so strongly erectophile, but still permits good light penetration.

Computer simulation studies have indicated that differences in leaf angle may have relatively little effect on total productivity, but the effect could be greater with some crops than others. The leaves of cassava are predominantly close to horizontal *(Cock [1983])*. Leaf longevity in cassava is reduced by shading, and death of lower leaves occurs at quite small leaf area indices *(Cock et al [1979])*. Simulation modelling has suggested that extended leaf life would give greater yields *(Cock et al [1979])*, and more erect leaves should reduce the shading of lower leaves, thus increasing leaf life.

4.4 Water stress

Water stress is a serious limiting factor to productivity of tropical crops in many areas. *Squire [1984]*, using data from *Rees and Tinker [1963]*, estimated a maximum conversion efficiency of 0.86 $g.MJ^{-1}$ for oil palms in Nigeria, appreciably lower than most values from Malaysia. This difference is almost entirely attributable to the occurrence of a regular 3 to 4 month dry season in Nigeria, while drought periods in Malaysia are comparatively rare.

The most obvious short-term effect of water stress is to cause stomatal closure. *Rees [1961]* showed that midday closure of oil palm stomata occurred during the dry season in Nigeria, with the degree of closure being greater at higher air temperatures. *Corley [1973b]* found a similar relationship in Malaysia. During a drought, water is removed from the soil by evapotranspiration, lowering the soil water potential. This in turn leads to lower plant and leaf water potentials, and stomatal closure results.

Stomatal closure may also occur as a direct response to low air humidity, without change in leaf water potential. *El-Sharkawy and Cock [1984]* have shown this to be important in cassava. Recent work with maize *(Blackman and Davies [1985[)* shows that stomatal closure may result when half the root system is subject to water stress, even though water supply from the other half was sufficient to prevent change in plant turgor or water potential. Stomatal closure was reversed by application of a cytokinin, suggesting that water stress may affect stomatal aperture by reducing cytokinin supply from the roots.

Stomatal closure limits further water loss, thus minimising plant water stress. However, it also limits uptake of carbon dioxide for photosynthesis, so reducing conversion efficiency. The simplest way of overcoming this problem is by irrigation. Watering of palms in Nigeria had two effects *(Rees [1961]):* first, the stomatal aperture was increased at any given shade temperature; second, the shade temperature was also reduced by watering. Large yield responses to irrigation of oil palms have been obtained in West Africa *(Desmarest [1967], Ochs and Daniel [1976])*. In Malaysia, drought periods are relatively uncommon, and responses to irrigation, though significant, are small *(Corley and Hong [1982])*.

Irrigation of cocoa increased pod number by 39 percent in Malaysia *(Lim et al [1984])*. The rainfall data presented by *Lim et al* suggest that periods of mild water stress were probably quite common under their conditions. Cocoa has a rather weak root system, and is probably more susceptible to water stress than the other crops considered here.

Not all crops respond to irrigation: in Benin, irrigation had much less effect on coconut yield than on oil palm, despite a severe dry season *(Chaillard et al [1983])*. Coconut may be more drought tolerant than oil palm, but the fact that stomatal closure may be caused in different ways could also explain differences in response between crops, and could affect the method of irrigation chosen. Drip irrigation gives good economy of water use, but usually only part of the root system is irrigated, and the effect on atmospheric humidity may be much less than with irrigation by sprinklers. With oil palm, *de Taffin and Daniel [1976]* have shown that drip irrigation may be fairly effective, but it may not be suitable for all crops.

Where irrigation is effective in increasing yields, the yield increase will certainly involve an increase in conversion efficiency, but may only bring the efficiency up to the levels obtained in more favourable environments without irrigation. The highest conversion efficiencies for oil palm were obtained in Malaysia *(Squire [1984])*, where responses to irrigation are small *(Corley and Hong [1982[)*. Coconut showed little response to irrigation, even in a dry climate *(Chaillard et al [1983[). Lim et al [1984]* showed a large yield response to irrigation of cocoa, but even their irrigated yield was not particularly high. The record yields for cocoa *(Chan and Lim [1984])* have been obtained in an environment with negligible water stress *(Phillips and Amstrong [1980])*.

4.5 Temperature

Daytime temperatures in the humid tropics are generally in the range 25 to 35° C. The complete absence of low temperature limitations to plant growth is one of the reasons for the high productivity of tropical crops; in effect, the growing season may be 12 months long, though in areas with a dry season water stress curtails this. As might be expected, tropical crops are adapted to these temperatures. The optimum temperature for photosynthesis for oil palm and cocoa is between 30 and 35° *(Hong and Corley [1976], Guers* *and Mousseau [1979]). Mahon et al [1977]* found an optimum temperature for photosynthesis by cassava of 25° C, but more recent work by *El-Sharkawy et al [1984b]* showed an optimum between 30 and 35° C, provided that leaf-air vapour pressure difference was maintained small, to prevent stomatal closure.

These crops appear to be adapted to tropical ambient temperatures, therefore, but in practice leaf temperatures are often above ambient, and may exceed the optimum for photosynthesis. *Hong and Corley [1976]* found that fully-exposed oil palm leaves might reach temperatures more than 10° C above ambient, even in regularly irrigated nursery plants. *Hutcheon [1977b]* showed that leaf temperatures on cocoa could reach 40° C. *Cock et al [1985]* found leaf temperatures of cassava averaged 3 to 4° C above air temperature, for both well-watered and unirrigated plants.

Where stomatal closure occurs in response to water stress, leaf temperature will inevitably rise, as transpirational cooling will be reduced, but, provided that actual structural damage does not occur, high leaf temperatures under these conditions may not be very critical, since photosynthetic rate will be limited by stomatal closure anyway.

More importantly, the maximum leaf temperatures observed in unstressed plants are often well above the optimum for photosynthesis. The main cause of high leaf temperatures in well-watered plants appears to be that wind speeds are generally low in the tropics. Low wind speeds will lead to large leaf boundary layer resistance, limiting both transpiration rate and convectional cooling of leaves. *Hong and Corley [1976]* showed that a regression on wind speed and incident radiation accounted for 78 percent of the variation in oil palm leaf-air temperature differences.

Unfavourable leaf temperatures may be one of the main factors limiting cocoa productivity. Cocoa is commonly grown under shade, and *Alvim [1977]* showed that photosynthetic rate of fully exposed leaves might be less than that of partially shaded leaves. Where the crop is not well supplied with water, severe leaf scorching may occur. *Hadfield [1968]* showed that one of the main effects of overhead shade in tea was to reduce leaf temperatures, and this could also be true for cocoa. Conversion efficiency for cocoa is probably higher under shade than without shade. If we assume that the shade trees above the cocoa crop described by *Thong and Ng [1980]* intercepted 50 percent of the incident radiation, the conversion efficiency for the cocoa crop would be 1.5 $g.MJ^{-1}$, appreciably higher than that for unshaded cocoa, even though the latter yielded more *(Lim [1980], Chan and Lim [1984]).*

The effect of shade on oil palm conversion efficiency may also be large. By making a number of assumptions, *e* can be estimated from data presented by *Rees [1963]* for nursery palms in Nigeria. For unshaded plants, *e* ranged from 0.9 to 1.2 $g.MJ^{-1}$. For shaded plants, values of over 3.0 $g.MJ^{-1}$ are obtained. These are approximations, but the conversion efficiency under shade is certainly much higher than in any of the trials studied by *Squire [1984]*, and closer to the figures for temperate crops.

It appears possible, therefore, that high leaf temperatures could be a major cause of the low conversion efficiencies of these tropical crops. It may be asked why tolerance to exposure has not evolved naturally in such crops. Cocoa is an understorey species, and wild plants would not normally be exposed to full sunlight. Oil palm and coconut are not thought of as shade species, but in wild stands of these palms most plants are shaded by the oldest and tallest individuals.

If intolerance of exposure to full sunlight is a limitation, we should examine the possibilities of breeding for greater tolerance. Cocoa varieties differ in degree of tolerance of exposure *(Hutcheon [1977b])*. Leaf temperatures will depend to some extend on canopy structure. *Hadfield [1968]* showed that, in tea, plant types with large, horizontal leaves developed higher leaf temperatures than those with small, erect leaves. While *de Wit et al [1979]* calculated that the effect of changes in leaflet angle on total productivity was likely to be very small for most crops, they only considered direct effects of light intensity on photosynthesis. If the effects of total radiation on leaf temperature are also taken into account, changes in canopy structure might be more important. There is little doubt that canopy structure could be changed by breeding. *Squire [1983]* showed differences in extinction coefficient between different oil palm clones, though these were not associated with differences in conversion efficiency. *Williams and Ghazali [1969]* demonstrated variation in canopy structure in cassava.

The conversion efficiency of the cocoa-coconut intercropping system has not been estimated, but, because cocoa performs well under partial shade, *e* may well be high. However, in a discussion of intercropping, *de Wit et al [1979]* stated that most systems depend on mitigation or exploitation of undesirable traits in the component crops. Two points suggest that this may be true of cocoa and coconuts. First, underplanting of coconuts with cocoa is only feasible because, traditionally, coconuts have been planted at densities giving relatively low light interception, but maximum coconut yields are obtained at a leaf area index of 5 to 6 *(Tan and Chan [1984])*, where light penetration below the canopy would be less than 10 percent, and inadequate for cocoa. Second, cocoa yields well under partial shade, but where conditions are optimal the best yields are obtained without shade. In environments where shade is necessary, it is obviously sensible to plant a productive tree such as the coconut, but an objective for cocoa research should be to extend the range of conditions under which unshaded cocoa can be grown.

4.6 Respiration rates

Monteith [1972] suggested that the proportion of assimilate used for respiration would be higher in the tropics than in temperate climates, because respiration increases more rapidly with temperature than does photosynthesis. If this is correct, it would help to explain the low conversion efficiencies of some tropical crops. However, as noted above, tropical crops are adapted to higher ambient temperatures than temperate species; growth of oil palm seedlings stops completely at 15° C *(Henry [1958])*, a temperature at which most temperate species grow well. Shoot extension of tea stops below 12.5° C *(Squire [1979])*. Respiration appears to be similary adapted. *Corley [1983b]* found dark respiration rates for oil palm leaves at 30° C of about 0.5 mg $CO_2.kg^{-1}.s^{-1}$, while *Hong [1979]* found rates rangeing from 0.5 $mg.kg^{-1}.s^{-1}$ at 20° C to 1.2 $mg.kg^{-1}.s^{-1}$ at 40° C. These rates are comparable to those for temperate crops at 10 to 20° C *(e.g. Penning de Vries et al [1979], Wilson [1982]). Ceulemans et al [1984]* found rather higher rates for rubber, though, averaging 2.2 $mg.kg^{-1}.s^{-1}$ at 32° C.

As already noted, respiration provides energy for growth processes, and also for maintenance of existing plant tissue. Most authors are agreed that growth respiration is tightly coupled to synthetic processes, and temperature will have little effect on its efficiency *(Beevers [1970], Penning de Vries et al [1983])*.

Cell maintenance involves resynthesis of degraded proteins and cell membranes. Degradation rates will increase with temperature, but it appears likely that tropical crops will be better adapted to high temperatures, with lower rates of breakdown than temperate crops at the same temperatures.

Perennial crops have a higher proportion of non-photosynthetic tissues to total dry weight than most annual crops. This might be expected to result in a higher ratio of maintenance respiration to photosynthetic production. *Rees and Tinker [1963]* pointed out that respiration by the large proportion of non-photosynthetic, but living, tissue in an oil palm would reduce even a high rate of photosynthesis to a low net dry matter production. The oil palm trunk contains much living parenchymatous tissue, and its mass increases steadily with palm age. However, *Squire [1984]* found that conversion efficiency did not decrease systematically with palm age. *Breure* (in preparation) has estimated maintenance respiration from gross photosynthetic production predicted by a canopy model, calculated respiratory requirements for growth, and actual total dry matter production. He found no significant trend in maintenance requirement with palm age, in agreement with *Squire's* conclusion. The biomass in the leaf canopy does not change appreciably with age after 7-9 years from field planting, so it appears that maintenance requirement for trunk tissues may be very small in relation to that for the leaf canopy. *Breure's* estimate of maintenance requirement is in agreement with an earlier estimate by *Corley [1976a]* that some 75 percent of gross photosynthetic production might be respired. The only way to reduce this would be by selection for lower respiration rates, as has been done in ryegrass *(Wilson [1982], Wilson and Jones [1982])*.

4.7 Leaf longevity

Many tropical perennials maintain a complete leaf canopy throughout the year, giving high light interception, but to ensure a constant high conversion efficiency, the leaves must either remain photosynthetically active for a long time, or be regularly replaced by new leaves. A crop which adopts the latter strategy will probably yield less, since if the leaf canopy has to be regularly replaced, this must be at the expense of partition of assimilates into economic product.

Oil palm leaves remain photosynthetically effective for at least 21 months *(Corley [1983b])*; in contrast, while rubber leaves remain on the tree for nearly 12 months, photosynthetic rate may decline quite quickly after leaf emergence *(Samsuddin and Impens [1979])*. Unshaded cassava leaves may remain active for 100 days, but normally the activity of leaves at the base of the canopy declines sooner than this, due to shading *(Cock et al [1979], Cock [1983])*. With some crops, therefore, decline in photosynthetic activity with leaf age may partly explain the low conversion efficiency.

5. Partition of assimilates

Major improvements in yields of some crops have resulted from changes in harvest index. For example, *Austin et al [1980]* showed that harvest index of wheat varieties had increased from 34 percent to 50 percent over a 70-year period, giving a yield increase of over 50 percent (much of this improvement probably resulted from selection for yield, rather than directly for harvest index). The best harvest indices for some of the crops reviewed here are comparable to those of annual crops (Table 4), but others might be improved. There is considerable variation in harvest index *(Templeton [1969], Corley et al [1971], Kawano [1978])*, and obvious scope for further improvement by selection.

Table 4. Best harvest indices recorded or estimated (from *Corley [1983a]*)

Crop	Harvest index (percent) of total dry matter	 of total energy fixed
Oil palm	61	73
Coconut	62	69
Rubber	37	54
Cocoa	30	36
Cassava	70	70

It is not always clear to what extent harvest index has been improved historically by breeders. *Hardon et al [1982]* showed that yield of the Deli *dura* oil palm variety had improved by some 65 percent over five generations of breeding (about 50 years), but harvest index was not measured in the trial they described. Harvest index in oil palm has two distinct components, the proportion of total dry matter in fruit bunches, and the proportion of oil in the fruit. The latter component has certainly been increased by breeding. In particular, the change from planting of the thick-shelled *dura* to the thin-shelled *tenera* fruit type *(Beirnaert and Vanderweyen [1941])* increased the oil content of the fruit, and hence the harvest index, by about 30 percent. *Squire [1984]* presents some data indicating that breeding may have improved harvest index and the ratio of leaf area to dry weight, but not conversion efficiency, of the *tenera* type.

Partition of assimilates between leaves and non-photosynthetic organs is also important. *Breure* (personal communication) has shown that selection of parent palms for high leaf area ratio (the ratio of leaf area to vegetative dry matter) is an effective method of improving progeny yield.

5.1 Planting density and partition

As a useful generalisation, crops have been divided into two groups, described as determinate and indeterminate *(e.g. de Wit et al [1979], Cock [1983])*. Determinate types are those in which the apical meristem becomes floral, so that growth is terminated by flowering and fruiting. Indeterminate types produce their fruits from axillary meristems, while vegetative growth of the apex continues. Most tree crops are indeterminate (the sago palm is an exception).

Determinate species are often insensitive to plant density. Maximum harvest index and yield may be obtained over a broad range of densities above that giving maximum light interception. In most indeterminate species, on the other hand, there is a strong tendency for growth of the vegetative meristems to take priority over reproductive growth when assimilate supply is limited. This has been demonstrated clearly for oil palm *(Corley [1973a], Squire [1984])* and cassava *(Cock [1983])*, and is probably also true for coconut *(Corley [1983a])*.

In indeterminate crops, harvest index declines at high densities, and the density giving maximum yield is usually below that giving complete light interception. In a study of oil palm fertiliser trials, *Squire [1984]* found that yield was positively correlated with *f* overall, but in the highest yielding plots yield decreased as *f* increased. Maximal dry matter production was achieved at maximal *f*, but harvest index started to decrease when *f* exceeded about 0.6, and maximal yield was obtained at $f = 0.85$. *Cock [1983]* showed that harvest index of cassava started to decline above a leaf area index of 2; tuber yield was maximal at leaf area indices of 2.5 to 3, but total dry matter production increased with L up to about $L = 4$.

There is, therefore, scope for an increase in total dry matter production from these crops by increasing light interception, but this would not be translated into increased yield with existing plant types. To improve total light interception by an oil palm canopy, an increase in leaf area index is needed, but because of the logarithmic relation between L and f, a large increase in L gives only a small change in f. For example, L must be increased by 28 percent, from 5.2 to 6.7, to increase f from 0.9 to 0.95. Because the leaf area/weight ratio does not change with density, an increase in leaf area requires a proportionate increase in total leaf weight, but dry matter production only increases in proportion to f. Therefore, the excess dry matter available for bunch production is reduced, and harvest index declines. *Squire [1984]* points out that to obtain high harvest index at maximal light interception, the constancy of the leaf area/weight ratio must be broken. *Corley [1976b]* has shown genetic variation for oil palm in the relationship between partition ratios and stress, with leaf area ratio increasing and vegetative dry matter production decreasing quite markedly under stress in some families. Such material might be suited to high density planting.

So long as leaf area ratio does not change with density, the optimal density for yield will always be below that giving complete light interception, but the optimum would approach towards maximal f if leaf area ratio and harvest index were increased by selection. While an increase in harvest index is a worthwhile objective *per se*, therefore, it has the added benefit of giving material which yields well at densities closer to those giving maximum light interception *(Breure and Corley [1983])*.

6. Effect of fertilizers

Large yield increases in response to fertilizers have been observed for all these crops on at least some soils, and it is therefore of interest to determine which physiological components are most affected.

Squire [1983] has made a detailed study of over 20 oil palm fertilizer trials in Malaysia. In most trials he considered only two treatments: the control treatment, which usually received no fertilizers, and that treatment combination giving the greatest yield. Most experiments involved factorial combinations of nitrogen, phosphate, potassium and magnesium treatments, but *Squire* made no attempt to distinguish effects of different elements.

Fractional interception, conversion efficiency and partition ratio were all correlated with yield, but much the greatest fertiliser response was in conversion efficiency. In 12 trials on poor inland soils, e was increased by an average of 29 percent, while on the richer coastal alluvial soils, the average increase was 13 percent.

The partition ratio (p, the ratio of fruit bunch dry weight to total dry matter production) was increased by 13 percent on inland soils and 6 percent on coastal soils. Mean leaf area was increased by 17 percent on inland soils, but because of the logarithmic relationship between leaf area index and light interception, this only gave a 5 percent increase in f. On coastal soils, an 8 percent increase in leaf area gave a 2 percent increase in *f*. The net result of all these effects was a 39 percent increase in fruit bunch yield on inland soils, and a 17 percent increase on coastal soils.

Corley and Mok [1972] studied the effects of individual nutrients in two fertilizer trials in Malaysia. A reanalysis of their data in the terms used here shows an increase in *f* of about 4 percent in response to both N and K, and a smaller response to P. Conversion efficiency increased by 26 percent in response to N in one trial, and by 16 percent in the other. The response to K was about 12 percent in both trials, and P also gave a small increase in *e*. Detailed results from one trial (Table 5) show little response to N or K in the absence of the other element, but together they increased *f* by 7 percent, e by 29 percent, and total dry matter production by 38 percent. As partition ratio was unchanged, yield of fruit also increased by 38 percent. The lack of effect of fertilizers on *p* in these two trials may be unusual; in a majority of the 22 trials studied by *Squire*, partition ratio was increased by fertilizers.

Table 5. Response of oil palm to nitrogen and potassium fertiliser (from data of *Corley and Mok [1972]*).

Fertiliser Levels N	K	Light interception f (%)	Conversion efficiency* e ($g.MJ^{-1}$)	Dry matter production* ($t.ha^{-1}.y^{-1}$)	Partition ratio p (%)
0	0	88.5	0.99	27.6	44.6
	1	87.8	0.92	25.6	43.7
	2	89.6	0.94	26.5	42.6
1	0	89.6	0.99	28.0	41.4
	1	93.2	1.25	36.6	44.8
	2	93.0	1.26	37.0	44.5
2	0	91.4	1.10	31.6	42.6
	1	94.1	1.25	37.1	44.4
	2	94.6	1.28	38.1	44.5

* Adjusted to allow for the high energy content of oil.

In the coconut thinning trial of Figure 1, a number of nitrogen and potassium fertilizer levels were also tested. Comparing the zero fertilizer plots and those receiving the highest levels of N and K, average light interception was increased by 6 percent, while conversion efficiency was increased by nearly 14 percent. Leaf area/weight ratio also increased by 4 percent, and harvest index increased by 15 percent. The product of these changes was a 40 percent increase in yield of copra.

If the planting density is such that light interception is high even in unfertilised plots, fertiliser application, by increasing vegetative dry matter requirements, may decrease *p* so that no increase in yield occurs. This is illustrated in Table 6, calculated from data of *Breure [1977]*. At 148 oil palms/ha, fertiliser increases *L*, *f* and *e*. Although *p* decreases, yield is increased by 6 percent. At 186 palms/ha the general pattern of response is the same, but the increase in *e* is slightly less, the decrease in *p* is greater, and there is no change in yield.

At 110 palms/ha there was a 27 percent increase in dry matter production, entirely due to an increase in *e*. In unfertilised plots, *e* was very much lower at 110/ha than at the higher densities; the reason for this is not clear.

Table 6. Response of oil palm to fertilisers at different planting densities (from data of *Breure [1977]*).

Palms per hectare:	110	148	186
		Fertiliser response* (%)	
Vegetative dry matter	+ 8.0	+ 12.1	+ 10.3
Leaf area ratio, L	− 7.3	− 6.0	− 4.6
Leaf area index	+ 0.3	+ 5.2	+ 5.2
Light interception, f	+ 0.1	+ 1.3	+ 0.8
Conversion efficiency, e	+ 27.2	+ 6.8	+ 4.0
Dry matter production	+ 27.2	+ 8.3	+ 4.2
Partition ratio, p	+ 12.3	− 1.9	− 4.2
Yield of fruit	+ 40.2	+ 6.2	− 0.2

* Based on comparison of fertiliser level 0 and level 2.

Conclusions

The yields obtained from these tropical perennial crops are already high, but there is little doubt that appreciable further yield increases can be achieved in future. In other crops, yield increases have been achieved by improvements in all three factors, light interception, conversion efficiency and harvest index.

Light interception can be improved in annual crops by changing planting dates and planting densities to achieve early ground cover. There are possibilities for increasing total interception over the life of a perenntial crop by the same approach, but increasing interception in the mature crop is more difficult. For determinate crops the density giving maximal f also gives maximal yield, but with these indeterminate crops, this is not usually true. Possibilities do exist for improving assimilate partitioning at high densities, though. Conversion efficiency of annual crops has been increased by eliminating stress, so that the potential efficiency is achieved, but there has been very little success in increasing the potential conversion efficiency (with the possible exception of the work on respiration rates in ryegrass quoted above). In the perennial crops discussed here, minimising stress by irrigation or fertilizer application increases conversion efficiency, as with annual crops. Careful management of shade is also important in maximising yield for some crops. However, there appear to be real possibilities of increasing the potential efficiency, by breeding for greater tolerance of exposure to full sunlight, and for reduced maintenance respiration. Both *Rees [1962]* and *Squire [1984]* concluded that improving e offered the greatest scope for increasing oil palm yields, and this appears to be true for other tropical perennial crops. Harvest index has been improved by breeding in annual crops, and there is little doubt that improvements can also be achieved in tropical perennials. In addition, harvest index of indeterminate crops depends partly on conversion efficiency, and is therefore affected by the same management factors.

Acknowledgements

I am grateful to *Unilever PLC* for permission to publish. The data for Figure 1 was provided by *Lever Solomons Ltd.*

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Nutrient Requirements for Exploiting Yield Potentials of Major Plantation Tree Crops in the Tropics

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Summary

Genetic yield potentials of oil palm, cocoa, coconut, and rubber have been enhanced through systematic plant breeding but commercial plantation yields todate show an appreciable gap between potential and realised yields. As the majority of soils planted to these crops are nutrient poor, a high plane of nutrition, dynamically linked to a *Productivity Plan* has been shown to generate high early yields which are close to real potentials.
The benefits of the *Steep Ascent Plan* are highly attractive from the economics of investment, while reduction of the stand at maturity should be able to sustain yields at moderately high levels and extend the economic life span, at least for oil palm and possibly for cocoa.
There is thus considerable scope in fuller exploitation of yield potentials of the crops concerned by tailoring fertiliser usage to dynamic plant growth and productivity, especially during the immature and early maturity phases.

1. Introduction

The advent and ensuing success of the superior rice varieties and the so-called *Green Revolution* in Asia over the past two decades has been widely publicised and acclaimed. In contrast, however, parallel advances in breeding of major tropical tree crops have been less well orchestrated, though collectively, they are no less significant in economic terms. The crops concerned are rubber *(Hevea braziliensis),* oil palm *(Elaeis guineensis),* cocoa *(Theobroma cacao)* and coconut *(Cocos nucifera).* These crops are economically important to many tropical countries, particularly in South East Asia, West Africa and Brazil, where high productivity is essential for sustained commercial cultivation.

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2. Yield progress via plant breeding

Through long term scientific breeding programmes including hybridisation and cloning, superior cultivars and clones with enhanced yield potentials have been engendered and become available for commercial production from about the early Sixties. The gains in potential yields as indicated in field trials for the four crops are substantial and range from 50-100% as shown in Table 1.

Table 1. Yield gains through plant breeding

Crop	Product		Older Cultivars	Modern Cultivars
Oil Palm	Oil	(t/ha/yr)	3.7-4.20	4.8-7.5 (a)
	FFB*	(" ")	20-25	24-35
Cocoa	Beans	(kg/ha/yr)	800-1200	1700-2700 (b)
Rubber	Dry Rubber	(" ")	1300-1800	2500-3000 (c)
Coconut	Copra	(t/ha/yr)	3.5-3.0	5.0-6.2 (d)

a) Soh, A.C. [1984] *c) Ani et al [1983]*
b) Chee, Y.F. [1972] *d) Gascon and de Nucé [1979]*

* FFB = Fresh Fruit Bunches

The figures quoted mainly refer to trial plots established over more representative soil conditions under plantation management.

It is evident that not all the gains in potential yields are attributed to breeding alone, as sound agronomic practices are also essential to make the most of such potentials. Among the cultural techniques available, in the context of generally low nutrient status soils in the tropics, optimal fertiliser usage is adjudged to be the key factor in achieving high productivity.

3. Nutrient supply — the key to high productivity of tropical soils

Leaving aside the climatic factor, which is outside the scope of management in most situations at present, both fertiliser trials and commercial plantation experience have amply demonstrated that nutrition and fertiliser usage constitute the key ingredient to achieving high yields. This is principally because the vast majority of soils planted to these crops fall into the kaolinitic and nutrient poor Groups of Ultisols, Oxisols and Inceptisols. Thus, in Malaysia, nutrient inputs per hectare for oil palm and rubber have increased over the 1980-1985 period *(ESCAP [1984])* with expanding use of better cultivars.

It is therefore not surprising that fertiliser inputs form the largest item of cost of production of these crops. Consequently, considerable research has gone into determining precise nutrient requirements and towards this objective, primary data on nutrient uptake for vegetative and crop biomass production have been studied for oil palm *(Ng and Thamboo [1967], Ng et al [1968],* cocoa *(Thong and Ng [1978],)* coconut *(Ouvrier and Ochs [1978], Teoh et al [1984])* and rubber *(Shorrocks [1965], Lim [1978]).* Their findings are presented in Table 2.

Table 2. Nutrient uptake values for oil palm, rubber, cocoa and coconut (MAWA) at productive stage (kg/ha/yr)

Crop		N	P	K	Ca	Mg	Cl	B	Cu	Zn
Oil Palm	a)	192	26.0	251	89.3	61.3	—	—	—	—
	b)	73.2	11.6	93.4	19.5	20.8	—	0.054	0.119	0.123
Cocoa	a)	198	197	260	90.2	37.0	—	—	—	0.540
	b)	69.7	10.9	121	10.9	11.7	—	—	—	0.195
Coconut (MAWA)	a)	125	19.8	234	29.3	40.8	—	—	—	—
	b)	47.0	8.6	106	4.3	8.8	75	—	—	—
Rubber	a)	184	23.7	148	172	31.1	—	—	—	—
	b)	23.9	7.2	22.3	—	4.1	—	—	—	—

a) Gross Uptake

b) Removed with Crop

The data show that for all crops, gross potassium and nitrogen uptakes are the largest and phosphorus the least.
In terms of cropping, oil palm, cocoa, and coconut remove considerably more potassium and nitrogen than rubber.

4. Importance of high early yields

It is pertinent to appreciate that the tree crops discussed have various gestation or immaturity periods from 2-6 years, which are inversely related to returns of investment. Hence, from the economic standpoint, the fertiliser strategy formulated for a specific soil and environment must attempt to achieve:

a) shortest immaturity period, and
b) maximum early yields during the first 4-5 years of cropping.

Unfortunately, fertiliser trials that commenced from the immature period of tree crops have been rare; consequently early yield levels reported may not reflect true potentials of productivity. However, work initiated in the Sixties by oil palm researchers in Malaysia showed that high early yields could be obtained from the inception of harvesting *(Ng [1970], Hew et al [1973])*. On the basis of these results, a productivity plan over the economic life of tree crops was conceived.

5. The productivity plan

The basic principle of the plan *(Ng [1983])* is to sustain high productivity throughout the economic life span of the crop cultivated. The model comprises three phases, *viz.* a) the *Steep Ascent Plan (SAP)* covering the first period up to about 9 years of planting, b) the *Plateau Yield Plan (PYP)* spreading over the adult period from 10-18 years, and c) the

(Declining Yield Plan (DYP) from 19 to 25 years of planting. For optimum yields, a very high plane of nutrition is provided during SAP and PYP periods, based on all available data and information for the soils and environment in question.

In order to avoid any complicating effects of luxuriant nutrient uptake and imbalances, only soils of low fertility were chosen for evaluation of the Plan, so that most of the nutrients required for the projected high yields would be derived from fertilisers applied. Nutrient inputs cover the macronutrients but in the case of oil palm, boron as well as copper on peat are provided as they have been shown to be critical *(Rajaratnam [1973], Cheong and Ng [1977])*. One striking feature of the approach is to provide for high rates of nutrient inputs from the inception of planting, tailored to the growth pathway of the crop.

Implementation of this approach commenced from the mid-Seventies on a commercial plantation scale and results todate are presented in the ensuing.

6. **Results** (see also: Appendix)

6.1 Oil Palm

Soils of Class III-IV grade falling into Sub-Groups of Tropopsamment, Paleaquult, and Tropofibrist were studied and each commercial planting was 300-800 ha in extent. A Tropaquept Class I soil was used as a marker. A standard density of 148 palms/ha was adopted.

6.1.1 SAP phase

For the SAP period, mean yields for the first 5-8 years of harvesting are presented in Figures 1 and 2, while yield ranges from the larger plantings are given in Table 3.

In Figure 1, it can be seen that with the Tropaquult soils, steeply rising yields were achieved and reached a peak at 7th-8th year of planting. Thereafter, the levels tended to show a slight declining trend. What is of greater significance though is that the poorer soils have been able to manifest comparable yield potentials as the Class I marker soil, which is considerably richer in nutrients. This has been achieved entirely by optimal fertiliser programming from the onset of field planting and indicates the vast scope in enhancing the productivity of low nutrient status soils like those evaluated.

Be that as it may, the higher yield values achieved by some of the fields indicate that mean yields could still be raised by another 15-20% but other limitations may be operative.

In Figure 2, results for the poorer Class IV soils of sandy alluvium and peat of 2-3 m in depth are presented. It is striking that for the first 4 years of cropping, the Tropopsamment performed as well as the good marker soil, while a less impressive start was made on peat. However, thereafter, the peat soil seemed to have held its own against the marker soil and superseded the sandy soil. Overall, the shape of the curve for SAP and high yield potentials have been accomplished.

The upper yield levels obtained with these soils are slightly below those achieved with the Tropaquults, which are likely related to differences in soil physical properties. Thus, on these soils, the full yield potentials of oil palms may not be realisable until other limitations of a non-nutritional nature are corrected. Nevertheless, as a whole, the findings show that up to now, intensive fertiliser usage has provided the key to near-maximum exploitation of yield potentials. Estimates of oil yield based on extraction rates returned by the mill show that the maximum levels reached at 6th-7th year of planting are within 10-15% of potentials shown in breeding trials (Table 4).

Annual leaf analysis was practised to monitor nutrient levels and the ranges of nutrient values for the various soils are shown in Table 5. In all the soils evaluated, boron was found to be critical while for the Histosol, copper was equally crucial during the early years of development.

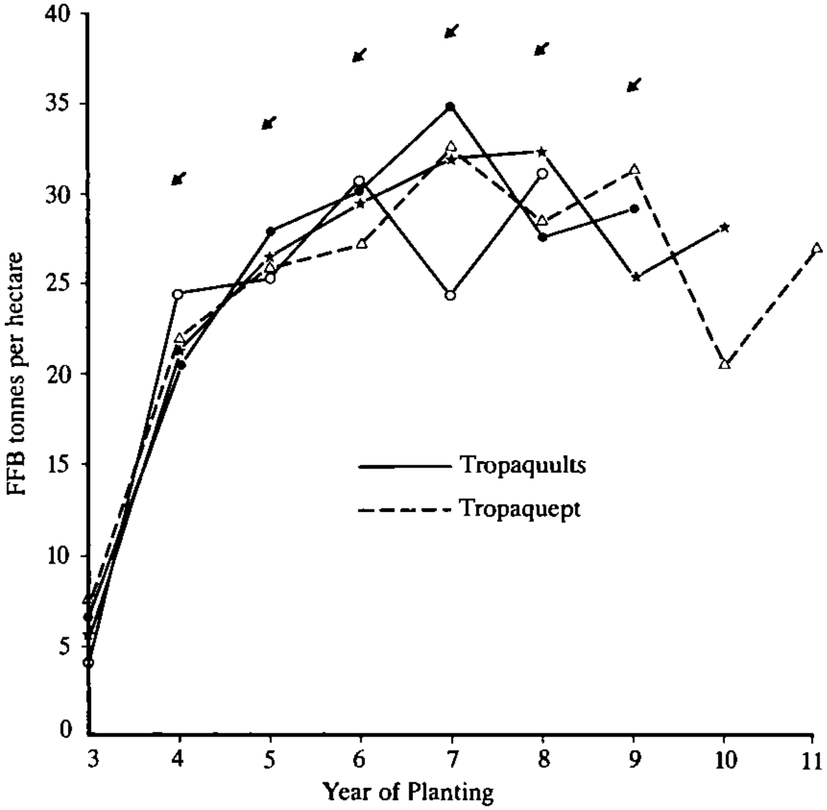

Fig. 1 Mean SAP yields for oil palms on Class III Tropaquults

Table 3. Yield performance of oil palm on class III terrace alluvium (Tropaquults)

Year of Planting	t/ha/yr FFB		
	769 ha (1976)	796 ha (1974)	370 ha (1975)
3rd	3.86- 4.35	4.68-6.30	5.72-7.36
4th	21.76-30.73	16.80-26.28	20.18-21.12
5th	25.47-33.42	19.54-31.20	21.07-30.56
6th	28.60-37.54	22.05-33.12	22.77-34.41
7th	21.04-34.99	28.43-34.85	31.00-38.82
8th	28.68-32.75	28.48-37.89	22.28-29.62
9th	—	19.78-28.31	25.12-35.74
10th	—	22.75-34.33	

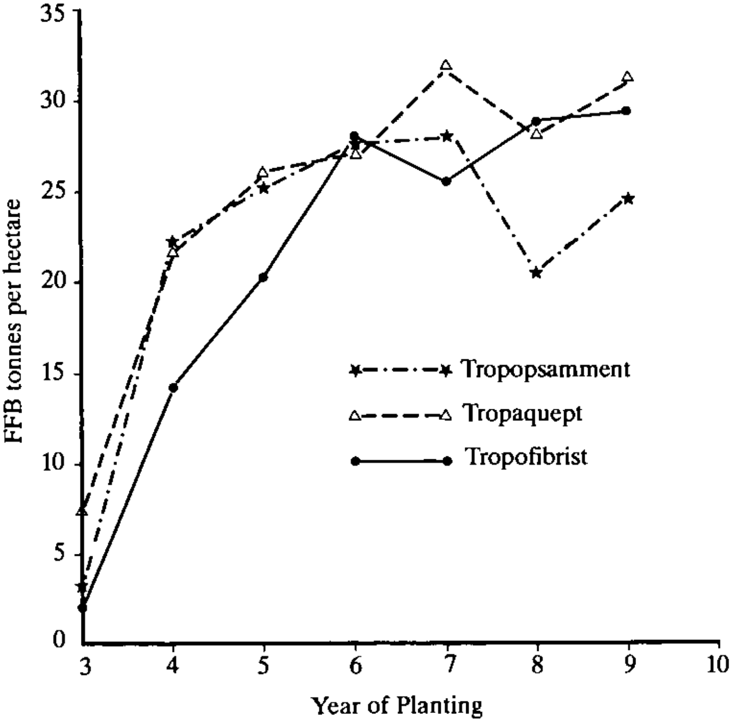

Fig. 2 Mean SAP yields for oil palms on class IV soils

Table 4. Estimated oil yields (t/ha/yr)

Year of Planting	(1)	(2)	(3)	(4)	(5)
4th	3.57	4.16	3.29	3.73	3.72
5th	4.71	4.54	4.73	4.52	4.68
6th	5.56	5.82	5.39	5.27	4.53
7th	6.34	4.98	6.94	5.58	6.42
8th	6.44	6.21	5.44	4.10	5.65
9th	5.03	—	5.75	4.95	6.24
10th	5.58	—	—	—	4.11
11th	—	—	—	—	5.38

(1) — (3) Tropaquult (4) Tropopsamment (5) Tropaquept (marker)

Table 5. Leaf nutrient ranges in frond 17 during the SAP period

	Soils			
Nutrient	Tropaquult	Quartzipsamment	Histosol	Tropaquept
% N	2. 64-3. 11	2. 61-2. 91	2. 47-2. 95	2. 75-2. 94
% P	0.165-0.186	0.152-0.182	0.157-0.180	0.150-0.162
% K	0. 84-1. 21	1. 02-1. 23	0. 91-1. 13	0. 88-1. 14
% Mg	0.204-0.280	0.200-0.280	0.215-0.300	0.230-0.280
% Ca	0.670-0.910	0.637-0.854	0.477-0.674	0.411-0.494
ppm B	10- 22	16- 27	12- 18	13- 17
ppm Cu	—	—	4.7-6.6	—

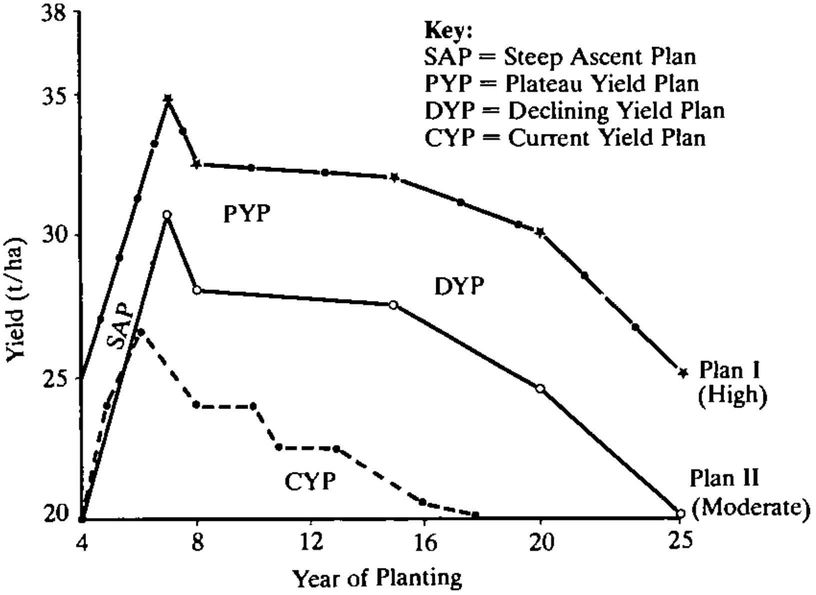

Fig. 3 Yield scenario for future oil palm planting

6.1.2 PYP phase

As indicated in Figure 3, at an average palm density of 138-148/ha, yield levels would tend to decline after the 8th-9th year of planting, and as a matter of fact, this is commonly experienced as shown by the graph *CYP (Current Yield Plan)* in Figure 3.

There are a number of causes for the decline but in our view, the major factor is severe interpalm competition resulting in a reduction of Bunch Index or proportion of total assimilates going into crop yield. In such a scenario, it is evident that maintenance of the high plane of fertilisation practised in the SAP period is less profitable during the adult PYP phase.

Reducing fertiliser inputs has been widely practised in such a situation but *Ng [1981]* advocated an alternative approach of maintaining a strong plane of nutrition coupled to reduction of palm stand. The responses to systematic thinning on a commercial scale with 8-12 year old palms on flat and undulating land are depicted in Figure 4.

The effects are quite clear cut and the order of response to stand reduction is significantly large, except perhaps for the 1965 planting. It is noteworthy that the average 14-15% stand reduction has been able to restore yields to levels which makes sustained fertilisation usage much more economic.

These results are in consonance with similar findings in Papua New Guinea *(Breure [1982])*, and have afforded the basis for formulating the *Plateau Yield Plan,* which is designed to arrest the sharp yield decline after the peak reached during the SAP phase. In this regard, the outstanding performance of the 1964 planting for the 18th-20th year of planting at a stand of 115/ha is most interesting in terms of longer economic exploitation of the oil palm.

6.2 Cocoa

There is appreciably less data concerning the yield potentials of cocoa at the commercial level. However, our two case studies involving a high level of fertiliser usage indicate that there is considerable scope in exploiting more fully the genetic yield potentials of existing F_1 hybrid materials (Table 6).

Table 6. Yield performance of hybrid cocoa under high fertiliser regimes

Age	(1) Tropaquult (10.6)	(2) Tropaquept (14.5)	(3) Paleudult (9.8)
2	309	367	—
3	1828	784	750
4	2230	749	1066
5	2229	1178	929
6	1847	1158	870
7	1302	1750	1152
8	2100 ✱	1483	1254
9	—	1028	1710
10	—	1014	1740
11	—	731	—

(1) Mono-Cocoa Planted 1977 (988 trees/ha) ✱ Projected.
(2) Cocoa/Coconut Planted 1973 (864 trees/ha)
(3) Mono-Cocoa Planted 1974 (1074 trees/ha)

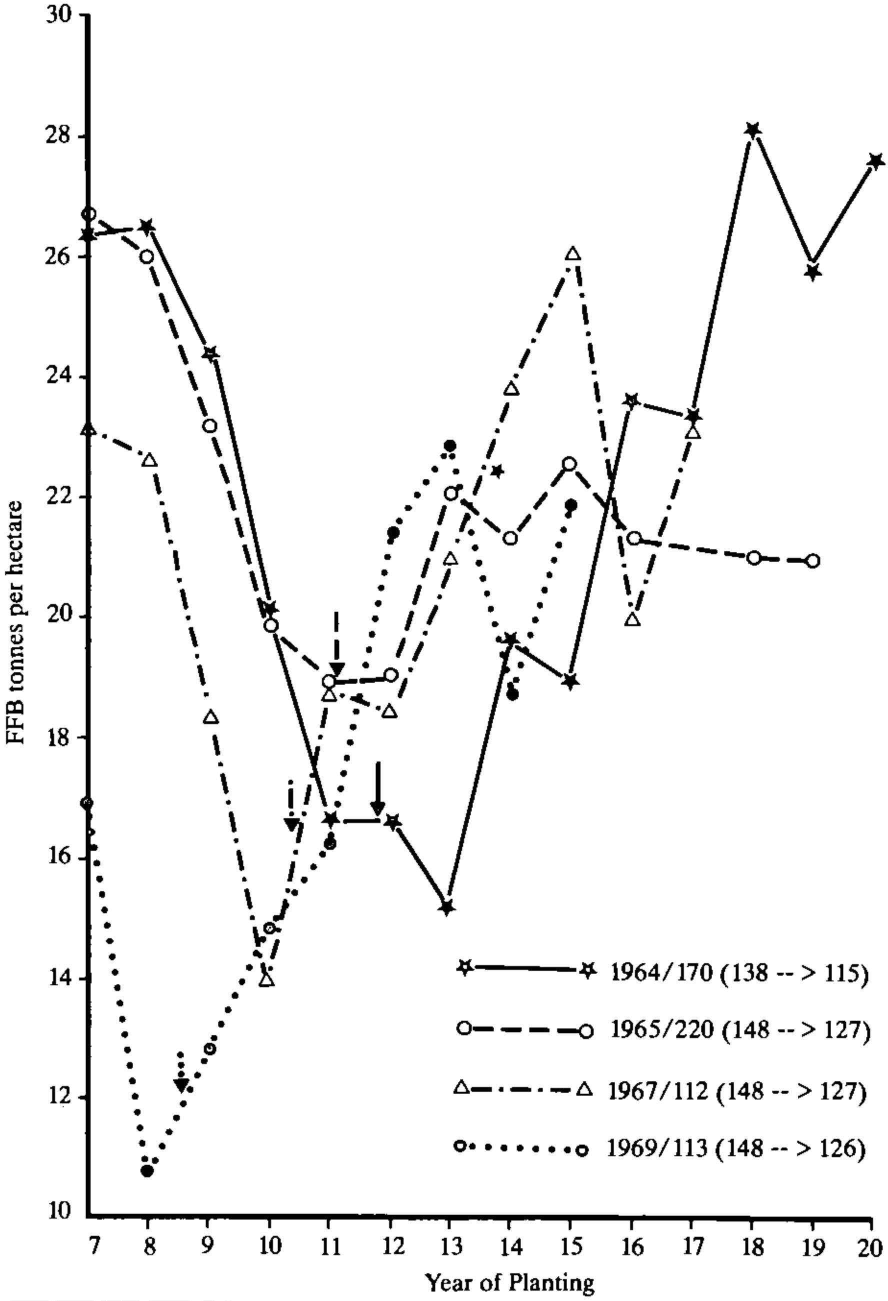

Fig. 4 Effects on density reduction at 9-12 years planting

Results for the poorest Tropaquult soil show that the goals of SAP can be fulfilled by providing adequate nutrients and eliminating water stress as this plot was irrigated by gravity feed from a nearby river. Over 2 tonnes/ha of cocoa beans were achieved by the 4th year of planting under the system. This yield potential is also indicated by the cocoa intercropped with coconut at a lower density though the SAP profile was not prominent, due mainly to rainfall variations. There was also evidence of yield decline after the 7th-8th year of planting.

With the Paleudult, the yield potential was not manifested till later at the 10th-11th year, largely a consequence of vagaries of rainfall in the intervening years after the promising start. Clearly, the importance of water availability must complement that of nutrient inputs for cocoa in order to attain maximum yields.

Leaf nutrient composition data monitored for cocoa planted on the Tropaquult soils show that the levels are generally higher than limits published in literature (Table 7). Thus, for high performing trees, there may be a need to re-assess the so-called critical limits, at least for the South East Asian region.

Data for the PYP phase would be forthcoming from the model block over the next few years but suffice it to say that a declining trend may be setting in.

Table 7. Leaf (No. 4) nutrient levels of cocoa on Tropaquult

Year	Age (Year)	% DM					ppm		
		N	P	K	Ca	Mg	Zn	Mn	B
1981	3-4	2.44	.185	1.81	1.14	.494	40	1057	28
1982	4-5	2.30	.189	1.77	.965	.432	41	706	44
1983	5-6	2.34	.175	1.99	.946	.440	37	763	43
1984	6-7	2.30	.183	2.11	1.01	.433	36	558	40
1985	7-8	2.28	.186	2.16	1.48	.412	23	930	41

6.3 Hybrid coconut (MAWA)

Only very limited data on the yield performance of the Malayan Dwarf x West African Tall hybrid (MAWA) in the South East Asian context is available. Information available shows that even on good members of Tropaquepts, the hybrid in Malaysia has fallen somewhat short of the potentials reported in the Ivory Coast *(Gascon and de Nucé [1978])*, as shown in Table 8. Apparently, this has also been found in the Philippines *(von Uexkull*, pers. comm.). It is not likely that the peak of over 6 t/ha of copra reported for the Quartzipsamments of the Ivory Coast would be realised in Malaysia or the Philippines.

Various factors are responsible for this but lower copra content per nut; 180-190 g/nut as against 210-220 g/nut in the Ivory Coast may be a principal cause. However, the importance of chlorine *(von Uexkull [1972])* should not be overlooked.

In the light of these findings, cultivation of hybrid coconut alone is unlikely to be economically attractive, but it is best used as a secondary crop in a cocoa-coconut system *(Lim and Chan [1976])*.

Table 8. Early yield performance of MAWA hybrid in (a) Malaysia and (b) Ivory Coast

Year in planting	Copra (t/ha/yr)	
	(a)	(b)
4	0.48	0.22
5	2.18	2.03
6	2.86	3.52
7	4.12	4.00
8	4.36	4.02
9	4.21	5.42
10	4.63	5.61

(a) Tropaquept, Malaysia
(b) Quartzipsamment, Ivory Coast

6.4 Rubber

Unlike the other crops discussed, rubber was not evaluated on the soils in question as they are considered less suitable for *Hevea* cultivation. Thus, published data of the *Rubber Research Institute of Malaysia* on clonal trials are utilised and the yield performance of two new clones is presented in Table 9. The higher yield potentials seem to be corroborated by early results of some commercial plantings.

It needs to be clarified that the higher yield potentials have not been achieved by raising the nutrient stakes significantly, as gross nutrient requirements of the better clones are not likely to be appreciably higher than older clones such as RRIM 600. Only slight adjustments for higher nutrients drainage need to be provided for.

Table 9. Mean yields of recommended clones (RRIM 1982) (kg/ha/yr)

Year of Tapping	(a)		(b)	
	GTi	600	PB235	PB260
1	700	720	1370	1180
2	1180	1210	1870	1820
3	1410	1600	2280	2220
4	1640	1860	2300	2200
5	1570	2310	2000	1960
Av.	1300	1540	1964	1880
6	1960	2320	2060	2370
7	2280	2350	3230	2760
8	2340	2470	2530	n.a.
9	2310	2700	2280	n.a.
10	1180	2360	n.a.	n.a.

n.a. = not available

7. Nutrient requirements for exploitation of yield potentials

(Tables 10-13)

The specific fertiliser requirements of a crop planted on a particular soil type and rainfall regime are dependent on yield potential and the nutrient balance as described by *Ng [1977]*. Even on a specific soil taxonomic entity, nutrient demands can vary dependent on cultural practices or clonal characters in the case of hevea. Thus, it is not feasible to give location-specific answers for all situations encountered in the field. What is attempted is to provide the nutrient ranges considered essential for achieving yield potentials for the common major soil Taxonomic Sub-Groups. These are presented in Table 10 to 13 for oil palm, cocoa, coconut (MAWA) and rubber respectively.

Table 10. Nutrient inputs for achieving yield potentials in oil palm (kg/palm/yr)

N	P	K	Mg	B_20_3	$CuSO_4$	Soil
1.15-1.40	0.32-0.37	2.25-2.75	0.16-0.22	0.10-0.12	Nil	Typic Tropopsamment
1.20-1.50	0.22-0.27	1.50-1.80	0.10-0.13	0.08-0.10	Nil	Oxic Paleaquult
1.00-1.25	0.25-0.30	2.00-2.50	0.12-0.15	0.05-0.07	Nil	Typic Paleudult
0.45-0.60	0.00-0.15	0.80-1.00	0.0	0.03-0.05	Nil	Aeric Tropaquept
0.30-0.45	0.00-0.15	3.00-3.60	0.0	0.12-0.14	0.001 (F)	Typic Tropofibrist

Table 11. Nutrient inputs for attaining yield potentials of cocoa (kg/tree/yr)

N	P	K	Ca	Mg	Soil
0.13-0.16	0.05-0.065	0.09-0.11	0.20-.025	0.010-0.012	Oxic Paleaquult
0.11-0.135	0.07-0.09	0.11-0.135	0.25-0.30	0.015-0.020	Typic Paleudult
0.10-0.13	0.08-0.10	0.09-0.11	0.25-0.30	0.012-0.015	Tropeptic Haplorthox
0.08-0.10	0.00-0.02	0.05-0.06	0.30-0.40	0.0	Aeric Tropaquept

Table 12. Nutrient inputs for attaining yield potentials of Hybrid (MAWA) coconut (kg/palm/yr)

N	P	K	Cl	Mg	Soil
0.45-0.60	0.00-0.15	0.60-0.75	0.40-0.52	—	Typic Tropaquept
0.50-0.65	0.17-0.24	1.00-1.25	0.70-0.85	0.08-0.12	Typic Paleudult
0.60-0.72	0.20-0.25	1.50-1.80	1.05-1.25	0.10-0.12	Typic Quartzipsamment

Table 13. Nutrient inputs for achieving yield potentials of rubber (kg/tree/yr)

N	P	K	Mg	Soil
0.12-0.15	0.00-0.02	0.30-0.36	0.015-0.020	Typic Tropopsamment
0.10-0.12	0.00-0.02	0.20-0.25	0.010-0.015	Typic Paleudult
0.11-0.13	0.02-0.03	0.17-0.21	0.010-0.012	Typic Haplorthox

8. Economic impact

Using oil palm as an example, it has been shown that raising productivity during the first 10 years of planting can prove very worthwhile in economic parameters (Table 14).

Table 14. Impact of raising productivity of oil palm during SAP phase on economic parameters

% Increase	IRR	PBP
0	16.45	10
20	20.00	8.5
30	21.79	8
40	23.59	7

Note: Base Yield 25 t/ha/yr FFB
IRR — Internal Rate of Return
PBP — Pay Back Period

Appendix: Soil analysis data of soil evaluated

					P (ppm)		Exch. me %					
Soil	Horizon (cm)	pH	C%	N%	A	T	K	Mg	Ca	6NHCl K me%	% Clay	% Silt
1. Typic Tropaquult	0-15	4.5	2.00	0.17	24	164	0.10	0.17	0.49	1.41	54.8	10.3
	15-30	4.5	0.87	0.14	21	176	0.20	0.38	0.89	1.36	47.6	19.8
	30-45	4.5	0.72	0.08	7	119	0.09	0.15	0.39	1.47	47.6	18.2
	45-60	4.4	0.66	0.09	13	152	0.11	0.22	0.59	1.58	50.6	14.6
2. Typic Tropopsamment	0-10	4.8	2.32	0.29	30	153	0.05	0.09	0.52	0.17	23.1	6.1
	10.40	5.0	0.80	0.18	16	111	0.03	0.07	0.27	0.21	25.2	6.1
	40-60	5.0	0.81	0.07	22	117	0.06	0.08	0.38	0.20	28.3	5.9
3. Typic Paleudult	0-12	4.3	1.13	0.44	21	139	0.08	0.16	0.41	1.12	31.9	3.2
	12-30	4.4	0.44	0.30	14	104	0.05	0.06	0.38	1.24	32.8	1.5
	30-60	4.4	0.23	0.17	16	126	0.08	0.08	0.41	1.91	35.5	2.0
4. Aeric Tropaquept	0-12	4.4	4.31	0.42	54	350	1.76	3.22	1.72	4.50	41.1	43.9
	12-30	4.0	2.29	0.19	40	283	0.56	1.63	0.86	4.56	43.6	48.6
	30-60	3.8	1.10	0.09	26	302	0.39	4.49	0.84	6.24	58.7	36.9

					P (ppm)		Exch. me %				
Soil	Horizon (cm)	pH	C%	N%	A	T	K	Mg	Ca	6NHCl K me%	LI %
5. Typic Tropofibrist	0-15	3.75	39.3	1.77	22	376	0.32	1.55	1.17	0.61	81.9
	15-30	3.85	43.5	1.67	40	223	0.12	0.35	1.13	0.43	88.3
	30-60	4.00	44.6	1.31	18	161	0.09	0.35	0.87	0.36	87.9
	60-90	4.00	39.1	1.21	15	145	0.11	0.35	0.69	0.43	80.5

Reference:
A = Available
T = Total
LI = Loss on Ignition

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Nutrient Requirement for Sustained High Yields of Rice and Other Cereals

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Summary

Increases in fertilizer consumption, irrigated area, use of modern varieties, and related technology resulted in an annual increase of 4.3% in rice production from 1981 to 1984. Countries which dramatically increased rice and other cereal production used massive quantities of fertilizer. With intensive cropping and increased grain yields of rice and other cereals, there will be a greater demand for fertilizers and a more balanced nutrient use.

In this effort, K use should be commensurate with increased N application and higher cereal yields. Increase in N rate and efficiency will be critical for sustained rice production needs of at least 2.7%. Basic studies on N transformation processes should be carried out to develop fertilizer use technology, thus, increase farm productivity and income in rice-based cropping systems. For other cereals such as wheat, maize, and sorghum, experiences of temperate countries should guide in developing science-based technology for increased production and profits with both conventionally bred as well as with hybrids in the tropics.

For rice and other cereals, maximum yield experiments can generate information on the critical requirement of nutrients to sustain high yields. The adoption of any fertilizer use technology at the farm level will largely depend on integrated nutrient use for sustained high productivity from land and higher income.

Introduction

Sustaining the 2.7%, or higher, growth rate of rice and other cereal production in the coming decade will require increased area under irrigation, more areas planted to fertilizer responsive modern varieties, and development of cost-efficient fertilizer use technology.

Grain yields of modern rice, wheat, maize, and sorghum increase when nutrients deficient in the soil are added. National average rice yields often reflect the amount of fertilizers used. Fertilizer consumption in developing countries, where rice is mostly grown, has increased by over 110% in the past decade *(Stangel and Harris [1985]).* Many of the cereal deficient countries, such as India, China, and Indonesia, have now become exporters *(Stangel and De Datta [1985]).*

The increase in fertilizer consumption, irrigated area, use of modern varieties, and related technology resulted in increased rice production: from 412 million tons in 1981 to 465 million tons in 1984, averaging a 4.3% increase each year. 426 out of the 465 million tons were grown in the Asia-Pacific region where the annual growth rate is 3.2% *(Puri [1985]).* For China, the annual growth rate of 4% from 1974 to 1984 was achieved due

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primarily to the massive fertilizer use which exceeded 180 kg NPK*/ha in 1984 compared with 50 kg NPK/ha in 1974.

Fertilizer usage in India is still 30 kg/ha. Nevertheless, in Punjab and Haryana states, where wheat and rice yields are extremely high, fertilizer usage is spectacular. Rice farmers in Java, Indonesia use as much as 200 kg/ha of nutrients (NPK) for a national average rice yield of 4 t/ha.

Researchers contend that the spectacular crop yield increases in the region still do not reflect the rice yield potential at the farm level. *IRRI's* constraints and cropping systems on-farm research confirms this contention. Realizing the rice yield potential is primarily hindered by inadequate fertilizer application and improper application methods which lead to high nutrient loss and low recovery. Improvement of plant nutrient recovery by only 10% worldwide will give a massive saving at the farm level of US$ 3.2 billion per year.

My paper deals with this subject in two parts: 1) nutrient requirements for sustained high yields in lowland rice, and 2) nutrient requirements for high yields in wheat, maize, and sorghum.

1. Nutrient requirements for lowland rice

More than 80% of the world's rice areas is grown to lowland about 50% of which and 75% of the production is obtained from irrigated rice. In the absence of known soil nutrient constraints, IR36, a modern cultivar producing 9.8 t/ha grains and 8.2 t/ha straw, removed 218 kg of N, 31 kg of P, 258 kg of K, and 8 kg S/ha (Table 1). These and other plant nutrients removed by the crop must be replenished to sustain high rice yields. K uptake of rice that produced 9.8 t/ha grain when given with 174 kg N/ha removed 258 kg K/ha compared with the 69 kg K/ha removed in a crop that yielded 3.4 t/ha without N fertilizer. Data indicate that as grain yield increases, demand for plant nutrients, particularly K, also increases.

Table 1. Nutrient removal of rice (variety IR36) with and without fertilizer N in a farmer's field experiment in Calauan, Laguna, Philippines. 1983 dry season. (Data source: *De Datta, S. K.* IRRI Agronomy Department).

Nutrient element	Amount of nutrient removed by the crop at harvest kg/ha					
	Without fertilizer			With 174 kg N/ha		
	Straw	Grain	Total	Straw	Grain	Total
N	18	34	52	75	143	218
P	2	10	12	5	26	31
K	59	10	69	232	26	258
S	0.8	1.0	1.8	3.3	4.9	8.2
	Yield (t/ha)			*Yield (t/ha)*		
Grain	3.4			9.8		
Straw	2.8			8.2		

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*Whenever NPK is mentioned in this paper, it stands for N, P_2O_5 and K_2O.

Nitrogen

Asia consumed 38% of the world's nitrogen in 1983. This compares with its 25% consumption a decade earlier. Growth in N consumption rate of 10.1% in Asia is nearly twice the world average of 5.6%. China, India, Pakistan, and Indonesia used the excess of 14% growth rate for most of the decade *(Stangel and De Datta [1985])*. Unfortunately, rice commonly utilizes less than 40% of applied N fertilizer (primarily urea) even under the best conditions *(De Datta [1981])*.

Magnitude of N loss. Recent evidence suggests that N fertilizer application at 2 weeks after transplanting results in ammonia loss of up to 35-45% *(Fillery et al. [1984])*. In other words, 1 out of 3 bags of applied urea can be lost through volatilization if improperly applied into the floodwater 10-15 days after transplanting (DT).

Water depth effects on N use efficiency. Our recent studies showed the effect of water depth on N fertilizer recovery by rice during urea-N application. In our 1985 dry season trial, an early maturing rice, IR58, showed significantly higher grain yield with properly split-applied urea and basal dose applied without or with 2 cm standing water. Equally important were the high grain yields obtained with a single dose applied at 20 DT or at 5-7 days before panicle initiation (DBPI) (Table 2). On equal N basis, deep placement made at 0-20 DT gave similar grain yields. With late maturing IR29723 line, their difference in application timing and water management was less apparent.

Table 2. Effects of water depth, method and time of urea application on the grain yield of an early maturing IR58 (102 days) and late maturing IR29723-143-3-2-1 (135 days). *IRRI*, 1985 dry season.

Urea source	N rate (kg/ha)	Method and time of application[a]	Grain yield[b] (t/ha)	
			IR58	IR29723-143-3-2-1
—	0	No fertilizer N	2.7 g	4.4 e
Prilled	58	½ at 10 DT + ½ at 10 DAPI	3.9 f	6.0 cd
Prilled	58	Single dose at 20 DT	5.0 de	6.3 bcd
Prilled	58	Single dose at 5-7 DBPI	4.5 ef	5.9 d
Prilled	58	⅔ B&I w/out water + ⅓ at 5-7 DBPI	5.2 cde	6.5 bcd
Prilled	58	⅔ B&I w/ 2 cm standing water + ⅓ at 5-7 DBPI	5.0 de	6.7 bcd
Supergranule	58	Hand point-placement at 0 DT	6.0 bc	7.1 ab
Supergranule	58	Hand point-placement at 10 DT	5.9 bc	6.7 bcd
Supergranule	58	Hand point-placement at 20 DT	5.5 cd	6.8 abc
Supergranule/Prilled	58	½ at 0 DT as USG + ½ at 5-7 DBPI as PU	5.4 cd	6.7 bcd
Supergranule	116	Hand point-placement at 0 DT	7.0 a	7.0 ab
Prilled	116	⅔ B&I w/out water + ⅓ at 5-7 DBPI	6.6 ab	7.6 a

[a] DT = days after transplanting, DAPI = days after panicle initiation.
DBPI = days before panicle initiation, B&I = broadcast & incorporated.
USG = urea supergranule, PU = prilled urea. Topressing at 10 DT and before or after PI were done with about 5 cm standing water.

[b] In a column, means followed by a common letter are not significantly different at the 5% level by DMRT *(Duncan's Multiple Range Test)*.

Phosphorus

P availability in flooded soils is generally higher than in nonflooded aerobic soils. Nevertheless, recovery appears to deviate only a little from the 10% average in aerobic upland soils.

It has been pointed out that a crop with 9.8 t/ha grains and 8.2 t/ha straw removed about 31 kg P/ha. This amount should be replenished with phosphate fertilizer such as superphosphate in any soil or rock phosphate, basic slag, fused Ca-Mg phosphate in acid soils. Evaluation of new P products is being conducted at the *International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER).*

In lowland rice, P application time and method is not as critical as in upland rice. In the Philippines, N, P, and K gave positive grain yield response in Vertisols in two sites. In another site (also Vertisols), N and P application alone was sufficient to get high yields (Figure 1).

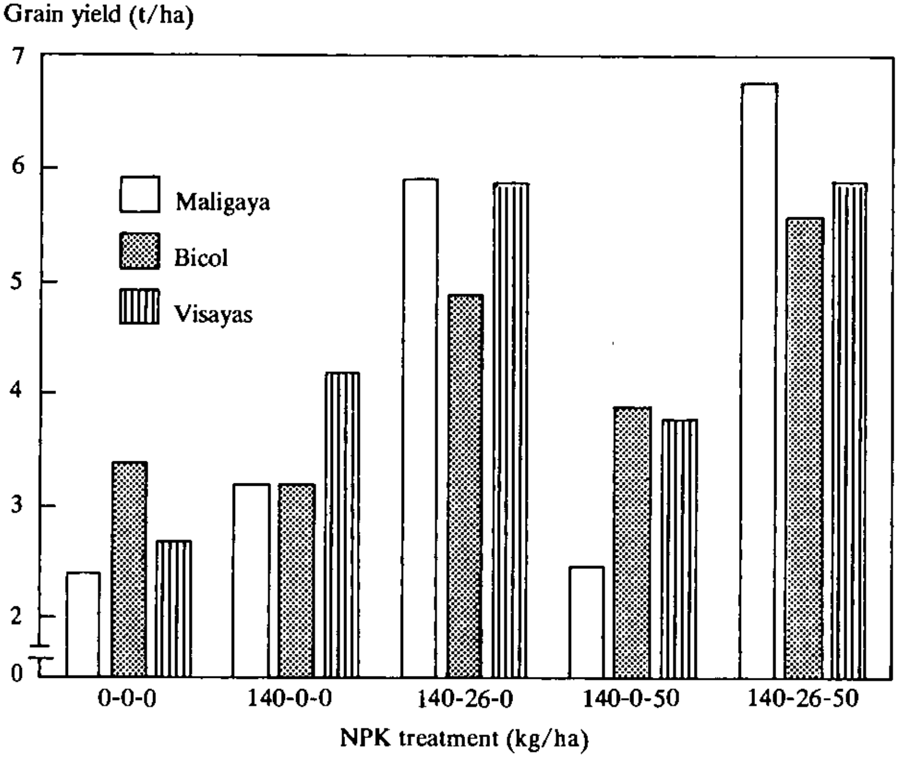

Fig. 1 Mean yield of 2 rices (IR36 and IR29723-143-3-2-1) as affected by NPK application during the dry season on the 17th year of cropping in the long-term fertility trials at 3 experiment stations of the Philippine Bureau of Plant Industry (Maligaya, Bicol, and Visayas), 1984 dry season *(IRRI-BPI cooperative experiment).*

Potassium

Many lowland rice soils are relatively young and occur in river basins or alluvial valleys, hence, their K content is frequently high *(De Datta and Mikkelsen [1985])*.

Many reports suggest that most lowland rice soils have adequate K. Potash fertilizer is not needed as much as N or P and added K fertilizer produces only a small and variable yield response *(De Datta [1981])*.

Where traditional agriculture has shifted to maximum yield concepts, farmers turn to NP, NK, and NPK rice fertilization for good economic returns.

Field trials in China suggest that K response in rice is limited to a few years. Average grain yield increase is estimated at 9.3 kg rice/kg K *(Lu [1981])*. In the red earth area of Zhejiang Province, the average rice yield increase due to K application was 17% in 31 early-season trials and 40% in 8 late-season trials *(Cao [1983])*. Even in fertile and high-yielding areas such as the Taihu Lake region, response to K is being recorded through large amounts of N and P fertilizer applications.

Note that the cost of K is relatively less than N and P and the economic advantage of K fertilization is very good. Moreover, rice straw and rice stubble are other important K sources for lowland rice *(De Datta [1981], De Datta and Mikkelsen [1985])*.

In light-textured soils such as those in Hubei Province, rice response to K application was higher than in clay soils. Differences in K response due to soil texture are summarized in Table 3.

Table 3. K response in lowland rice on soils with different textures in the People's Republic of China *(Agricultural Bureau of Xi-hui county, Hubei Province, [1976])*.

Soil texture	Experiments (no.)	Grain yield Without K fertilizer (t/ha)	Grain yield With K fertilizer (t/ha)	Yield increase (t/ha)	Yield increase (%)
Sandy	2	4.5	5.3	0.8	17
Clay loam	9	4.4	4.8	0.5	11
Sandy clay	15	5.1	5.6	0.4	8

Similarly, rice response to K was favorable on sandy and coarse-textured soils in Vietnam, Sri Lanka, and Malaysia. On red sandy or loam soils in Karnataka, leaching losses may have contributed to low K response.

655 trials showed an average increase of 0.5 t/ha over NP fertilized plots *(Mahapatra and Prasad [1970])*. In the high rainfall areas, India has K-deficient rice-growing soils *(Goswami et al. [1976])*.

Most rice soils in Bangladesh are low in exchangeable K. Of the 800 field trials from 1975-1979 in an FAO-funded program, half was reported with over 0.4 t/ha grain yield increases due to K application *(Kemmler [1981])*. As these soils are intensively used for rice-based cropping systems, their response to K increases.

Most rice soils in the Philippines are geologically young and release considerable K from weathering primary minerals. In soils low in K, however, apparent K fertilizer recovery may be up to 30%.

Topdressing split application of K. K is normally applied during final land preparation because of its relative immobility in clay soils. Research in Japan, China, and India suggesting split K application resulted in higher grain yields under the following conditions:

1. warm areas,
2. light soils with low CEC,
3. poorly drained soils which tend to accumulate toxic substances that affect root activity,
4. high N application,
5. coastal areas with high rainfall *(Roy [1985])*.

A farmer has the option to topdress K in case he missed applying the basal dose of K. Response to split K application is somehow related to an optimum N/P ratio. A basal application should not be made when:

1. Low-tillering type rice varieties are used
2. Conditions are not favorable for tillering *(De Datta [1981])*.

Eight-year data on clay soils with high CEC in the Philippines did not show any beneficial effect of split K application compared with single basal application *(De Datta and Gomez [1982], De Datta and Mikkelsen [1985])*.

Zinc

Zn deficiency is the most common micronutrient problem in flooded rice. It is manifested by chlorosis, necrosis, early death of seedlings, delayed plant development, and reduced crop yields.

The incidence of Zn deficiency has increased recently due to the wide use of modern varieties which are less tolerant to Zn deficiency, high Zn removal by modern rice varieties, replacement of ammonium sulfate with urea, increased P fertilizer use, and double or triple cropping of irrigated rice fields *(De Datta [1981])*.

Zn deficiency occurs in plants grown in calcareous soils. $ZnCO_3$ formation in soils high in calcium carbonate is responsible for Zn unavailability to plants in calcareous soils. Many studies suggest that on severely Zn deficient soils without Zn application, no grain yields are obtained. With added Zn, grain yield increases were as high as 6 t/ha *(De Datta [1985])*.

Phosphorus and zinc interaction

The interaction between P and Zn is designated as P-induced Zn deficiency in many crops. *Kankoulakes [1973]* believes that Zn precipitates in the soil solution and on the root surface. *Lindsay [1972]* reported that Zn precipitation by P is not the cause of P-induced Zn deficiency in plants. He suggested that P affects root absorption of Zn from the soil in other ways. Literature proving P-induced Zn deficiency in rice is virtually nonexistent.

Potassium and zinc interaction

The relationship between K and Zn nutrition in rice is not well understood. There are contradictory reports on the interaction effects of K and Zn. *Mariam and Koshy [1979]* reported that Zn application does not affect the K content of rice grains and straw. On the other hand, *Sarkunam and Venkataraman [1979]* found that K uptake decreased in straw and increased in rice grains with Zn application. Another study showed how Zn application reduced K contents of rice grain and straw *(De and Chatterjee [1978])*. The application of Zn to NPK treatment often reduces the effect of K and it is likely that yields may be higher by omitting K application *(Randhawa and Pasricha [1975])*. However, *Tandon [1982]* reported that Zn application significantly enhances K uptake by rice. In a given crop, an optimum concentration of each essential element is needed to produce maximum yield. Maintaining high yields requires fairly close adherence to the optimum balance in nutrient concentration *(Munson [1982])*.

K and Zn interactions in lowland rice. Field experiments were conducted in the 1984 dry and wet seasons in farmers' fields in Pangasinan and Nueva Ecija provinces, Philippines. The sites were selected on the basis of low K and Zn availability and difference in texture of their soils (Table 4). Treatments included various combinations of K and Zn at different rates.

Table 4. Chemical and physical properties of soil. 1984 dry season.

	Location		
Properties	Aguilar, Pangasinan	Cabanatuan, Nueva Ecija	San Miguel Bulacan
pH w/v H_2O (1:1)	6.6	6.7	6.5
Organic C (%)	1.5	1.6	1.2
CEC (me/100 g)	19	32	37
Exch. cation (me/100)			
K	0.07	0.22	0.30
Mg	8	10	11
Ca	13	23	21
K/Ca ratio	0.01	0.04	0.06
Ca + Mg/K ratio	300	150	110
Ca/Mg ratio	1.6	2.3	1.9
Available P (ppm) by *Olsen*	2.0	7.5	2.4
Available P (ppm) by *Bray II*	9.1	20	12
Available Zn (ppm)	0.3	0.21	0.25
Clay (%)	19	36	41
Silt (%)	41	56	41
Sand (%)	39	8	10
Soil texture	Sandy loam	Silty clay	Silty clay
Taxonomy classification[1]	Coarse loamy, isohyperthermic, mixed Typic Haplaquoll.	Fine, mixed, isohyperthermic, Aeric Tropaquept.	Fine, montmorillonitic isohyperthermic, Entic Chromustert.
Soil series	San Manuel sandy loam	Quingua silty clay	Bigaa silty clay

Before final harrowing, 13 kg P/ha and 67 kg N/ha were broadcasted and incorporated before transplanting with applied K and Zn. An additional 33 kg N/ha was topdressed uniformly at 7 DBPI. With K and Zn applications, grain yield was significantly higher than that of control (Figure 2). In San Manuel sandy loam, grain yields were increased with K application, the highest at 100 kg K/ha and 20 kg Zn/ha, whereas in Quingua silty clay, the highest yield was obtained with high rates of K and Zn (200 kg K/ha and 40 kg Zn/ha).

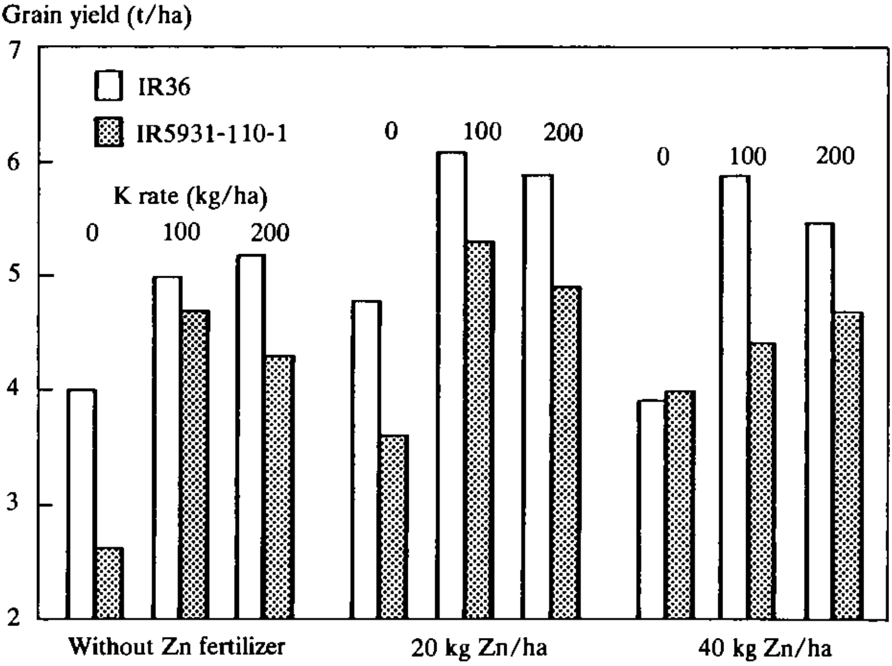

Fig. 2 Effect of K application on grain yields of IR36 and IR5931-110-1 at different Zn application levels in San Manuel sandy loam soil. Aguilar, Pangasinan, 1984 dry season.

K uptake increased with K and Zn applications (Figures 3 and 4). In San Manuel sandy loam soil, K uptake at crop maturity increased with 20 kg Zn/ha but decreased at 40 kg Zn/ha. Further, K uptake was lower in San Manuel sandy loam than Quingua silty clay. This might have been due to the effect of Ca + Mg/K ratio which is higher in San Manuel than in Quingua. The response, however, varied with rice variety. Using IR36, K uptake in San Manuel sandy loam at 100 kg K/ha was almost equivalent to that in Quingua silty clay without K application. On the other hand, about 200 kg K/ha was needed to obtain almost similar K uptake using IR5931-110-1. Results suggest the differential K uptake and K response in different rice varieties. However, rice response to K application also depends on soil characteristics possibly on the relationship of K to Ca and Mg. In soil with high Ca + Mg/K ratio, K uptake was lower than with low Ca + Mg/K ratio.

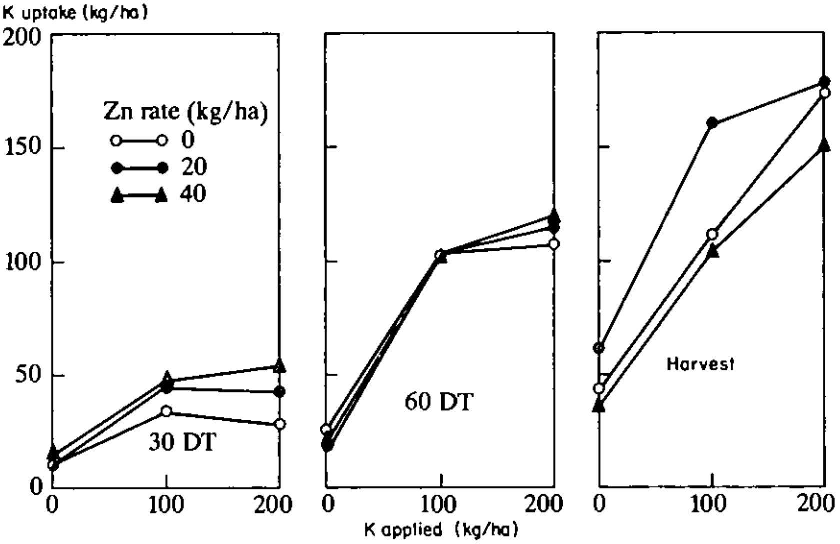

Fig. 3 Effect of K and Zn applications on the K uptake at different growth stages of IR36 in San Manuel sandy loam soil. Aguilar, Pangasinan, 1984 dry season. (Data source: *IRRI Agronomy Department)*

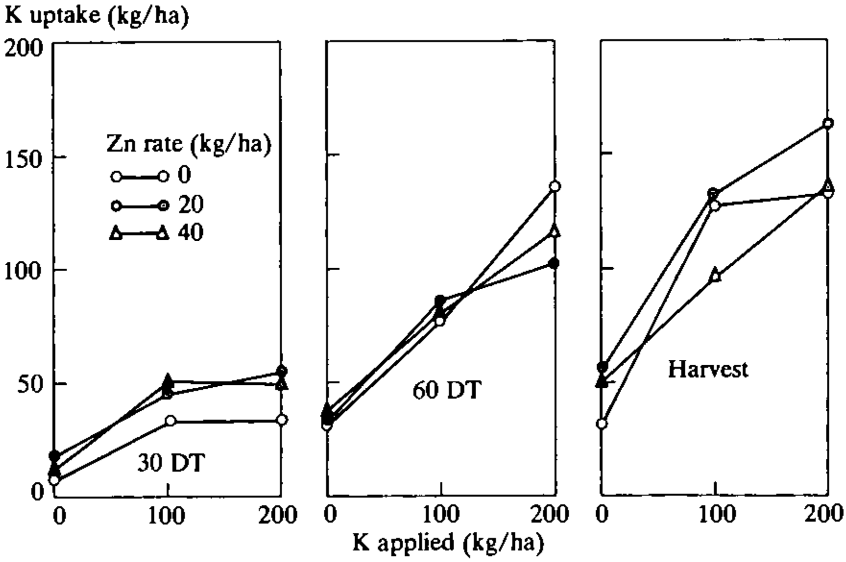

Fig. 4 Effect of K and Zn applications on the K uptake at different growth stages of IR5931-110-1 in San Manuel sandy loam. Aguilar, Pangasinan, 1984 dry season. (Data source: *IRRI Agronomy Department)*

Trials were repeated in the 1984 wet season to evaluate IR36 K and Zn response with emphasis on Ca/Mg and Ca/K ratios of the soils. Two sites in Pangasinan province (Bugallon and Mangatarem), with soils both high in Ca and Mg but low in available K and Zn, were selected.

Response to K on both soils and to Zn in Bugallon was noted. At Mangatarem site, the combination of 100 kg K + 20 kg Zn/ha gave the highest yield, whereas the combination of 200 kg K + 60 kg Zn/ha gave the highest yield on Bugallon soil (Figure 5). Increasing Zn rates but without K on Mangatarem soil showed a yield decline, whereas the opposite was observed on Bugallon soil. Bugallon soil, a coarser (loamy) soil with higher Ca/Mg or Ca/K ratios than Mangatarem soil (clay), showed higher response to K and Zn and a greater demand for these nutrients. This agrees with the 1984 dry season results that soils with different Ca/K or Ca/Mg ratios affect yield responses to K and Zn. It further confirms earlier contention by *Munson [1982]* that a definite interrelationship among K, Ca, and Mg concentrations in the different portions of the crop exists, hence, interaction responses to these nutrients deficient in the soil.

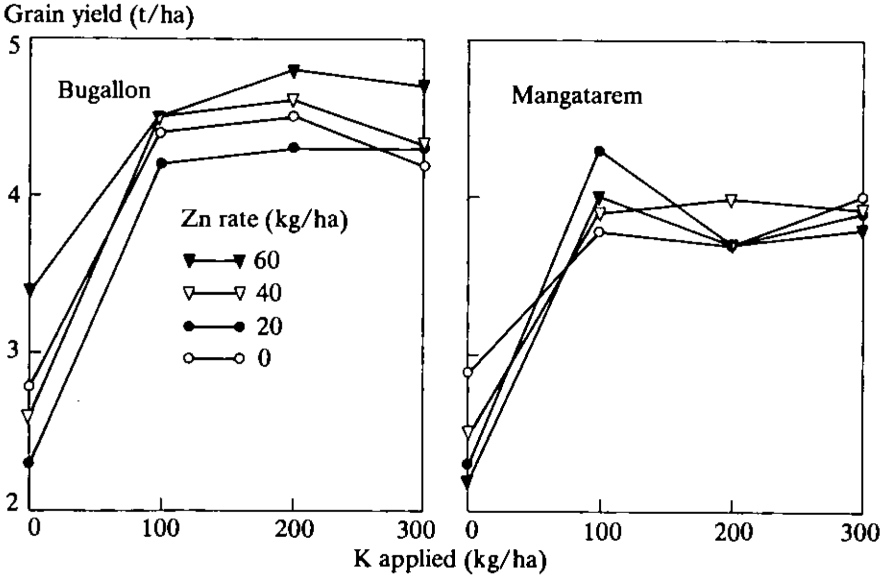

Fig. 5 Grain yield of IR36 as influenced by Zn and K application. Bugallon and Mangatarem, Pangasinan, Philippines, 1984 wet season. Data source: *IRRI Agronomy Department).*

Sulfur

Rice response to S has been reported from many countries in the world *(De Datta [1981]). Mamaril et al. [1976]* reported that yields in farmers' fields in South Sulawesi, Indonesia were 12-45% higher with application rates of up to 100 kg S/ha more than the control. In a recent paper by *Ismunadji [1985]* IR36 removed 61 mg S in grain and 72 mg S in straw/pot (Table 5). S accumulation was greater in the grain and straw with increased application rates. In Bangladesh, where S deficiency has been recorded in sizable rice areas, yield increases of 0.3-2.2 t/ha were obtained in farmers' fields from transplanted rice in the wet season *(Hoque and Hobbs [1980])*.

In a recent study of 99 sites in the Philippines *(Mamaril et al. IRRI [1985]*, unpublished), 14% of the sites were classified as very low, 23% as low, 44% as moderate, 6% as high, and 12% as very high in S status. Sites from Cagayan, Isabela, and Tarlac provinces were found to be potentially sulfur-deficient.

Continued use of modern varieties with intensive cropping could remove 10-13 kg S/ha per crop and result in increased S response in many lowland rice soils *(De Datta [1985])*.

Table 5. The effects of sulfur rate on the nutrient status by weight of IR36 grown under flooded condition at harvest *(Ismunadji [1985])*.

S rate (ppm)	Straw (mg/pot)					Grain (mg/pot)				
	N	P	K	S	S_1	N	P	K	S	S_1
0	372	64	718	40	2645	1078	211	264	38	1386
40	300	57	500	47	2518	812	241	436	69	1114
80	362	75	611	72	2890	905	294	462	61	1801

Balanced nutrition and long-term fertility experiments

Nutrient balance is a critical factor in maximizing the grain yield of a crop as well as in crop intensification. The biochemical reasons of grain yield decrease due to imbalance of mineral elements in rice are not clearly understood.

Under the intensive rice-rice cropping systems, the demand for P and K increases but often after only two or three croppings. Findings from long-term fertility experiments since 1968 at three experiment stations in the Philippines show that response to P was observed only when N and K were applied *(De Datta and Gomez [1982])*.

IRRI-BPI long-term fertility trials: responses to phosphorus and potassium.

Response to P. Some significant yield responses to P were observed on three soils and throughout the 17 crop years (1968-1984). While responses to P were observed in both seasons, they were generally higher in dry season than in wet season, especially in later crops.

The change in response to P over time was more drastic in dry-season crops than in wet-season crops and much more drastic at Maligaya and Santa Rita than at Pili (Figure 6). At Maligaya, for example, dry-season responses to P were relatively stable for the first 12 crops (1968-1979). It started to increase sharply from the 13th crop with the average dry-season P-response of 1.3 t/ha for the first 12 crops and 3.7 t/ha for the last 5 crops. With Santa Rita clay, the average dry-season P-response of the first 7 crops was 1.2 t/ha and the last 4 crops, 2.5 t/ha.

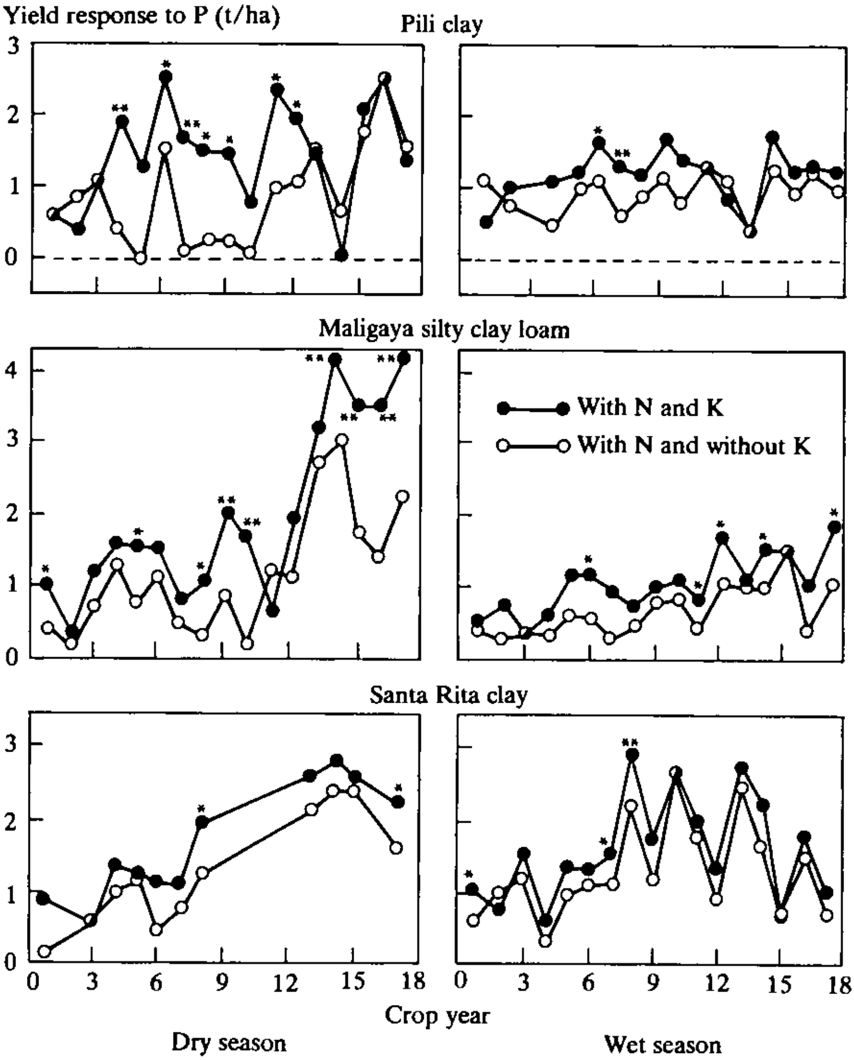

Fig. 6 Changes in yield response to P, with and without K (with N), in successive croppings on three soils in the Philippines. IRRI-BPI cooperative long-term fertility experiments, 1968-84. *,** = significantly different from the open circle at the 5% and 1% levels of significance, respectively. (Data from *IRRI Agronomy Department*).

Response to P was generally higher with applied K. The largest difference in response to P was observed at Maligaya in dry-season crops and in later years. This implies that dependency of the P-response on K application seemed to increase with time only at Maligaya.

Averaging over the first 12 dry-season crops (1968-1979), P-response was 1.3 t/ha with K and 0.7 t/ha without K (with a mean difference of 0.6 t/ha) at Maligaya (Maligaya silty clay loam). But for the last 5 years, P-responses averaged 3.7 t/ha with K and 2.3 t/ha without K (with a mean difference of 1.4 t/ha). At Pili (Santa Rita clay), on the other hand, such dependency of P-response on K application seemed to have disappeared in the past 5 years.

Response to K. Significant responses to K were observed at Pili and Maligaya. Response was also generally higher in dry season than in wet season crops (Table 6).

Table 6. Average response to K with and without P in long-term fertility experiments at two *Philippine Bureau of Plant Industry Stations (IRRI-BPI* cooperative experiments, 1968-1984).

	Average response[1] to K (t/ha)	
Season	With P	Without P
	Pili[2]	
Dry	1.38	0.83
Wet	0.59	0.36
	Maligaya[3]	
Dry	0.89	0.08
Wet[4]	0.56	0.17

[1] Averaged over 17 years.

[2] Santa Rita clay.

[3] Maligaya silty clay loam.

[4] No trial was conducted in 1970.

The trend of K-response over time varied greatly between the two sites (Figure 7). While at Maligaya, the trend seemed to increase in the first 10 years and stabilized later on, the trend at Pili seemed to decrease consistently since the 5th crop when it reached its peak of 3.6 t/ha. In the past 5 years, dry-season response to K at Pili only averaged 0.6 t/ha, whereas the average response of the first 12 years was 1.7 t/ha with P and 0.9 t/ha without P.

Response to K was generally higher with P than without. However, such dependence of K-response on P application also started to disappear over time at Pili but increased over time at Maligaya.

Excess K. In the long-term fertility experiment at IRRI (Andaqueptic Haplaquolls) the exchangeable K in soil increased from 0.8 meq in 1968 to 1.6 meq/100 g in 1984 (Table 7). The critical exchangeable K is 0.2 meq/100 g soil. High K content in soil and high Na and K contents in irrigation water at *IRRI* farm were suggested as some of the factors of reduced maximum yields (9-10 t/ha in 1966 to 7-8 t/ha in 1984) over the years. Deposits of 250 kg K/ha per season, assuming 1 cm water use/day, may lead to nutritional imbalance. *IRRI Soil Chemistry Department* is currently conducting research to determine this possibility. However, long-term fertility trials for 21 years at *IRRI Agronomy Department* did not show any grain yield reduction due to K application.

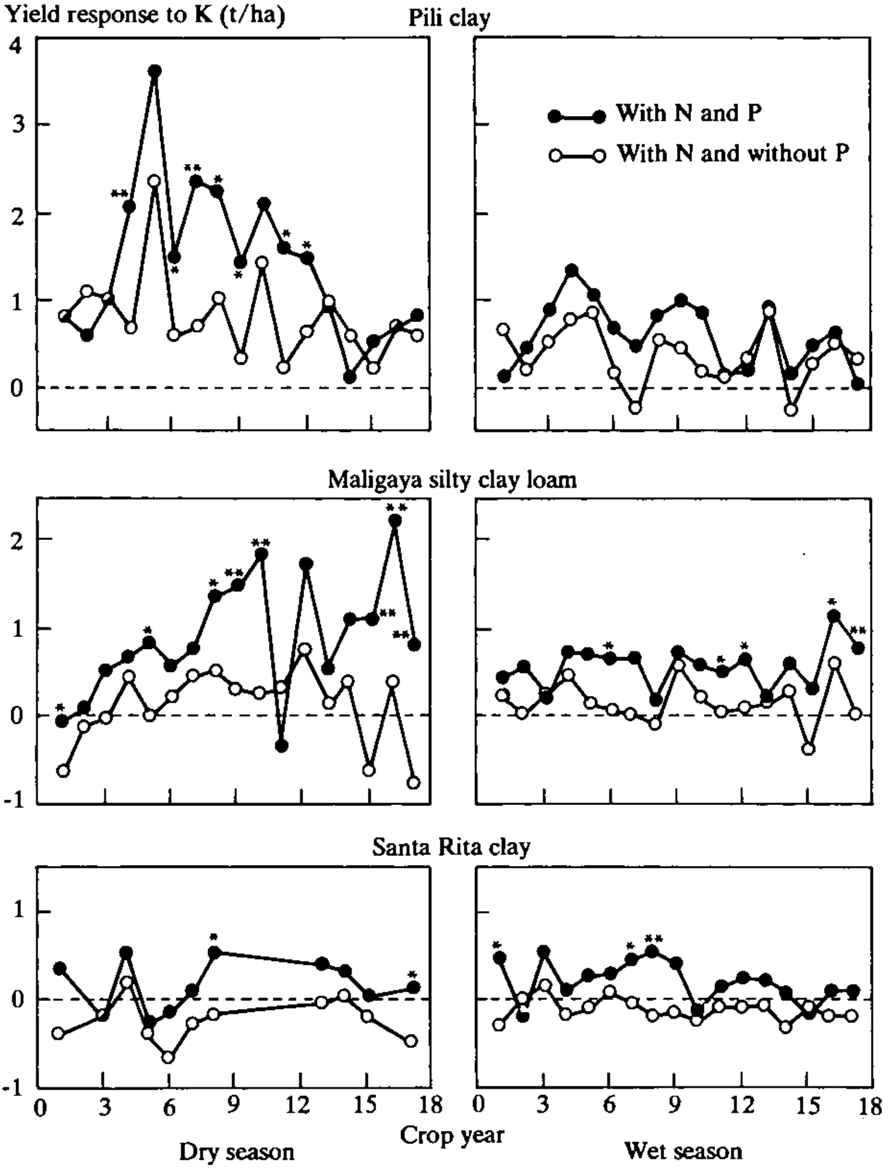

Fig. 7 Changes in the yield response to K, with and without P (with N), in successive croppings on three soils in the Philippines. IRRI-BPI cooperative long-term fertility experiments, 1968-84. *,** = significantly different from the open circle at the 5% and 1% levels of significance, respectively. (Data from *IRRI Agronomy Department).*

Table 7. Changes in soil characteristics in the long-term fertility trial. IRRI Block N_{15}, 1968-1984. (Data source: *De Datta, S. K.* IRRI-Agronomy Department)

Soil characters	1968	1984		
		No fertilizer	All inorganic N source[a]	Inorganic N source + 24 kg N/ha from compost
pH	6.0	6.0	5.6	5.8
Organic matter, %	2.0	3.7	4.1	4.2
Total N, %	0.14	0.19	0.21	0.22
CEC, me/100g soil	45	39	38	39
Avail P (Bray 2), ppm	12	16	26	24
Exch K, me/100 g soil	0.8	1.8	1.6	1.8

[a] Both fertilizer treatments received 13 kg P and 25 kg K/ha with the same rate of N application.

Fertilizer recommendations

The amount of fertilizer to be applied to a crop will largely depend on:

1. inherent soil fertility,
2. nutrient removal by a target yield, and
3. profitability.

For rice, a rule of thumb for a high-yielding crop is 2:1:1. Therefore, it is imperative that soil tests and plant analyses should guide the amount of fertilizer to be applied for a high yielding crop. Table 8 shows a general schedule for a high yielding modern rice as suggested by *IPI [1976]*.

Table 8. Fertilizer schedules for high yielding varieties *(International Potash Institute,* Bull. No. 3, 1976).

Season	Expected yield level (t/ha)	Fertilizer rates (kg/ha) N	P	K
Dry	4.0	60-80	13	25
	5.0	80-120	22-26	42-62
	6.0	110-140	26-33	50-75
	7.0	120-160	33-39	66-100
	8.0	130-180	39-52	83-125
Wet	3.0	20-40	0-13	0-25
	4.0	30-50	13-17	25-33
	5.0	50-75	22-26	42-62
	6.0	75-90	26-33	62-83

Soil test. Chang [1978] and *De Datta [1981]* reviewed various soil and plant analyses methods to evaluate the N, P, K, S, and Zn available to lowland rice from flooded soils. The best correlation with rice response to the given elements was the determination of:

1. Available N, by waterlogged incubation and alkaline permanganese, total N, and organic C.
2. Available P, by Olsen and Bray P_1 methods.
3. Available K, by exchangeable K and K dynamics by EUF technique.
4. Available S, by extraction with $Ca\ (H_2PO_4)_2 \cdot H_2O$.
5. Available Zn, by extraction with buffered chelating agent or weak acids.

Considerable care should be taken in evaluating soil nutrient availability by relating soil test to crop response since varietal differences exist in rice response to tolerance and its susceptibility to a nutrient.

Plant analysis. Critical limits are established which together with soil test values may guide fertilizer recommendation. These limits are reported by *De Datta [1981 and 1985].*

Current usage of fertilizer

Countries that are able to produce an average grain yield of 6.0 t/ha or more such as Japan and Korea use 250-300 kg NPK/ha. On the other hand, those producing about 5.0 t/ha such as China use about 180 kg/ha of inorganic fertilizer plus 10 t/ha organic manure. Indonesia's average yield dramatically increased to 4.0 t/ha with 150-180 kg NPK/ha used by Javanese farmers. Further, tropical countries such as India, Bangladesh, and Philippines produced between 2.0 and 2.4 t/ha average rice yield using 50-60 kg NPK/ha.

Price support, government policy, and farmers' socio-economic conditions largely determine the level of fertilizer use. Countries currently producing 2.0-2.5 t/ha can increase grain yield to 4-5 t/ha by dramatically increasing NPK use with greater area under modern varieties, increased irrigation, and improved soil and crop management practices.

Rational recommendations should consider soil test, balanced nutrition concept, and integrated nutrient management practices that maintain soil fertility to sustain high rice yields and rice-based cropping systems. In these efforts, considerable recycling of farm wastes, rice straw, compost, and use of azolla and green manures will play a significant role in increasing soil productivity.

2. Nutrient requirement of other cereals with emphasis on potassium nutrition

Besides rice, wheat, maize, and sorghum are important cereals in Asia. There will be an increase in fertilizer requirement for higher cereal yield per unit area. One way of obtaining rational fertilizer rates for wheat, maize, and sorghum in different soils and climatic conditions is by determining how these crops respond to a given amount of nutrient from the soil and fertilizer. If crop response to fertilizer application is calibrated with soil test then the optimum (biological and economic) rate of fertilizer application can be determined.

Increasing evidence suggests that nutrient uptake of modern cereal varieties is less than the amount of nutrients applied by farmers. It is necessary then to apply more limiting nutrients to restore soil fertility and supply the nutrient requirement to sustain high yields. The nutrient supplying capacity of the soil should be considered in determining the nutrient requirements of low, medium, and high cereal yields. Nutrient concentration at high yields provides a basis for evaluating the nutrient balance and nutrient requirement.

Cereal response to K and to other nutrient elements depends on the type and amount of clay, climate, varieties, and management practices. In India, *Pillai [1985]* reported that 20% of soils are K-deficient. K response of cereals is high in Orissa, Karnataka, Kerala, Madhya Pradesh, and Uttar Pradesh.

Wheat

In 1980-1982, 239 million hectares of land were grown to wheat *(FAO [1983])* accounting for 28% of the world's production of major cereals. In Asia, China, India, and Pakistan are the leading wheat producing countries.

Wheat requires as much K as N *(Kemmler [1983])* and K uptake varies with yield levels. Potassium removal for aerial parts of wheat varies from 40 to 200 kg/ha *(Beaton and Sekhon [1985]). Lal and Sharma [1974]* reported from India that a wheat crop which produced 5.4 t/ha grains and 9.2 t/ha straw removed 172 kg N, 26 kg P, and 226 kg K/ha. *Kemmler [1983]* reported that wheat yielding 10 t/ha will remove 160-242 kg K/ha. Varietal differences in K uptake are also substantial. Results from India suggest that K response in wheat was maximum in Himachal Pradesh, Madhya Pradesh, and Uttar Pradesh. From 3768 trials, grain yield of wheat in control plots averaged 1.4 t/ha, while with 120 kg N/ha, 60 kg P/ha, and 60 kg K/ha, grain yield was 3.4 t/ha *(Pillai, [1985])*. K contribution at 50 kg K/ha was 19%. High wheat response to K (25 kg grain/kg K) in light alluvial sandy soils of Ludhiana, Punjab and a rising trend in response to K (14 kg grain/kg K) in old alluvium of Delhi were reported. *Tiwari et al. [1982]* found significant wheat response to K in the alluvial soils of eastern Uttar Pradesh and Bundal Khand region. Table 9 shows the wheat response to 33 kg K/ha in India. Recently, *Beaton and Sekhon [1985]* summarized the magnitude of K response in India and Pakistan (Table 10).

Table 9. Response to K in wheat in farmer's field experiments in India, 1977/1978-1982/1983. (AICARP data, adapted from *Pillai [1985]*).

Province	No. of trials	Grain yield (t/ha) in control (without fertilizer)	Av grain yield (t/ha) with N 120, P 26 K 50 kg/ha)	K response (t/ha) at 33 K/ha over N 80 and P 40
Himachal Pradesh	85	1.4	3.8	0.4
Bihar, Punjab, and U.P.	1406	1.8	4.4	0.2
Madhya Pradesh (MP)	882	1.1	2.8	0.3
M.P. and Maharasthra	1145	1.4	2.9	0.2
Karnataka	250	1.4	2.4	0.2

Table 10. Wheat response to K in India and Pakistan *(Beaton and Sekhon [1985]).*

Country	Grain yield (t/ha) without K (60 kg N+13 kg P)	K rate (kg/ha)	Increase due to K (t/ha)	K efficiency (kg wheat produced /kg K added)
India	3.0	25	0.2	8
Pakistan (Punjab)	3.6	50	0.3	6

Maize

Maize was grown in 129 million hectares in the world in 1980-1982 *(FAO [1983]).* It is grown in Asia for food as well as for feed.

K nutrition plays an important role in maximizing economic yield of maize. Growers in the USA provide adequate K in order to maximize yields and profits.

Table 11 shows the nutrient removal of maize at different yield levels in the Philippines suggesting larger amounts of N and K removal at a higher yield of 6.2 t/ha than at 3.0 t/ha. Table 12 shows the K amount removed by different maize plant parts grown on a clay loam soil. As N rates increased, K removal also increased.

Most of the season's K uptake occurs before maize pollination. As much as 10 kg K/ha may be absorbed by maize daily for a period before pollination *(Welch and Flannery [1985]).* Moreover, maize plants may contain inadequate K amounts even though deficiency symptoms are not visible.

Table 11. Nutrient uptake of maize at different yield levels of DMR (Downey mildew resistant) Composite 2 in the Philippines *(Samonte, H. P.,* University of the Philippines at Los Baños, Philippines, *unpublished data).*

Yield level (t/ha)	Nutrients (kg/ha)				
	N	P	K	Ca	Mg
2.5-3.0					
Total	52	20	31	13	14
Grain	32	13	20	5	4
% in Grain	63	64	64	35	31
3.4-4.0					
Total	77	24	47	18	20
Grain	51	19	22	5	6
% in Grain	66	78	47	28	32
4.2-5.0					
Total	103	35	69	22	23
Grain	70	30	35	8	10
% in Grain	68	84	51	34	42
5.8-6.2					
Total	130	39	88	25	21
Grain	86	34	43	8	10
% in Grain	66	88	49	34	49

Table 12. K uptake of maize plant parts at different N levels on a Lipa loam in the Philippines *(Samonte, H. P.,* University of the Philippines at Los Baños, Philippines, *unpublished data).*

Treatment (kg N/ha)	K uptake (kg/ha)				
	Roots	Stover & husk	Cobs	Grain	Total
0	2.1	15.7	1.4	19.8	30.9
60	3.6	18.7	2.6	21.7	46.6
120	3.8	27.9	2.1	35.3	69.2
240	2.9	40.2	1.6	42.8	87.5

In India, an average yield response of maize of 8 kg grains/kg K applied at 25 kg K/ha was observed. This was based on 173 trials conducted in farmers' fields in Himachal Pradesh, only 81 trials of which reported significant K response *(Pillai [1985]).* Significant yield response to 50 kg K/ha was recorded in dry season where maize was grown with irrigation.

Recent reports from *All-India Coordinated Research Project* on long-term fertility experiments *(ICAR)* indicate high maize response to K (26 kg grain/kg K) for the first time even in K-rich black soils of Coimbatore after 8 cropping cycles *(ICAR [1984], Pillai [1985]).* In Punjab, India, *Kapur et al. [1984]* reported significant response to K: up to 75 kg K/ha in low and medium K soils and up to 50 kg K/ha in soils of high K-status.

Sorghum

Sorghum was grown in 47 million hectares in the world in 1980-1982 *(FAO [1983]).* Like maize, it is consumed as food and as feed in many parts of the world.

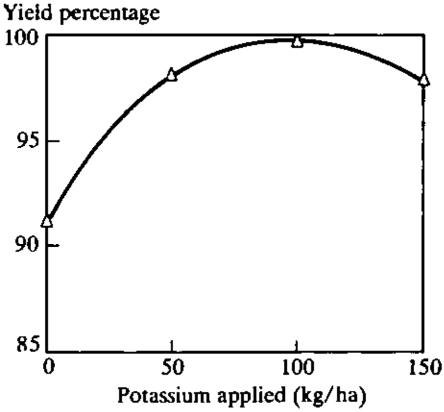

Fig. 8 Relationship between sorghum (UPL Sg 5) percentage yield and K application rates on a Bolinao clay in the Philippines, *(Samonte, H. P.,* University of the Philippines at Los Baños, *unpublished data).*

Krishnan [1978] reported data on sorghum from farmers' field trials (356 dry season and 672 wet season) in India in 1967-1971. Of 7 districts where experiments were conducted only in 2 (Andhra Pradesh and Tamil Nadu) was response to 25-50 kg K/ha in the order of 260-590 kg/ha *(Beaton and Sekhon [1985])*. In later years (1974-1977), only 4 out of 8 districts showed good responses to K for irrigated sorghum crops and 2 out of 8 districts for rainfed crops.

In the Philippines *(H. P. Samonte*, University of the Philippines at Los Baños, *unpublished data)*, relative grain yield increased with increased K application up to 100 kg K/ha (Figure 8). The grain yield difference, however, was small (ca. 8%) and within the experimental error because of high K status of the test site in Bolinao. Moreover, K application frequently decreased unit production costs and improved net returns. Increased returns on K investments for sorghum ranged from 49 to 226% *(Beaton and Sekhon [1985])*.

Maximizing grain yields of irrigated maize, sorghum, and rice

With increased emphasis on higher yield and productivity per hectare per crop and per hectare per day, high yields of hybrids as well as of conventionally bred varieties will become more important.

In maximum yield experiments conducted at the *IRRI* farm, maize, sorghum, and rice were grown on irrigated but nonpuddled soil. Three cultivars of maize, Pioneer 6181 (hybrid), IPB Var. 1 (composite), and SMC 305 (hybrid), and three sorghum varieties, COSOR 3, UPL SG 5, and CS 110 were grown on a clay loam soil (pH 5.6, total N = 0.145%).

Another experiment was installed side by side with IR43 rice, a recommended upland variety in the Philippines. All agronomic practices including irrigation, pest, and disease management were at optimum levels. Figure 9 shows the grain yields of three maize culture with SMC 305 hybrid yielding about 8.0 t/ha. Figure 10 shows the grain yields of

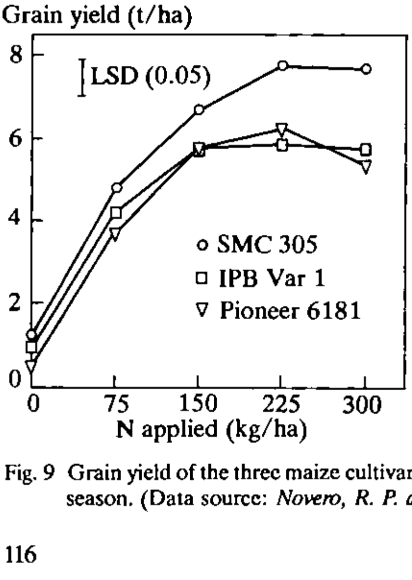

Fig. 9 Grain yield of the three maize cultivars at different levels of N applied/ha. IRRI, 1985 dry season. (Data source: *Novero, R. P. and De Datta, S. K. IRRI Agronomy Department)*.

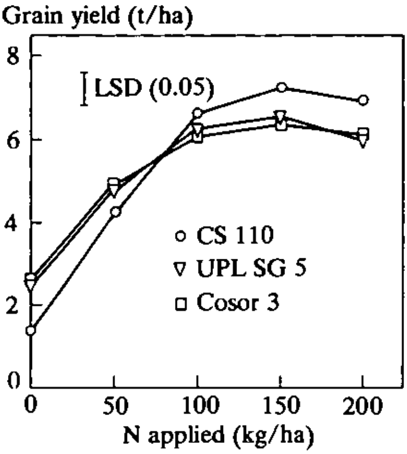

Fig. 10 Grain yield of three sorghum cultivars at different levels of N applied/ha. IRRI, 1985 dry season. (Data source: *Novero, R. P. and De Datta, S. K., IRRI, Agronomy Department).*

three sorghum varieties with the hybrid yielding more than 7.0 t/ha. The highest rice yield was 3.5 t/ha (Figure 11).

K contents in maize and sorghum stover were higher than in rice straw. However, K contents in grains of the three crops were similar (Figure 12). Results further showed that increased N application level increased N and K contents of maize, sorghum, and rice. These results suggest that high cereal yields are only possible with high fertilizer application rates containing growth limiting nutrients which consequently result in higher demands of K.

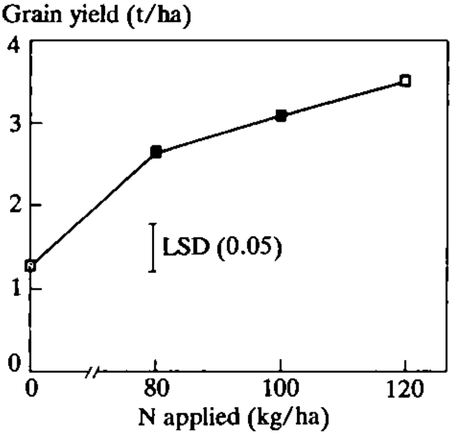

Fig. 11 Grain yield of irrigated rice grown on granulated nonpuddled soils at different levels of N applied. IRRI, 1985 dry season. (Data source: *Novero, R. P. and De Datta, S. K., IRRI, Agronomy Department).*

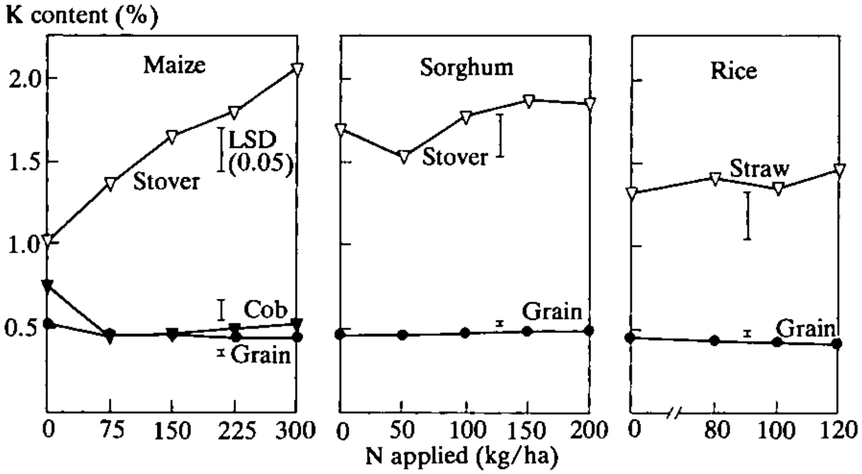

Fig. 12 K content of the different plant parts of irrigated maize, sorghum, and rice grown on granulated soil at different levels of N applied. IRRI, 1985 dry season. (Data source: *Novero, R. P. and De Datta, S. K., IRRI Agronomy Department).*

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Co-ordinator's Report on Session No. 1

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Yield Potentials and Nutrient Requirements of Crops

In the *First Working Session* we have concerned ourselves with the yield potentials of food crops in the humid tropics. The physical resources of the region were described comprehensively in the opening lecture by *Dr. van Keulen*, with supporting papers on the plantation tree crops, rice and other cereals, root and tuber crops by *Ng* and *Thong*, De Datta and Juo, respectively.

The major point that emerges from this session is that «the physical resources of the humid tropics permit high agricultural production levels»; however, in «extensive areas the potential set by crop characteristics, radiation and temperature are not reached». «Sustained high production requires inputs of materials from outside agriculture» of which, of course, application of fertilizers is a lead practice.

There is no doubt that the discrepancy between the levels of productivity that can be achieved and those actually achieved by the majority of the farmers is considerable and widespread. In a study by *IRRI* on the factors that constrain rice yields in the Philippines, it was found that actual yields were about one-fifth of the potential. These results are typical for most food crops in the Third World countries.

The constraints preventing the achievement of the high yield potentials mentioned by the speakers at this session are environmental, agronomic and socio-economic. Each of the authors discussed one or more of these constraints. Amongst those mentioned were:

– *Soils and nutrients*: *Ng and Thong* indicated that the vast majority of the soils devoted to plantation crops «fall into the kaolinitic, nutrient-poor groups of ultisols, oxisols and inceptisols». *Van Keulen* added that soils such as laterites, under heavy rainfall regime, are subject to heavy leaching. The soils are especially poor in P, and its availability is restricted. *De Datta* stressed that realizing the rice yield potential is primarily hindered by inadequate fertilizer application and improper application methods, which lead to high nutrient loss and low recovery. *Ng and Thong* too, stated that plantation crops require large amounts of K and N.

In brief: Most soils in the tropics are inherently poor, and adequate fertilization is a prerequisite for achieving high yields.

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— *Water supply: Van Keulen* pointed out that even in the humid tropics exist large areas where during part of the year water supply is a serious limitation to crop production. To these constraints I would add that the humid tropics provide an ideal environment for the proliferation of pests, diseases and weeds, and that endemic diseases debilitate agricultural workers and farm animals, reducing their productivity — with indirect effects on crop productivity. Another constraint not mentioned in the papers presented, was, that at times, excess water can be as much a problem as water shortage at other times.

The constraints due to environmental factors can, to a certain degree be overcome by appropriate management practices. The nutrient deficiencies can be resolved by adequate fertilization; solutions to the weed problems and control methods for pests and diseases can generally be provided by appropriate research. Measures are available to combat endemic diseases of man and farm animals. Water stress can be alleviated by seasonal irrigation and excess water removed by drainage.

The situation regarding socio-economic constraints is however entirely different. *Van Keulen*, on analyzing the present situation in many parts of the world (and this certainly includes the humid tropics), states that «not so much the physical resources are the limiting factor for agricultural production, but it is the economic climate in which the farming community is operating which is the serious limitation to crop production». The *Director General* of the *Thai Departement* of *Agriculture (Yookti)* made a similar statement in his adress to the colloquium.

Whilst the environmental and agronomic constraints to high productivity have been dealt with in depth in the papers presented at this session, the socio-economic constraints have only been mentioned in these presentations. However, everybody agrees that they are of major importance in impeding progress, and I therefore feel justified in allocating a few minutes of our time to discuss these problems.

A yield gap between the potential and what is actually achieved exists in the developed countries as well as in the less developed countries. The reasons for the gap and its extent are basically different for the two groups of countries. In the developed countries the gap is mainly one of *time:* when a technological innovation is proposed to the farmers, it is rapidly adopted by relatively few so-called «innovators», namely farmers with initiative, capital and healthy curiosity, who are ready to take a risk in order to increase their income. They are soon followed, at an increasingly rapid rate, by other farmers, until after a certain time-lag, the great majority of the farmers have adopted the innovation.

In the Third World countries the situation is entirely different: in the rural areas of most of these countries exist, sometimes side by side, two distinct agricultural sectors. One consists of commercial plantations and large farms, with considerable financial resources and easy access to credit and government incentives. For this sector, the use of yield increasing inputs poses no problem. This sector responds to innovations in the same way as farmers in the developed countries. In many cases, they are even the originators of the innovations they apply, as they frequently maintain research structures to service the specialized commodities that they produce. They therefore achieve very high yields in these commodities, and this confirms the view that when economic factors are *not limiting*, the gap between potential and actual yields is no greater in humid tropics than elsewhere.

The other sector is that consisting of the vast majority of the farmers — the small subsistence farmers — producing mainly food crops and using traditional methods of production. They are imprisoned in a vicious circle of low productivity, little or no marketable surplus, and therefore no income with which to purchase yield increasing inputs such as fertilizers and agro-chemicals, and hence, a perpetuation of low productivity. For the farmers of this sector, there are the socio-economic constraints that make it impossible to overcome the agronomic and environmental constraints. For them, the technology gap is *not* a matter of time needed for the diffusion of improved methods throughout the rural sector. The gap remains unchanged until the socio-economic constraints are eliminated or at least alleviated.

It is this so-called «dual economy» which explains why the gap between the high potential yield of the tropical commercial plantation crops and their actual yields is relatively small, whilst an enormous gap persists in regards to the food crops produced in the same region by the vast majority of the farmers. In their case, the ratio between potential and actual yields can be of the order of 5:1 or even wider, as in the case of the rice crop mentioned by *IRRI* survey.

This situation explains the tragic paradox that countries in which less than 5% of the active population are engaged in agricultural production are capable of producing enormous amounts of food for export, whilst in the countries in which more than half the population is engaged in agriculture, almost all of the World's hungry, undernourished and starving people are to be found.

Subsistence farmers are not capable of breaking the vicious circle into which they are born by their own efforts. The gap between potential and actual yields can only be closed if governments act to make this possible, by providing credit at reasonable terms for the purchase of essential inputs, insurance against risks involved when adopting new technologies, supply of fertilizers and agro-chemicals at the right time and at reasonable prices, marketing infrastructure and adequate supporting services such as research and extension.

Governments in the developing nations are becoming increasingly aware of the need to remedy the critical food situation in their respective countries and they have come to realize that this can only be achieved by improving the productivity of the majority of the farmers. No wonder that they have become sensitive to this problem. Since the 1970's, the need to improve the lot of the small farmers in the developing countries by modernizing their agriculture has been dinned into the ears of government leaders and policy planners by all the international bodies concerned with rural development in the Third World.

Why should these matters be the concern of the researchers — our concern? For two very good reasons: First — it is a major source of frustration for the researcher when his work affects only a very small sector and has no impact on the great majority of the farmers he is supposed (and wants) to serve; second — he too finds himself imprisoned in a vicious circle; as long as the majority of the farmers are *unable* to adopt improved practises, agricultural research will have a negligeable impact on the country's agriculture and, therefore, on the rural economy as a whole. As long as this situation remains unchanged, it will be difficult to convince the policy makers, who also hold the purse-strings, and who in any case are sceptical about the value of agricultural research, to allocate adequate funds to the research organizations. Agricultural research will remain ineffective, thereby confirming the scepticism of the policy makers.

It therefore follows that agricultural research workers cannot remain passive in this situation and must act to change it. To achieve this purpose it is necessary for the research organizations to create strong links with the establishment responsible for agricultural development. The need to convince policy makers of the potentials inherent in applying the results of agricultural research on a national scale is as important and crucial to the research organizations and their workers as publishing papers. Doing good research is not enough, it must be perceived as an effective tool in promoting agriculture. Unfortunately, many agricultural research organizations in the developing countries hold themselves aloof: links with government institutions involved in development and those that hold the purse-strings are minimal and often antagonistic. These links often consist in nothing more than going hat in hand to request budgetary allocations, barely sufficient to maintain the *status quo.*

First and foremost, the research organizations need to establish long-term research programs, based on priorities congruent with the national agricultural development plans. It is essential to show that the realization of the development targets is largely dependent on the implementation of the proposed research program and the effective application of the results of this research. Every effort must be made to demonstrate the links between research and development. The policy makers and planners should be enticed to visit the research stations, see on-farm trials and pilot farms. They should be invited to attend research seminars, to present their problems, and to learn what is being done to solve them. They should also be involved in the planning of the research program. The same links need to be forged with the extension service and the farmers' organizations.

A research organization that shows initiative and drive in these matters can achieve very much in improving its ability to do good and important work. It is also a prime candidate for help from international organizations, such as the *World Bank, FAO, UNDP, ISNAR,* and the *International Research Centres.*

In brief: Agricultural research must not only be part of the development process, it must also make its own special contribution. A significant part of the research effort must be specifically directed to solve the special problems of the small farmers, such as: devising and testing improved farming systems, rational management of mixed cropping, diversification of the commodities produced, improved tools and equipment, socio-economic studies of the constraints preventing the adoption of yield-increasing inputs. These efforts will make a major contribution in reducing the gap between farming practice and the yield potentials described in this session.

Chairman of the 2nd Session

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2nd Session

Dynamics of Potassium in Soil/Plant Systems

The Dynamics of Potassium in the Soil-Plant System

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Summary

Soil and plant interact in a variety of ways. This interaction is especially evident in the processes concerning the nutrient supply to plants growing in a soil. The plant itself initiates the transport processes involved in the nutrient supply. Growth rate and root system determine within the limits of the soil's capability the supply rate. Important factors determining the soil's capability to provide for the K demand of the plant are K concentration in the soil solution, buffer power, K quantity and soil water content.

The same principles apply to temperate as well as to tropical conditions. The importance of the various factors, however, differs. The larger part of the soils in the humid tropics have low storage capacity for nutrients and water and it is more difficult to keep them in a productive state. Food crops in the tropics do not require particularly high supply rates but some have a higher total requirement than temperate crops. Fertilizing strategies for K in the humid tropics have to be different from those in temperate regions taking heed of the large possible fluctuations of K supplying power due to the peculiarities of soils and climate.

1. Introduction

The term dynamics as opposed to status infers change and mobility. It appears self-evident that plants and soils are dynamic systems that undergo changes while they exist. And as far as nutrient supply is concerned plants and soils form a highly ineractive dynamic system. However, looking at the soil-plant system in this way has been a fairly recent development in the history of soil-plant research. Yet great progress has been made within this short timespan.

There have been many attempts to characterize the nutrient supplying power of soils by trying to simulate the feeding action of plant roots and to determine that fraction of the nutrients contained in the soil that is available to the plant during the vegetation period. A long list of chemical, physical and biological methods exists having been developed in pursuit of this goal *(Grimme,[1980])*. But by and large all these efforts met for various reasons with limited success, one of the reasons being that the nutrient supplying power is not a simple function of an (more or less arbitrary) extractable quantity but is related to a number of parameters that govern the nutrient supply of the plant. It was tacitly assumed that the roots could effectively scavenge the soil for nutrients provided a sufficient quantity was present to meet the plants requirement. No thought was given to a consideration whether the nutrients would be present at the root surface at an appropri-

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ate time. It was *Bray [1954]* who realized this limitation. He put forward the idea that nutrient mobility is an important factor of availability and suggested a conceptual framework that introduced nutrient mobility, nutrient quantity and plant foraging power into a concept of soil plant relationships with regard to nutrient supply. His main conclusion then was that, if a nutrient is mobile, the total quantity present will determine uptake. If the nutrient is immobile the amount absorbed by a crop is a function of length of root produced. Thus chemical analysis for determining nutrient supply would be adequate only for mobile nutrients. This was confirmed later on by the successful introduction of nitrate analysis in soils for N fertilizer recommendation *(Soper et al. [1970])*. Ironically enough that nutrient that was believed to be the most difficult with respect to the use of soil analysis for making fertilizer recommendations turned out to be the one which was to manage most successfully *(Dahnke and Vasey [1973]; Soper et al. [1970]; Scharpf [1977])*, at least for cereal crops in temperate regions. The reason for this is that nitrate is fully mobile in the soil and its availability in the soil volume explored by plant roots depends mainly on soil water content *(Casper [1975])*. The problem of N-mineralization appears also to be amenable to soil analysis *(Németh [1982] Németh and Wiklicky [1982])*.

With an immobile nutrient, such as potassium the situation is far less straightforward and despite persistent efforts since *Way's [1850, 1852]* discovery of the ion exchange property of soils and *Dyer's [1894]* citric extraction procedure up to *Nemeth's [1979, 1982]* reintroduction of electro-ultrafiltration (EUF) no generally accepted soil testing method for potassium has been developed which would allow to identify with certainty potassium responsive soils and to determine with satisfactory accuracy the K fertilizer requirement for maximum yield.

Bray's ideas were taken up by *Barber [1962, 1984]* and *Barber and associates [1963]* and by *Nye and his group* (see *Nye and Tinker [1977]*. This new approach did not have a direct bearing on soil testing practice for K but it helped to understand why soil analysis has its limitations and what these limitations are and that it is impossible to simulate by means of an extraction procedure, however ingenious and elaborate, the feeding process of the plant. Extraction procedures determine a K status (a different one for each method) of a soil whereas, in fact, the K supplying power of a soil is not only a function of the K status — in itself a vague term — but also of other soil properties, as well as of a number of interacting processes. That is, we are dealing with a dynamic system which cannot be adequately described by one static parameter *(Grimme [1976, 1980]; Tinker [1978])*.

2. Principles of potassium supply to plants

There exist already a number of monographs and reviews dealing with the principles of nutrient supply to plants and giving detailed accounts, especially of the theoretical aspects *(Olsen and Kemper [1968]; Nye and Tinker [1977], Barber [1984], Mengel [1985])*, so that for details and mathematical treatment of the problem the reader can be referred to those. The theory of nutrient supply and an understanding of the underlying principles appears to be fairly advanced, whereas the practical application of these principles is lagging behind. This is not because of incompetence on the part of those involved, but because of the complexity of the problem.

A model calculation (Table 1) reveals that only a minor part of the total requirement of a plant is found in the immediate vicinity of the root surface in exchangeable and soluble

Table 1 Comparison of the surface area of solid soil particles with root surface area in a cereal field with a rooting depht of 100 cm. The calculations are based on data of *Dittmer [1937], Gliemeroth [1952]* and *Vetter and Scharafat [1964]*. Root hairs are not included. According to *Drew and Nye [1969]* root hairs increase the root surface area by a factor of 3-5 on those root sections on which root hairs oxist. Their lifespan however, is comparatively short.

Surface area of soil	$5 \times 10^6 - 5 \times 10^7$ ha/ha
Root surface area	$1 \times 10^2 - 1.5 \times 10^2$ ha/ha
Ratio of soil surface area to root surface area	$1 : 10^4 - 10^5$
Soil exchange capacity in contact with roots	$10^4 - 10^5$ me/ha (equivalent to 0.2 – 2 kg Ca/ha)

form *(Barber et al. [1963]; Drew and Nye [1969]; Drew et al. [1969])*. It can also be shown that plants absorb the nutrients from the soil solution, and that a direct transfer from the solid soil particles into the root is not possible without passing through the soil solution *(Mengel, et al. [1969])*. The uptake rate is, therefore, largely governed by the K concentration in the soil solution surrounding the root surface. Thus a concentration gradient builds up, initiating diffusive flux towards the root, since under normal conditions convection or massflow cannot supply sufficient K to meet plant demand *(Oliver and Barber [1966]; Brewster and Tinker [1970]; Renger et al. [1981])*. K transport to the roots — be it diffusion or massflow — takes place in the soil solution and its rate depends, among other factors, on the K concentration in the soil solution *(Rowell et al. [1967]; Nye [1972])*.

2.1 Available potassium and its availability

With respect to soil-plant relationships, there exists a number of vague terms which are being used liberally without giving thought to their precise meaning. Examples are, for instance, the terms available K, K availability and K status, which are quite often used as if they were interchangeable whereas, in fact, they have rather different meanings and are, unfortunately, not very well defined.

The term K status should only be used in connection with the method which was used to determine it, otherwise it is meaningless. The K status of a soil is most commonly determined by extracting a fraction of soil K that is in a fast reacting equilibrium with the soil solution and comprises — depending on the extraction procedure — more or less completely the exchangeable K which is for most practical purposes a fairly well defined fraction of soil K.

Available K is a very unsatisfactory term since in the last analysis nearly all soil K would eventually be available if cropping and weathering were carried to the extreme. No precise definition can be attached to it. Soluble, exchangeable, interlattice and lattice K, all these fractions of soil K are eventually available to plants *(Schachtschabel [1937]; Mortland [1958]; Scheffer et al. [1960]; Rich [1968]; Malquori et al. [1975]; Grimme [1980])*, however, to varying degrees, depending on the energy with which they are held by the soil and the length of the diffusion path they have to cover before entering into the soil solution, and from there on to the plant roots. In other words, the rate of release into the soil solution and the travelling distance times velocity determines their availability. In fact, the word «available» suggests more information than it actually carries, unless it is further qualified by stating the method by which the «available» quantity has been determined. But in that case the word «available» would be redundant. The term «available K» should only be used if the time during which it can be rendered available can also be stated.

The term K (or nutrient) «availability» describes an obviously complex situation and must not be confused with «available K» (meaning a quantity) and denotes a quality which is difficult to quantify. Previous concepts of availability have been stated in terms of quantity and intensity factors. But these give only a static picture, whereas, in fact, one is dealing with a highly dynamic system which includes soil properties as well as plant properties which exert a great influence on the kinetics of the system. Nutrient transport rates in the soil can only be defined in terms of root systems and rooting pattern. Morphological, anatomical and physiological root properties have to be taken into account in addition to such soil properties (porosity, soil water content) which are normally not considered in conventional soil analysis. For this reason there is no single clear-cut value for nutrient availability in a given field, because it is not an invariant, constant property like clay content. For this reason it is also unlikely that the dynamic approach will supersede the conventional analytical methods as a practical tool. But it will help us to understand the results of these simple analytical techniques better and use them more effectively. In addition it should help us to use technical terms in a more careful and precise way.

2.2 Mechanisms of K supply to plants

Let us assume that a root grows into a soil compartment in which the individual components and phases are in equilibrium. The moment when the root begins to take up water and nutrients, this equilibrium will be disturbed and a number of interdependant processes will be initiated. The root absorbs potassium from the soil solution which is in direct contact with the root with the uptake rate being proportional to the initial K concentration in the soil solution. This will reduce the K concentration near the root and a concentration gradient will be generated, resulting in a net diffusive flux towards the roots. This diffusive flux is kept going as long as the root is absorbing K.

Besides nutrients the roots also absorb water of which only a small proportion of total plant demand is in proximity of the root so that most of the water taken up by a plant has to flow to the roots along a water potential gradient. The water then takes along the solutes dissolved in it. This type of transport is called mass flow. The solutes will be taken up by the roots if there is a demand or else they will accumulate around the root with a concomitant effect on exchange and solubility equilibria and on release processes.

It is obvious, therefore, that a growing plant sets off a whole string of processes in the soil around its roots which without the plants action would not take place at all or would proceed at a much slower rate. It is, therefore, important to include plant properties in any considerations of nutrient availability. Each of the above-mentioned factors can be a limiting factor in nutrient supply. Even if it is difficult to assess the quantitative effect of these processes which are involved in the nutrient supply it is important to bear in mind that they are set off by the plant itself, and are an important component of availability.

2.2.1 Mass flow

Mass flow is called the movement of nutrients through the soil pores in the convective flow of water to plant roots. Its magnitude depends on the water consumption of the plants and the nutrient concentration in the soil solution. It is obvious that the amount of nutrient transport by mass flow is highly variable in space as well as in time. Its contribution to potassium supply to the plants is rather low. Until recently this statement was based on calculations, taking into account total water use by a crop and mean average K concentrations *(Barber et al.[1963]; Mengel et al. [1969]; Barber [1984])*. These were only rough approximations.

But there are also field data available which support the above assumptions. In these experiments, water and nutrient uptake, nutrient concentrations in the soil solution and mass flow were determined in weekly intervals for each 10 cm layer of the whole rooted soil profile throughout the growing period. This was done for several crops *(Strebel et al. [1980]; Renger et al. [1981])*. The data for spring wheat are presented in Figure 1 as cumulative curves over time for the 0-30 cm, 30-60 cm depth and the whole rooting depth. At anthesis total K uptake had been 205 kg K/ha. Only 4 kg K/ha had been supplied by mass flow up to that stage. After anthesis no further K uptake occurred. Thus supply through mass flow had been negligable. Similar results were obtained for sugar beet and spring barley. The contribution of mass flow will not always be as low as in these experiments, but even a tenfold increase in our case would have accounted for only 20% of total supply.

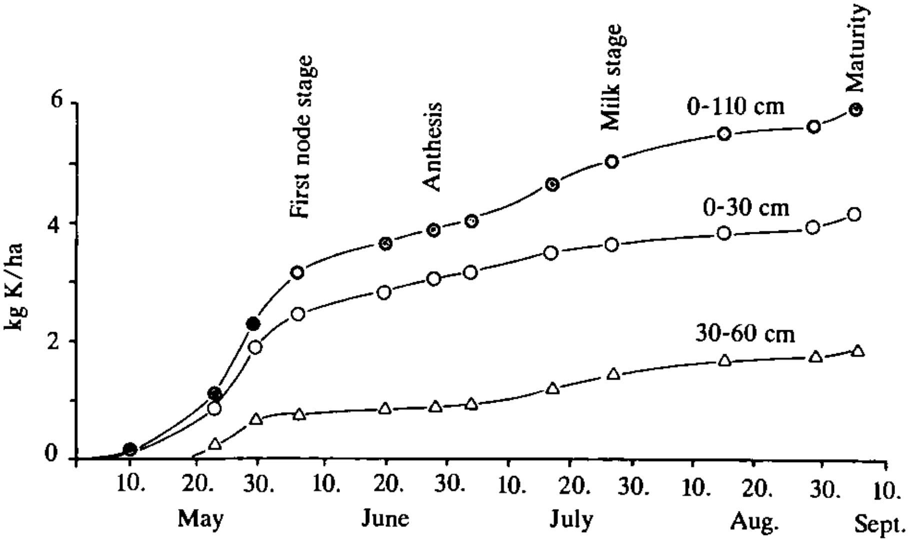

Figure 1 Cumulative curves of potassium supply through mass flow to a crop of spring wheat. The different curves represent the total mass flow for the whole rooting depht as well as the individual contribution from top- and subsoil. There was hardly any mass flow below 60 cm because of low rooting density and low K concentration in the soil solution. Maximum K uptake was 205 kg K/ha at anthesis. *(Renger et al. [1981])*.

2.2.2 *Diffusion*

There are extensive theoretical treatments of solute movement by diffusion in the soil *(Nye and Tinker [1977], Barber [1984])* and the interested reader is referred to these monographs for details. This review will concentrate on the more practical aspects of the subject.

As explained in the previous chapter, transport by diffusion is the major K supply mechanism to plant roots. It results from a disturbance of equilibrium by K uptake through the roots. A mathematical expression for the simplest case of one-dimensional flow and stationary conditions is given by *Fick's* First Law:

$$\text{Diffusive flux} = -D\frac{dc}{dx} \qquad (1)$$

where c is the concentration of the mobile species and x is the distance over which net diffusion occurs. D is the diffusion coefficient.

For soil systems equation (1) has to be modified, since the cross sectional area available for diffusion is restricted to the water filled pore space and a term for the tortuosity of the diffusion path has to be included *(Nye [1972]).*

$$\text{Diffusive flux} = -D_e\, vf\frac{dc}{dx} + F_e \qquad (2)$$

D_e is the diffusion coefficient in the soil solution, v is the fractional volumetric soil water content, f is an impedance factor taking account of the tortuosity an discontinuity of the soil pore system. F_e represents the contribution of the solid component which is negligibly small if at all existing.

Since the cross sectional area and the tortuosity factor are functions of soil water content, ion concentration in the soil solution and soil water content emerge as the important factors governing K diffusion in soils. A further elaboration of the equation would also include the buffer power of the soil for K in solution

$$b = \frac{dc_e}{dc_e} \qquad (3)$$

The driving force for K to diffuse towards the roots results from the K depletion around an absorbing root. This depletion zone was demonstrated by *Farr et al. [1969]* and more recently and in more detail by *Claassen and Jungk [1982].* Figure 2 demonstrates that plants can, indeed, reduce the K concentration around their roots to very low levels generating a steep concentration gradient. One notes also the difference between the loamy and the sandy soil. The depletion zone extends only a few mm away from the root and is larger in the sandy soil, although the sandy soil had a higher initial K concentration and exchangeable K content. But the sandy soil had also a lower buffer power which proved to be a very important soil property with respect to K supply.

All these factors combined lead to a larger depletion volume in the sandy soil and a steeper gradient over short time intervals (1-3 days). With increasing duration of K

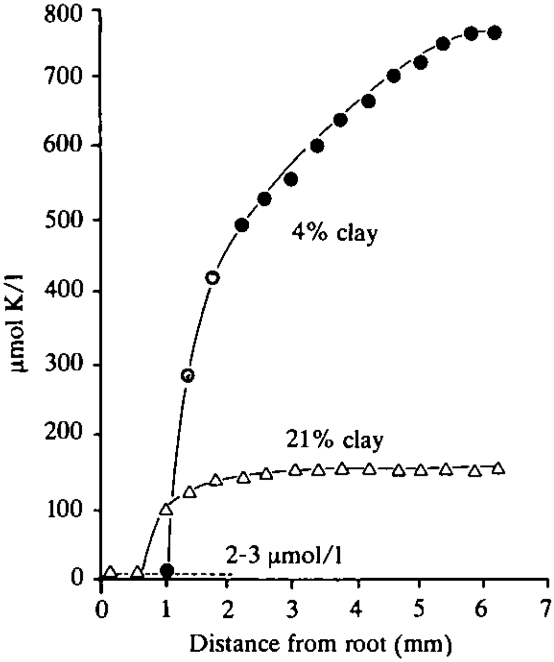

Figure 2 Potassium concentration in the soil solution around a maize root in two different soils after 3 days. The initial exchangeable K content was 0.17 me/100 g in the loamy soil (21% clay) and 0.37 me/100 g in the sandy soil (4% clay). Because of the lower buffer power of the sandy soil the difference of concentrations in the soil solution were higher than that of exchangeable K. *(Claassen and Jungk [1982]).*

uptake the depletion zone would extend further into the soil but more so in the less well buffered soil with a proportional reduction of the concentration gradient and hence diffusive flux. This reduction would be much less in the well buffered soil.

These were results from short term experiments with young plants under controlled conditions. There are no methods available to do such direct measurements in the field. But there is no reason to doubt that the situation under field conditions would not in principle be the same. The knowledge of the contribution of mass flow to K supply to the plants from individual soil layers (see previous chapter) allows us to make an estimate of the K supply through diffusion from various depths of the profile. If rooting density and soil water content are known as a function of depth and time, one can use diffusion measurements done in the laboratory on samples taken in the field from the individual soil layers, in order to calculate K diffusion to the plant roots for specified time and depth intervals *(Grimme et al. [1981]; Fleige et al. [1983]).* Figure 3 compares the calculated total K supply to a crop of spring wheat through diffusion with the actual K uptake up to the stage of maximum uptake, which was at anthesis. The agreement is quite good considering the uncertainties involved in such a calculation. The K supply from each horizon changed during the course of the growing season (Figure 4). This change reflected mainly the effects of root growth and soil water content. The contribution of the plough layer to total supply dropped from 100% at the beginning of the growing season to about 50%, so that during the period of maximum uptake a substantial share of K supply came from the subsoil. The B_t horizon had the largest share with about 25%. Similar results were obtained with a different technique by *Kuhlmann [1983]*.

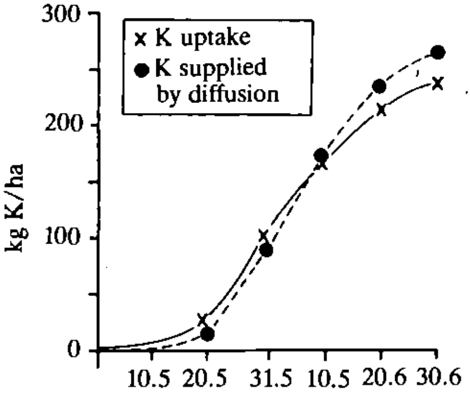

Figure 3 K uptake curve of spring wheat and calculated K supply through diffusion up to the stage of maximum uptake at anthesis. *(Fleige et al. [1983])*.

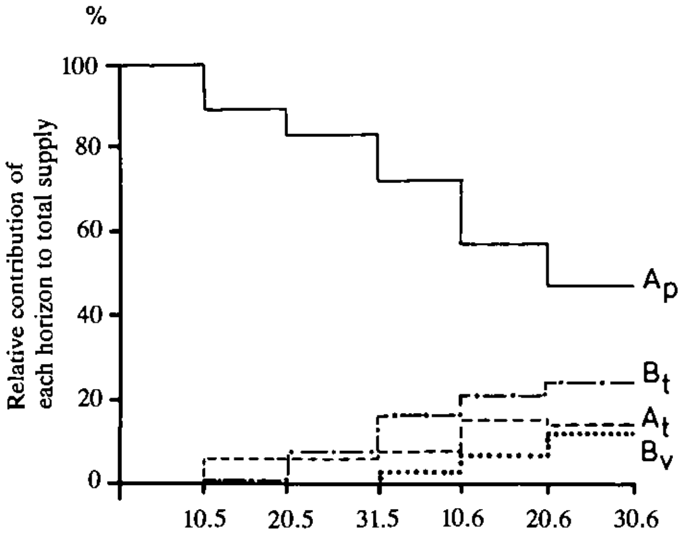

Figure 4 Calculated relative contribution of individual horizons to K supply through diffusion for a wheat crop. The data were calculated stepwise for 10 day intervals. *(Fleige et al. [1983])*.

2.2.3 K release

During the course of the growing season the K in the soil solution is continually being replenished through release from exchangeable and non-exchangeable forms (non-exchangeable K denotes all forms of K that do not exchange against NH_4, because it does not seem appropriate to distinguish between non-exchangeable and mineral or lattice K. It would rather be appropriate to differentiate between K in layer silicates and other silicates such as feldspars, which really have a different quality). It depends on the degree of the reduction of K concentration whether only exchangeable K or also non-exchangeable K will be involved in this replenishment — release process, which means that K release from interlattice sites will be especially great in the soil nearest to the root surface *(Claassen and Jungk [1982])*.

Equilibration between solution K and exchangeable K is rather rapid and will hardly ever be a limiting step provided the pool of exchangeable K is large enough to satisfy demand. The K release from interlattice sites of clay minerals, however, is a rather slow process as compared with K mobility in solution, as is evidenced by the apparent diffusion coefficients. The diffusion coefficient may vary from $5 \cdot 10^{-19}$ cm²/s in an illite *(Quirk and Chute [1968])* to $7 \cdot 10^{-9}$ cm²/s in an interstratified (10-14 Å) clay mineral *(Smith et al. [1968])* as determined from release rates, whereas in solution it is about $2 \cdot 10^{-5}$ cm²/s.

Release at an appreciable rate involves expansion of the mineral lattice and hydration of interlayer ions. It is for this reason that in already partly expanded clay minerals the apparent diffusion coefficient is so much greater than in illite (see above), and only small zones along the edges are involved. Comparatively small amounts are released during a growing season *(Martin and Sparks [1985])*, but over longer periods or with intensive cropping, release can be substantial *(Schachtschabel [1937]; Scheffer et al. [1960]; Arnold and Close [1961])*. But even under normal cropping conditions, release can locally be very high at microsites in that part of the soil that is explored by the root hairs, the so called rhizo-cylinder *(Claassen and Jungk [1982])*, even though the exchangeable and solution K outside this zone is too high for release to take place *(Fergus and Martin [1974])*.

Soils differ in their release potential depending on clay content, clay mineralogy and degree of weathering. *Abel and Magistad [1935]* demonstrated that once the exchangeable K had been depleted, less weathered Hawaiian soils released more non-exchangeable K than highly weathered soils. In a more recent study of soils derived from loess it was found that on intensive cropping with rye grass those soils with a high initial exchangeable K content had also a higher K release potential than soils with a low initial exchangeable K content (*Weber*, in prep.), which points to a larger pool of loosely bound interlayer K along the edges with short travelling distance into the soil solution. Although it is a firmly established fact that plants are able to take up more K than is present in the soil solution and in exchangeable form it is also an established fact that the growth, especially of vigorously growing plants, is impaired if a substantial part of its K requirement has to be drawn from non-exchangeable K (Figure 5). It could be demonstrated that yield decreased with an increasing proportion of non-exchangeable K contributing to the K supply of the plants *(Grimme [1974])*. This corroborates the above-mentioned laboratory finding on diffusion rates in clay minerals. Release rates are apparently not high enough to supply the major part of the K demand of a high yield crop.

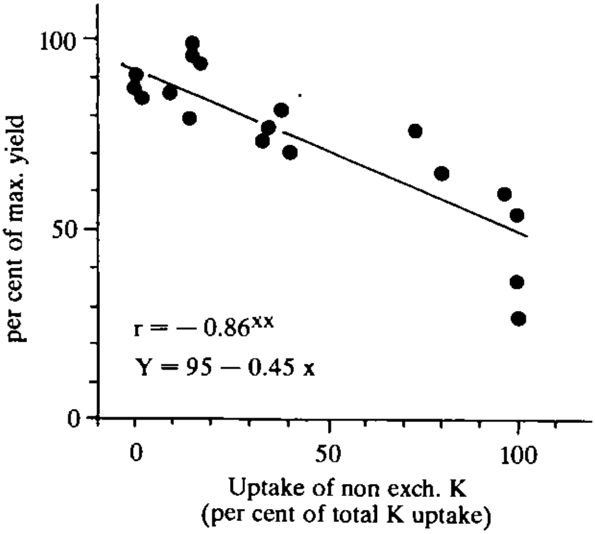

Figure 5 Relationship between yield and the percentage of K taken up from non-exchangeable sources *(Grimme [1974]).*

2.3 Factors affecting K supply to plant roots.

Soil properties as well as plant properties have an influence on the quantity and rate of nutrient supply to plant roots. As the title of this paper stresses «dynamics» and the K supply is mainly through diffusion, only the factors related to diffusion, and of those only the most important ones and of which pertinent experimental data are available, will be included in the discussion.

The question of nutrient supply can only be discussed adequately when the soil-plant system is seen as a whole. Plants interact with the soil in such a way as to modify the soil environment in the vicinity of the roots by exuding organic compounds, protons or bicarbonate ions, by withdrawing water and nutrients. Thus the movement of solutes towards the roots is started off by the plant itself. Therefore, uptake properties of the plants, growth rate at different growth stages and nutrient demand are important factors. Unfortunately it is only recently that more research is being directed in this direction, so that in many respects only qualitative statements can be made.

2.3.1 K concentration in the soil solution

A high initial K concentration ensures a high initial uptake rate. A high uptake rate for a given root segment can only be sustained if either transport through the soil is rapid enough to meet plant demand or the buffer power of the soil is high enough to maintain a certain level in the soil solution. In most soils a combination of both factors will be operating.

At equilibrium the K concentration in the soil solution depends on exchangeable K, clay content, clay mineralogy and pH *(Németh et al. [1970]; Németh and Grimme [1972];*

Németh and Grimme [1974]). At a given exchangeable K content the K concentration in the soil solution will be higher in the soil with the lower clay content, provided the clay mineralogy of the two soils is not too different. A lower pH means a lower selectivity for K than a high pH and a change of slope of the buffer curve towards less buffer power. The K selectivity of soils also decreases in the sequence illite, > vermiculite > smectite > kaolinite. An example is given in Figure 6 comparing an illitic with a kaolinitic soil.
In soils with a well buffered soil solution the depletion zone around a root will be smaller and the concentration gradient will be steeper than in a soil with a low buffer power (sandy or kaolinitic). Both factors result in a better K supply in the former case.

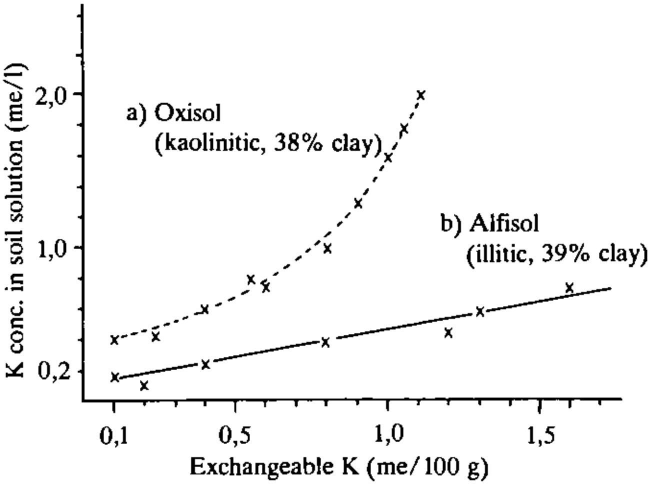

Figure 6 Relationship between exchangeable K and K concentration in the soil solution of two soils with the same clay content but different clay mineralogy. The steeper slope of the kaolinitic soil indicates less buffer power. *(Németh,* unpublished).

2.3.2 Soil water content

Soil water has two main effects on plant growth which operate independantly. Water is in the first place an important constituent of the plant and is as such essential for plant life. On the other hand water is the medium from which the plant absorbs the nutrients and it also serves as the transport medium with which and in which the nutrients move in the soil to the roots and are translocated in the plant. One can, therefore, visualize a situation where the water content is below field capacity yet the water supply is still adequate for plant growth but the nutrient transport to the roots is already impaired because soil water content determines the cross sectional area available for diffusion and the tortuosity and continuity of the diffusion path.
K availability is, therefore, not a constant soil property depending on the amount of K present in the soil and the energy with which it is held by the soil. The K level may be more than adequate in a period with sufficient rainfall and considerably below optimum in a dry period. Quite a number of experiments testify to this conclusion. *Van der Paauw [1985]* obtained the largest difference in yield between no K and 400 kg K_2O/ha in

those years that had the largest number of rainless days during the months of May, June and July. He attributed these findings to restricted K availability in dry soil which could be compensated for by higher doses of K. *Barber [1959]*, too, found a differential response to K application although the K contents in the soils of the respective treatments remained practically constant over the years. The yield decrease in dry years was least on those fields that had the highest nutrient levels. He interpreted his results in the same way as *van der Paauw* did. Similar results were obtained by other authors *(Bruns [1935]; Peters and Russel [1960])*.

However, all these experiments provide only circumstantial evidence. Unequivocal proof and a quantitative estimate of the effect of soil water content on K availability can only be obtained through an experimental design that rules out a reduced water supply to the plants but allowing at the same time variations of K availability caused by variations of soil water content. This can be achieved by employing a split-root technique *(v. Braunschweig and Grimme [1973])*. Using this technique it could be shown that by reducing soil water content in a loess soil from 30% to 20% (corresponding to water potentials of 0.1 and 5 bar) K availability was reduced between 35 and 50%.

In the field it quite often happens that the topsoil dries out while the subsoil is still quite wet. The plants can then maintain the water supply but their nutrient supply may be impaired because the nutrient content in the subsoil is normally substantially lower than in the arable layer. In an experiment with soil columns in which only the topsoil was fertilized and either the topsoil or the subsoil were kept dryer than the other layer, this effect could be demonstrated. Although total water supply was the same in both treatments, yield and nutrient uptake were significantly reduced when the topsoil was kept dry (Table 2). In this experiment the yield difference could be entirely attributed to reduced nutrient availability.

Table 2 Effect of soil water content on dry matter yield, mineral composition and nutrient uptake of berseem (Trifolium alexandrium). Plants were grown in 80 cm long and 25 cm wide soil columns consisting of a reconstituted chernozem profile. Water was supplied through porous cups (3 each in the topsoil, 0-40 and the subsoil 40-80 cm) (30 cm long, 3 cm wide) connected to water reservoirs which were under a specified negative pressure. Total water supply was equal in all treatments. *(Grimme* unpublished)

Topsoil dry (0.7 bar) Subsoil wet (0.1 bar)		Topsoil wet (0.1 bar) Subsoil dry (0.7 bar)	
D.M. yield (rel)	100	130	
		Mineral composition (%)	Rel. Diff.
K	2.1	2.8	33%
Mg	0.25	0.30	20%
Ca	1.9	2.3	21%
P	0.26	0.47	67%
N	3.6	4.0	11%
		Nutrient uptake (g/soil column)	
K	2.26	3.58	58%
Mg	0.27	0.38	41%
Ca	1.97	2.86	45%
P	0.26	0.61	135%
N	3.57	5.19	45%

2.3.3 Plant roots

An adequate exploitation of soil nutrient reserves depends on a well developed root system. For an efficient exploitation of mobile ions such as nitrate it is essential that a large soil volume is enclosed by the roots, whereas a high root density is a prerequisite for a successful and efficient utilization of soil reserves of immobile ions *e.g.* K *(Bray [1954]; Baldwin [1975])*. Apart from these morphological features physiological characteristics such as root absorbing power and nutrient demand have to be considered.

Claassen and Jungk [1984] did a very thorough study of plant factors determining potassium concentration in plants and came to the conclusion that at least 3 factors have to be taken into account in order to characterize adequately the uptake properties of different plant species. They evaluated the influence of the rate of K uptake per cm of root (KAR), the root-shoot ratio (cm) root per mg dry weight (RSR) and the mean root age as a measure of the time a root absorbs potassium (MRA) on potassium uptake efficiency of different plant species. Percent K in the shoots was taken as a measure of uptake efficiency. None of these three parameters was correlated with K concentration in the shoots. Only a combination of them to one composite parameter resulted in a significant correlation (Figure 7). The conclusion is, that although all three factors have an influence on uptake the contribution of each varies markedly between species.

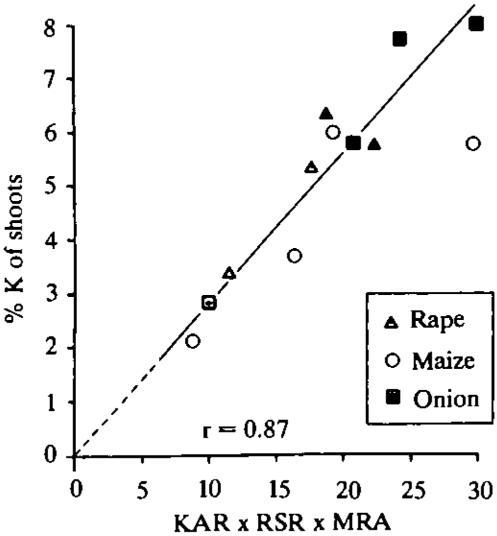

Figure 7 Correlation between the K concentration in shoots of onion, maize and rape and the product of K uptake rate (KAR) root/shoot ratio (RSR) and mean root age (MRA). *(Claassen and Jungk [1984]).*

The K uptake rate per unit root length is strongly affected by root hairs *(Claassen and Jungk [1984])*. The radial distance of the depletion zone around a root increases with the length of root hairs and thus the uptake efficiency and the capability to make use of K reserves of low mobility. The reserves of non-exchangeable K are nearly exclusively tapped only within the root hair cylinder *(Kuchenbuch and Jungk [1984])*. The K uptake is closely related to the soil volume permeated by root hairs (Figure 8). Plants with no or only few root hairs like onion are characterized by a low uptake rate per cm root. Other factors may camouflage this fact, if, for instance, a shoot with a high K demand is com-

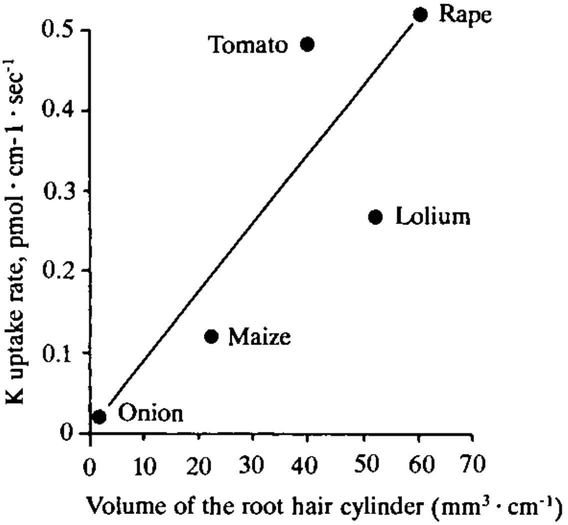

Figure 8 Correlation between the volume of the root hair cylinder and K uptake per unit length or roots of 5 plant species. The volume of the root hair cylinder was calculated for a cm length of root, and the diameter by taking the mean length of root hairs. *(Claassen and Jungk [1984])*.

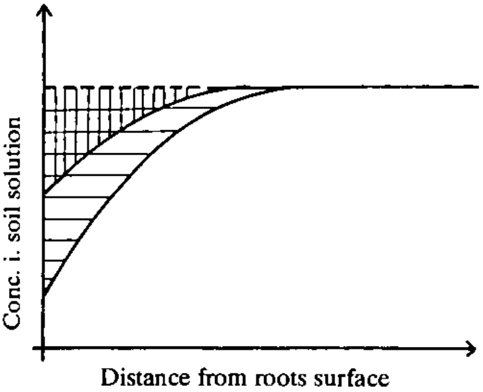

Figure 9 Schematic representation of concentration profile around an absorbing root. With a given initial nutrient concentration in the soil solution the supply rate will increase with the plants'ability to reduce the concentration at the root surface. With a lower concentration at the root surface a steeper concentration gradient is generated resulting in a greater diffusive flux towards the root. The shaded areas represent the depletion zone and are proportional to the quantity of nutrient taken up. *(Grimme [1978])*.

bined with a low density root system. *Mengel and Steffen [1985]* found that the uptake rate per unit length of root was by a factor of 2 higher in clover as compared with ryegrass although the latter had a much larger root hair cylinder.

A plant which is able to reduce the nutrient concentration at the root surface to a very low level and maintain this level, generates favourable conditions for uptake and has an advantage over species that cannot reduce the concentration to the same low level. A low concentration at the root surface means a steep concentration gradient and consequently a higher flux rate and eventually also a larger depletion zone (Figure 9).

Increasing the number of roots per plant, that is, the rooting density, results in less uptake per unit length of root and a reduction of the depletion zone around each root but also to a higher uptake potential. This would mean a safety margin for stress periods, or the average initial K concentration in the soil solution could be lower before a critical level would be reached.

2.3.3 K uptake of different crop species

The roots are the mediators of nutrient supply between soil and plant shoots. The roots cannot supply more nutrients to the shoot than the soil can yield. On the other hand the roots need not supply more nutrients than the shoot demands. The apparent efficiency of a root system is to a large extent determined by the sink properties of the shoot. This is clearly seen when comparing red clover and rye grass *(Mengel and Steffen [1985])*.

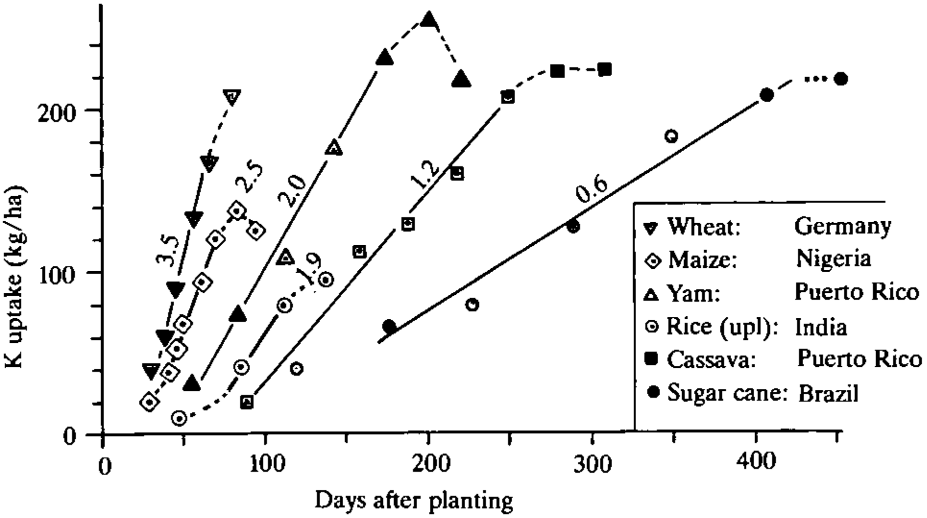

Figure 10 K uptake by various crops as a function of time. The numbers on the uptake curves represent uptake rates in kg/day. The uptake rates were calculated for the periods of most rapid uptake to which a linear regression line could be fitted. The data were taken from the following authors: Wheat: *Grimme*, unpublished; Maize: *Grimme and Juo*, unpublished; Yam: *Irizarry and Rivera [1985]*; Rice: *Kumbhar and Sonar [1980]*; Cassava: *Irizarry and Rivera [1983]*; Sugar Cane: *Orlando [1983]*.

Crop plants differ in total nutrient uptake as well as in nutrient uptake rate. This fact has to be taken into account when discussing optimum nutrient levels in soils and is one of the reasons why crop plants do not grow equally well on all soils. Figure 10 shows the K uptake curves of a number of crops. The slopes of the linear parts of the uptake curves represent the uptake rates (kg K · ha^{-1} · day^{-1}) during the period of maximum uptake. These examples were arbitrarily chosen, just to illustrate the point. It is, of course understood that a wide range of uptake curves does exist for each crop species depending on variety, location and year, and that, especially, the magnitude of total uptake does vary to a large degree.

Figure 10 demonstrates quite clearly that different crops mag pose quite different demands on the K supplying rate of soils although they may take up similar total quantities of K. It is interesting to note the high uptake rate of wheat, the only temperate crop in the examples given. Sugar cane (150 t cane/ha) required a rather low supply rate owing to its long growing season and could probably rely to a large extent on subsoil reserves or on slow release sources *(Hunsigi and Srivastra [1981])*. Upland rice, a low yielding crop, but with a high uptake rate over a short period required a high supply rate per unit soil volume since it has a sparse not very deep root system. The total reserves that can be made available during a growing season need not be particularly high for this crop.

3. The situation in the humid tropics

The basic principles set out above and which are governing the soil-plant relationship, as far as mineral nutrition is concerned, have been worked out with a view to conditions of intensive agriculture in temperate regions. However, these principles do also apply under tropical conditions since only the boundary conditions are different in terms of soils and climatic conditions.

The humid tropics are often seen as a great reserve for food-crop production. It has, in fact, been shown, that high yields of many crops can be achieved provided appropriate technology and proper soil and crop management is applied *(Sanchez [1981, Sanchez et al. 1983]; Kang and Juo [1983]; Kang et al. [1985])*. The indiscriminate transfer of unadapted agricultural technology and management practices from the temperate regions, however, has often proved disastrous.

The luxuriant and lush vegetation of the natural vegetation in the humid tropics suggests a high level of fertility. But this picture is deceptive. After clearing and burning an area, yields of food crops very rapildly decline *(Sanchez et al. [1983]; Kang and Juo [1983])* unless fertilizers are applied. Even then productivity cannot always be maintained, because of acidification and deterioration of soil structure. The common practice is, therefore, to abandon the field to natural regrowth after 3-4 years of cropping and move to another piece of land. Shifting cultivation is widely practiced in the tropics and is still the dominant practice of food production. It is probably the most effective and stable system — yet on a low level — of food production in the humid tropics, if there is abundance of land. But it does not produce enough surplus to provide food for a numerous urban population.

The nutrient reserves of a forest site in the humid tropics are to a large extent stored in the vegetation. *Klinge [1976]* found in the Amazon basin up to 90% of total K contained in the vegetation and in Columbia more than 70%. In Ghana the figures were 58% *(Greenland and Kowal [1960])*. This contrasts with 70-96% of total nutrients of forest sites in

North-America and Central Europe stored in the soil *(Klinge [1976])*. These figures demonstrate quite drastically how different the situation with respect to nutrient supply is in the humid tropics as compared with temperate regions, and how easily the ecological balance can be upset in the tropics.

3.1 Soils

Oxisols, Ultisols and Alfisols predominate in the humid tropics *(Sanchez [1981])*. In tropical South-America they make up 85% of the total land area. All three soil orders are characterized by a predominance of Fe-Al-oxides and Kaolinite in the clay fraction and the complete absence or low contents of weatherable minerals and low CEC *(Juo [1981])*. The effective CEC is quite commonly in the range below 5 me/100 g, a large part of which is contributed by the organic matter and may, therefore, rapidly decline under unsuitable management practices. These characteristics make for a low storage capacity for cations *e.g.* and a low selectivity for K. Incidentally, these soils have quite often also a low storage capacity for water in the non-limiting water range.

Inceptisols, Entisols which also occur in the humid tropics may have properties quite different from the above-mentioned but they occur worldwide only on a limited scale. But locally they may be of great importance. This rather general characterization of tropical soils does not mean that these soils are uniform. Their variability is at least as great as that of temperate soils, but on a different level.

3.1.1 Soluble and exchangeable K

There is no sense in giving ranges of soluble and exchangeable K of major tropical soils, because there is no typical range characteristic of these soils. Owing to recycling through the fallow vegetation the soluble and exchangeable K content of virgin land is in the same range as that of fertile temperate soils *(Juo and Grimme [1980])*. The difference lies in the rapid and large changes that may take place in the K concentration in the soil solution during a growing period (Figure 11) and the rapid decline of exchangeable K when fallow land is converted into crop land *(Sanchez et al. [1983])* (Figure 12). These findings testity to the fact that the buffer power of these soils is rather low as well as the K reserves that would replenish the exchangeable K fraction.

There is a number of studies which show that the buffer power of «low activity clay» soils — as the Oxisols, Ultisols and Alfisols of the humid tropics are commonly called, because of the low exchange capacity of the clay fraction — is rather low (Table 3). The potential buffering capacity of the «low activity clay» soils is by an order of magnitude lower than in the other soils. The potential buffer capacity is derived from the Quantity-Intensity relationship as proposed by *Beckett [1964]*, and represents the capacity of a soil to resist changes of K concentration. The magnitude of this potential buffer capacity for K or rather buffer power[1] depends mainly on clay mineralogy clay content and pH. This is borne out by the adsorption isotherms in Figure 13 which show that in different soils very different quantities of exchangeable K are in equilibrium with a given solution concentration. The extremes are represented by the Vertisol and the Oxisol which have the same clay content but very different mineralogy (and hence CEC and K selectivity). The

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[1] According to the definitions used in the physico-chemical literature the term buffer capacity is not correct and should be replaced by buffer power *(Nye and Tinker [1977] p. 42)*.

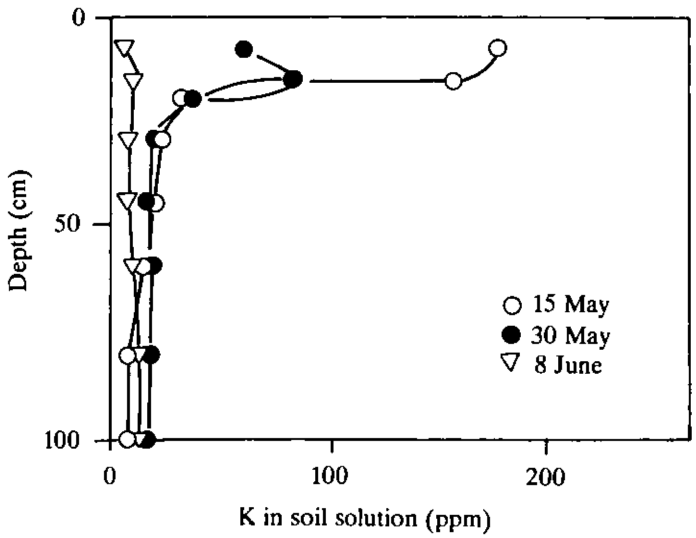

Figure 11 K concentration in an Alfisol (Egbeda series, Southern Nigeria) under maize at three different dates during the growing period. The concentrations in the subsoil were very low throughout the growing season. In the topsoil they decreased rapidly from rather high to very low levels *Grimme, Juo, Kang, [1983])*.

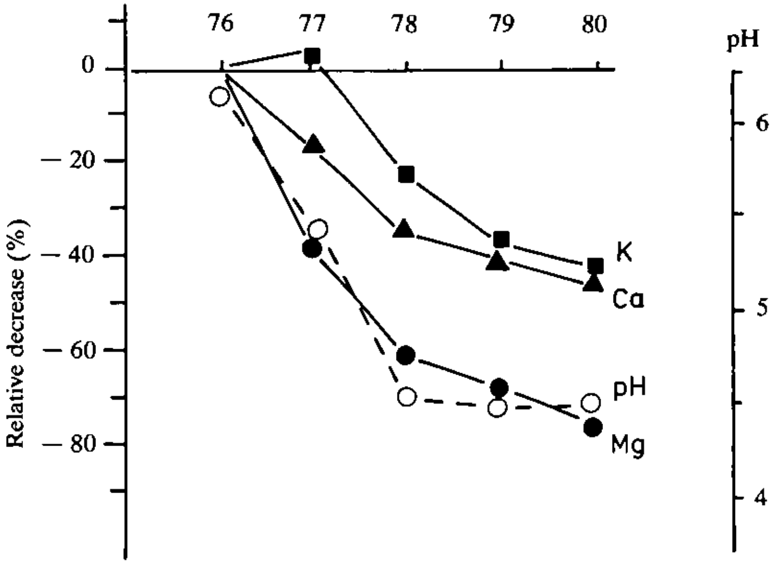

Figure 12 Relative loss of cations and decrease of pH in an Alfisol (Egbeda series, Southern Nigeria) under maize-cowpea rotation (two crops per year). Initial exchangeable K content was 24 mg K/100 g *(IITA* Ann. Rep. *[1979])*.

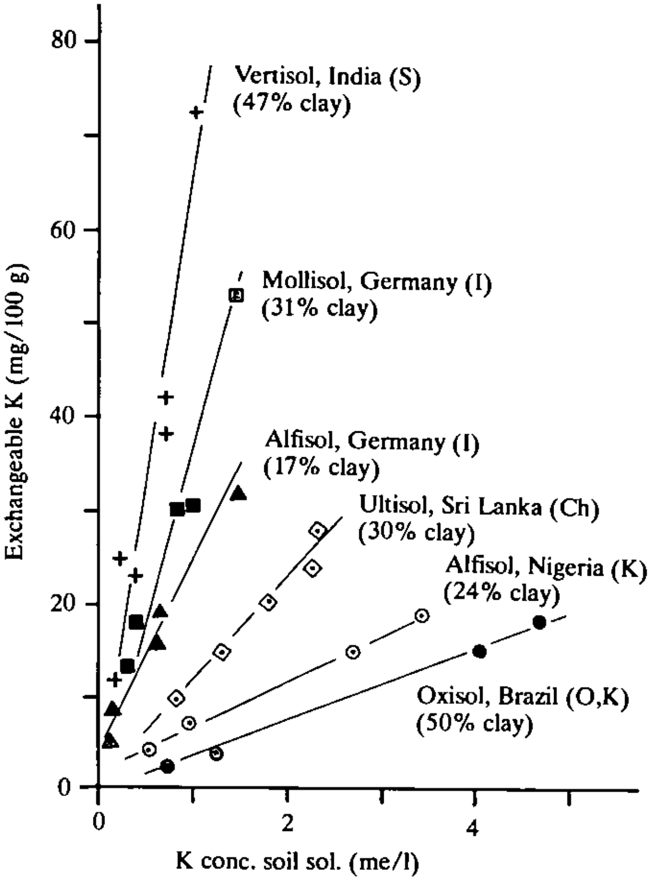

Figure 13 Adsorption isotherms from various locations in different climatic zone (humid tropics, semiarid tropics temperate) and with different clay mineralogy and clay content (S = smectite, I = illite, CH = chlorite, K = Kaolinite, O = Al, Fe-oxides) (Adapted from *Busch [1980]*).

Mollisol and Alfisol (having a similar composition of the clay fraction) from Germany demonstrate the effect of clay content. The soil with the higher clay content has a higher exchangeable K content at a given K concentration. The Ultisol from Sri Lanka has a fairly high clay content and as clay mineral secondary chlorite with K selective adsorption sites but, because of the low pH, a low effective CEC and ranks as intermediate in its K adsorption behaviour. The Alfisol from Nigeria which is a typical example of a soil order that covers large areas in West Africa is nearly as low in its adsorption capacity as the oxisol owing to the «low activity clay» fraction.

The slopes of the adsorption isotherms are a measure of the buffer power of the soil which is comparable with *Beckett's* potential buffer capacity. A steep slope means a well buffered soil and vice versa. In a well buffered soil removal of soil K will result only in small changes of K concentration in solution whereas in a soil with a low buffer power the concentration will drop substantially which explains the rapid changes that «low activity clay» soils in the tropics undergo with respect to their K content (Figures 11, 12). This is of particular importance for the situation around a root where the depletion zone of a poorly buffered soil will extend further into the soil than in a well buffered soil and will have a less steep concentration gradient. Both factors will result in a smaller K flux into

Table 3. Potential buffering capacity (PBC) of soil potassium as related so soil types, clay content and clay mineralogy (Compiled by *Juo [1981]*)

Soils	pH (H_2O)	Clay (%)	Dominant* clay minerals	PBC⁺	References
Kaolinitic Alfisols and Ultisols	4.2-6.0	10-55	Kt	1- 20	*Pfeiffer [1977]*
Oxidic Ultisols and Oxisols	4.0-5.5	40-80	Kt, Fe	13- 32	*Goedert et al. [1975], Pfeiffer [1977]*
Andepts (Andosols)	5.2-6.5	> 60	A, Fe	104-673	*Graham and Fox [1971]*
Vertisols	7.0-8.7	30-70	SM	60-100	*Acquaye et al. [1968] Le Roux and Summer [1967], Pfeiffer [1977]*

*Kt kaolinite, Fe crystalline and amorphous Fe oxides and hydrous oxides, A allophane, Sm smectite.

⁺PBC is expressed in $(me/100\ g)/(M/1)^{1/2}$

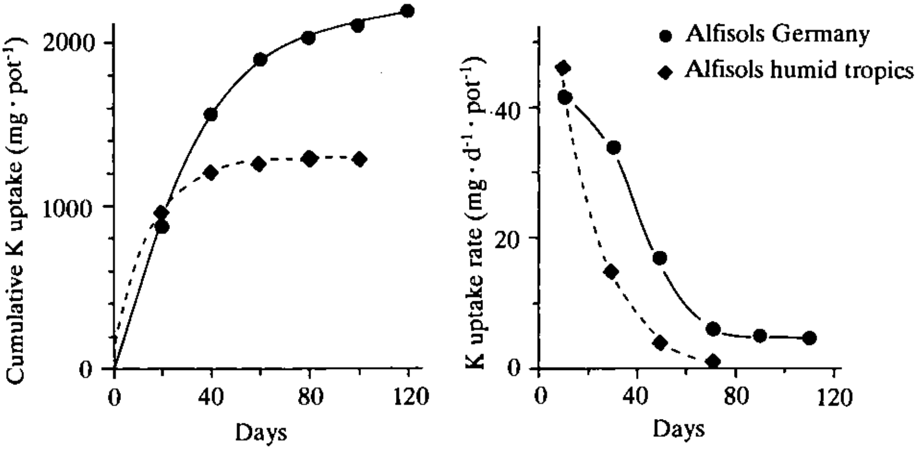

Figure 14 Cumulative K uptake and K uptake rate of rye grass as a function of time. Points represent the average of three of each group of soils. The soils were selected for similar initial exchangeable K (15-18 mg/100 g) and uptake (Adapted from *Busch [1980]*).

the root, so that an initial high supply rate may drop off rather quickly. There is no direct proof for this theoretical reasoning but some circumstantial evidence.
Busch [1980] studied in an extensive pot trial with rye grass the K supply potential of soils from various tropical regions and compared them with Alfisols and Mollisols derived from loess in Germany. In Figure 14 cumulative uptake and uptake rate of Alfisols from the humid tropics with low activity clay and from Germany with an illitic clay fraction are compared. The total K supply from the temperate soils was nearly double as high as from the tropical soils, although at the first harvest both groups of soils were at a par. But what is more important was the rapid decline of the K supply rate of the tropical soils which reflects their poor buffer power and supports the argument of the previous paragraph. Similar results were reported by *Martini and Suarez [1977]* and *Mutscher [1984]*.

3.1.2 K reserves

The K reserves (non-exchangeable ~ total K) of the highly weathered soils of the tropics in general are rather low, as one would expect. But the overall variation of total K is as great as in the temperate regions. The level of total K depends on the type of parent material, degree of weathering and on the mineralogy of the sand and silt fractions.
The availability of the non-exchangeable K depends largely on whether it is contained in micas or in feldspars and on the particle size of the K bearing minerals. In general the release rates are rather poor *(Martini and Suarez [1977]; Mutscher [1984])* and cannot support optimum growth of high yielding rapidly growing crops such as for instance yams and maize.

3.1.3 K desorbable in an electric field

Ion desorption in an electric field (EUF) is a fairly recent addition to the already large number of soil testing methods. To the knowledge of the author the EUF method (short for electro-ultrafiltration) is the only method practiced in routine soil testing that takes dynamic aspects of nutrient supply into account. For details the reader is referred to the literature *(Németh [1979, 1982]; Grimme and Németh [1979])*. It is a method that allows to assess the immediate as well as the longterm K supplying power of a soil and to differentiate between «low activity clays» and others *(Németh and Grimme [1974]; Thiagalingam and Grimme [1976])*. An example is presented in Figure 15. The desorption curves behave in a similar manner as the uptake rate curves (Figure 14) in so far as the desorption curves of the Oxisol and the tropical Alfisol go down to zero. The illitic Alfisol, after a decrease of desorption rate up to 20 minutes desorption time, maintains a steady desorption rate thereafter, which nicely parallels the supply rate to a crop over time *(Grimme and Németh [1979])*. The ratio between the seventh and second fraction or the sum of extracted K during the first 30 minutes over K extracted in the last step are a measure of the buffer power of a soil *(Németh [1979, 1982]; Grimme [1980])*. The advantage of the method lies in the fact that it provides several parameters in addition to the total desorbable quantity and, therefore, allows a better evaluation of the K supply potential of a soil.

3.1.4 Leaching

Leaching losses have been a major concern in the humid tropics under high rainfall conditions and good soil permeability. Leaching losses are recognized as a major factor limiting the productivity of the soils of the humid tropics. Despite its significance, however, only few quantitative data are available to elucidate the extent of leaching losses. Under natural vegetation leaching losses are small. They have been estimated to be in the range of 0-5 kg K/ha and year *(Nye and Greenland [1960]; Tourte et al. [1964]; Klinge [1976])*, but they can be substantial on cleared land after fertilizer application. *Omoti and Abaga [1980]* found 35% of 260 kg/ha applied in the leachate of one year when the lysimeters were being cropped and nearly 100% when kept bare. Even in the savannah region of Senegal 40 kg K/ha of 108 kg K/ha applied were lost through leaching which shows that not only total rainfall but also rainfall intensity have to be considered *(Tourte et al. [1964])*.

Pleysier and Juo [1981] in laboratory study with a rainfall simulator and undisturbed soil columns (Ultisol) found that after having applied an amount of water corresponding to two years of rainfall (4800 mm), 80% of added K (300 kg K/ha) had been retained in the 100 cm long soil column and 60 kg/ha had been leached. All the nitrate had been washed out. Thus leaching losses of K are not negligible especially when a soil is fertilized, but they are not dramatic and can certainly be reduced by splitting fertilizer application.

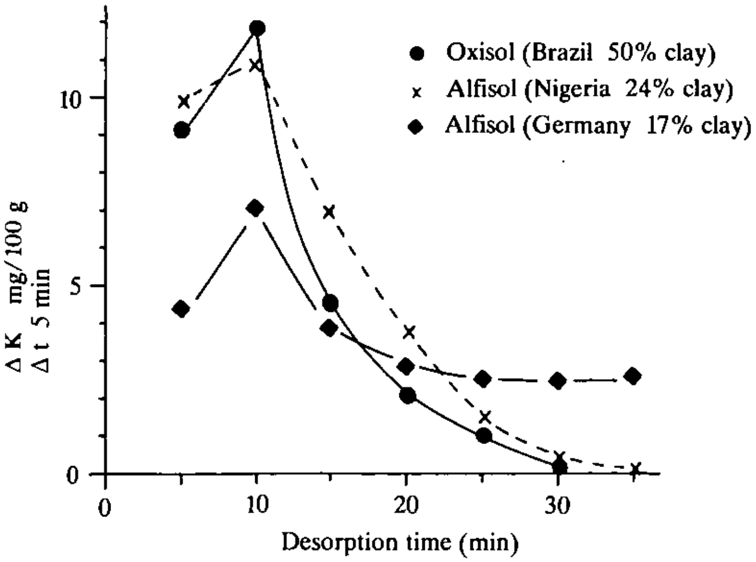

Figure 15 EUF desorption curves of 3 soils with different desorption characteristics *(Grimme, unpublished)*.

3.2 Crop plants

Misconceptions about the productivity of the humid tropics are widespread. If we compare crops grown in the humid and subhumid tropics as well as in temperate climates like maize or similar crops like rice and wheat we find that the maximum yield obtainable with high inputs are at best about the same in both climatic zones. Generally the temperate regions have an edge over the humid tropics.

Short days, often overcast skies and high night temperatures are among the factors preventing higher yields, so that the demand on nutrient supply rate is not higher than in a temperate climate. There may be a higher total requirement from certain crops with a long growing season. Where the humid tropics are at an advantage is the longer growing season which allows to grow two crops a year, or even more, if there is no pronounced dry season. There are tropical food crops like cassava that can under favourable conditions produce more marketable dry matter than any temperate crop but at the expense of a long growing period. The same applies to sugar cane and bananas.

3.2.1 K concentration in crop plants and K uptake

Munson [1982] has compiled extensive tables of critical K concentrations in crop plants and of K uptake. From these data it appears that for comparable yield levels critical levels in the plants and total uptake are about the same as in temperate regions so that in the tropics plants do not seem to have a higher demand to attain their maximum yield level.

Typical tropical plants like cassava, bananas, sugar cane, to name a few, may have under good growing conditions high total uptake — a notable example is banana with over 1000 kg K/ha total uptake — but this high uptake is spread over a long growing period, so that the demand of these crops on supply rate is not necessarily very high (Figure 10).

3.2.2 The soil-plant system in the humid tropics

Bush fallow and shifting cultivation, the traditional farming system in the humid tropics worldwide has proved to be a stable agricultural system. This system is gradually being abandoned because of population pressure, which then results in a disruption of the delicate equilibrium between climate, soils and vegetation. Figure 16 demonstrates how drastically the productivity of newly cleared land may decline but shows also that by replacing nutrient losses occurring through offtake and leaching, the original yield level can be maintained if, however, with large variations between years. The nutrient recycling of the fallow trees has to be replaced by fertilizer inputs. Considering the nature of low activity clay soils, fertilizer management has to be adapted to the characteristics of the dynamics of the tropical environment. This does also apply to potassium. Because of the low storage capacity, high rainfall (in intensity as well as quantity) no large reserves can be built up and no ameliorative dressings are advisable. Losses through leaching would impair the efficiency of such measures.

The kinetics of K uptake of tropical crops are often about the same as those of temperate crops (Figure 10). Buffer power of low activity soils is poor, so that the increase of K concentration in the soil solution (Figure 13) and initial supply rate through fertilization will be adequate for optimum growth. It must be ensured, that the quantity of K required is at the disposal of the plants. Since K concentration in the soil solution (Figure 11) and the supply rate (Figure 14) may drop off very sharply a splitting of the required fertilizer dose is called for.

Provided the quantity of K required is present in diffusible form the supply rate would not be a limiting factor when growing plants on the low activity clays in the humid tropics. This is in contrast to the situation on the well buffered soil in temperate climates where supply rate rather than quantity can be a constraint.

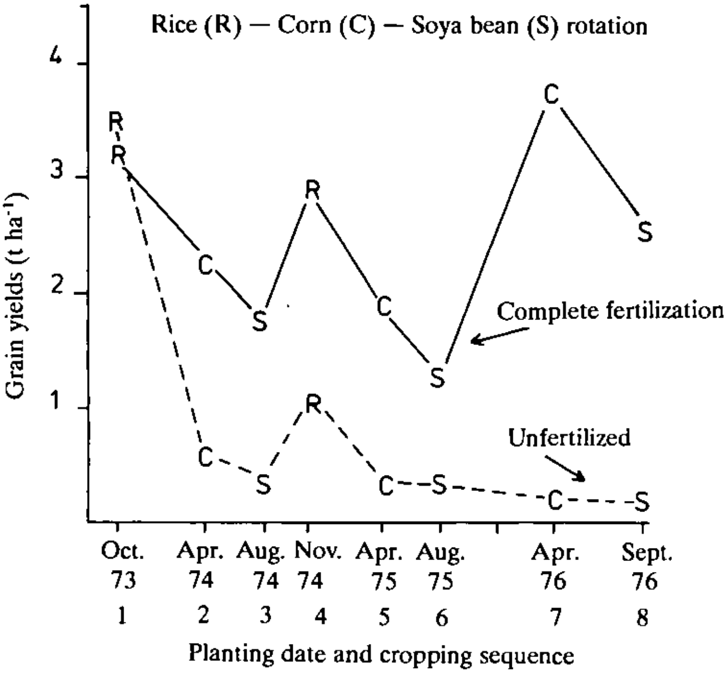

Figure 16 Yield development with time comparing fertilized (N-P-K; 80-60-80 kg/ha) and unfertilized treatments. Amazone Jungle, Peru *(Sanchez [1981])*.

Acknowledgement

Sincere thanks and appreciation are expressed to Dr. *Zehler* and his team of the Documentation Department for valuable assistance in the literature search.

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Relationship Between Mineralogy of Soil and Assessment of Potassium Availability

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Summary

Two aspects of the relationship between the mineralogical composition of the clay fraction and the assessment of the labile potassium status in highly weathered soils are discussed:
Firstly importance of residual 2:1 layer silicates and secondly dynamics of charge as a function of shifts in pH and electrolyte concentration.
Principal differences in clay composition should be taken into account in rating systems for exchangeable potassium.
Q/I isotherms with K concentration as intensity factor seem to provide the best basis for defining soil groups with similar potassium dynamics. There are significant gaps in our understanding of impacts of charge dynamics on the assessment of potassium status in highly weathered soils. Research must be done in several directions in order to improve the rating systems and the management or potassium supply to crops on these soils.

Introduction

The supply of potassium to crop roots is more closely linked to soil mineralogy than that of most other nutrients. The relationship between mineralogy and potassium status of a given soil must not only be restricted to the amount and type of potassium bearing minerals which may serve as a source of potassium. Still more important is the influence of clay sized minerals on retention and transformation of the so-called «labile potassium» (exchangeable and watersoluble K), regardless of whether it is soil-borne or provided from fertilizers.

Because the subject of our colloquium is limited to the humid tropics the latter statement may be of particular concern.

Soils of the humid tropics are essentially highly weathered and leached low base status soils. During a long evolution these soils have lost most of their weatherable primary minerals including the potassium containing silicates and their clay fraction is composed of low activity constituents with variable electrical charge. In most cases kaolinite-like secondary silicates with variable proportions of crystaline free oxides and amorphous

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materials dominate the highly dispersed fraction of soil. Normally, residual 2:1 clay minerals are present, if at all, in small amounts only. Mineralogically the potassium status of highly weathered soils in the humid tropics is characterized by low content of K bearing minerals and the peculiarities of potassium adsorption on clay constituents with variable charge. Therefore, the correct management of potassium supply to crops is much more difficult in the humid tropics than in the drier parts of the tropics. More than that, there are still quite a number of problems not yet sufficiently studied for practical conclusions.

But within the boundaries of the humid tropics some less weathered soils with appreciable content of weatherable silicates and proportions of 2 : 1 layer silicates do occur too. Their less advanced weathering of the surface and subsurface horizons may be due to impeded drainage, rejuvenation by erosion or deposition of high base status materials, for instance of volcanic or aeolian origin, to the type of parent material or to several of these factors. Notwithstanding, though the proportion of medium to high base status soils in the humid tropics is relatively small, they are important because of their higher agricultural potential.

From the agronomical point of view the ultimate aim of any mineralogical research and consideration might be a better understanding of the potential potassium supply to crops and the provision of a framework for differentiation of soils with a particular mineralogically determined transformation behaviour pronounced enough to be relevant for practical decisions. It would be erroneous to conclude that the mineralogy of soils of the humid tropics might be of minor importance in the assessment of potassium status because they are generally low in potassium content. Quite to the contrary, the principle holds that the more impoverished the soil is and the more difficult its potassium management due to content and nature of clay constituents, the more precisely we must understand its transformation behaviour and the influence of minor variations in mineralogical composition.

With regard to the subject of this paper there are three main topics of interest:

1. The importance of the 2:1 layer silicates in the clay fraction for the evaluation of exchangeable potassium
2. Special considerations for the assessment of the status of labile potassium in soils dominated by variable charge clays
3. The role of replenishment processes in potassium supply to crops and methods for its assessment.

Time constraints restrict discussion to the first two topics.

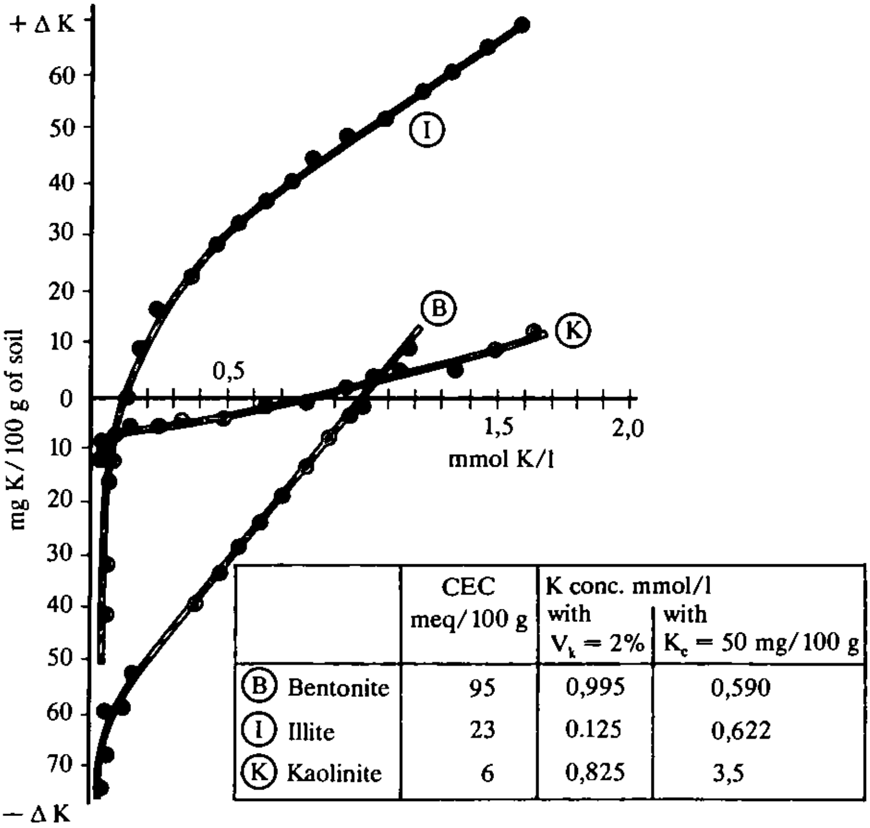
1. Evaluation of exchangeable potassium with regard to layer silicates

The amount and type of layer silicates in the clay fraction has a strong influence on storage capacity for and binding force of exchangeable potassium. Both govern the equilibrium concentration of potassium in the external soil solution, its buffering by the adsorption and desorption equilibrium and thus the potassium supply to roots. It is quite clear that the adsorbed potassium which is exchangeable against cations of neutral salts constitutes the most important source of potassium for short term supply to roots. Thus we have to focus our attention on this form of potassium.

From an agronomic point of view we are interested in having soils which can fulfil the following requirements:

1. High cation exchange capacity to maintain a sufficient stock of exchangeable potassium and to allow economic fertilizer dressings.
2. Equilibrium concentrations of potassium in the external soil solution in the optimum range, that means high enough for sufficient diffusion to roots and not so high as to cause severe leaching losses.
3. Stable and favourable ionic environment for roots in order to avoid nutritional stresses.

The main groups of clay sized secondary layer silicates have different characteristics as far as their storage capacity and binding forces are concerned. These differences can best be expressed by quantity/intensity isotherms. Figure 1 gives an example for three of the important types of clay minerals.

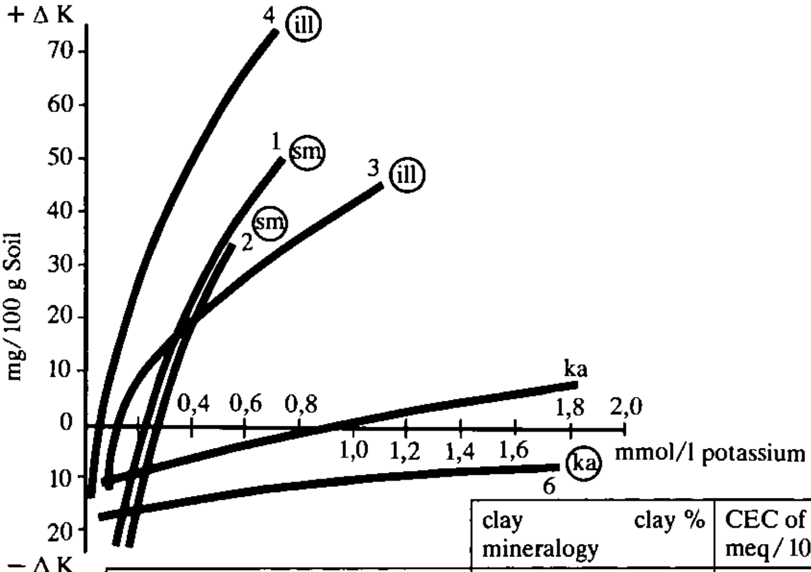


	CEC meq/100 g	K conc. mmol/l with $V_k = 2\%$	K conc. mmol/l with $K_e = 50$ mg/100 g
Ⓑ Bentonite	95	0,995	0,590
Ⓘ Illite	23	0.125	0,622
Ⓚ Kaolinite	6	0,825	3,5

Fig. 1 Q/I relationship of clay minerals saturated with potassium at 3%

It should be emphasized that the differences clearly visible on minerals from deposits are not, in general, equally strongly marked in soils. This is mainly due to the different conditions of formation, the occurrence of numerous transitional forms and the effect of weathering on mineral surfaces. Besides, the clay fractions of soils usually comprise mixtures of different types of clay minerals. However, the basic differences are also readily discernible in curves from soils with different clay mineralogy and similar clay content as shown in Figure 2. The main facts represented by these Q/I relationships are:

- clay minerals vary in their storage capacity
- clay minerals have different amounts of selective binding sites with various binding forces
- the potassium saturation or the content of exchangeable potassium per 100 g of clay needed to maintain optimum concentration within the range of 0.5 to 1.0 mmol x l^{-1} are equally different for the minerals tested.



		clay mineralogy	clay %	CEC of clay meq / 100 g
1. Eutric Fluvisol	Egypt	smectitic	44,7	86,0
2. Chromic Vertisol	Algeria	smectitic	29,8	104,1
3. Haplic Xerosol	India	illitic	18,3	62,4
4. Chromic Luvisol	Algeria	illitic	59,7	50,0
5. Rhodic Ferralsol	Tanzania	kaolinitic	54,9	17,8
6. Rhodic Ferralsol	Congo	kaolinitic	70,0	11,8

Fig. 2 Q/I relationship of soils with different mineralogical composition of the fraction and saturated with K at 3%

These are the facts. The question to be raised is: how far and, if necessary, in which manner we have to take them into account with respect to the assessment of the exchangeable potassium status of soils.

Several decades ago under temperate climatic conditions we have learned to establish rating systems for exchangeable potassium taking into account the texture of soils. The introduction of texture classes was the inevitable consequence of the selectivity behavior of 2:1 layer silicates. With increasing clay content the capacity of selective binding sites also increases, and this means the soil contains larger amounts of only difficultly or practically non desorbable potassium.

As concerns the kaolinitic soils of the humid tropics it seems to be questionable to which extent texture classes must be differentiated with regard to threshold values for exchangeable potassium. Recently, *Boyer [1982]* has proposed a system for the evaluation of exchangeable potassium in ferrallitic soils with three texture classes (Table 1).

Table 1 Evaluation of the exchangeable potassium in ferrallitic soils according to *Boyer [1982]*

	strong to very strong deficiency	weak to medium deficiency	weak or no deficiency
	meq K/100 g of soil		
Sandy soils (clay + silt <15%)	<0.05 .. 0.07	0.07 .. 0.14	>0.14
Medium soils (clay + silt 15 .. 45%)	<0.10	0.10 .. 0.20	>0.20
Heavy soils (clay + silt >45%)	<0.20	0.20 .. 0.40	>0.40

Theoretically, kaolinitic clays should not have selective binding sites for potassium, an assumption which is largely confirmed by the absence of marked curved parts on the Q/I relationship of kaolinite. Consequently, if we need any, differentation in threshold values for kaolinitic soils with different clay content should not be large. But the higher the content of residual 2:1 layer silicates in the clay fraction of low base status soils, the more adsorbed potassium ions are associated to selective binding sites and the more necessary is differentation by textural class.

The situation is quite different as concerns the consideration of clay composition. Clay composition may have as strong an impact as texture on exchangeable potassium availability.

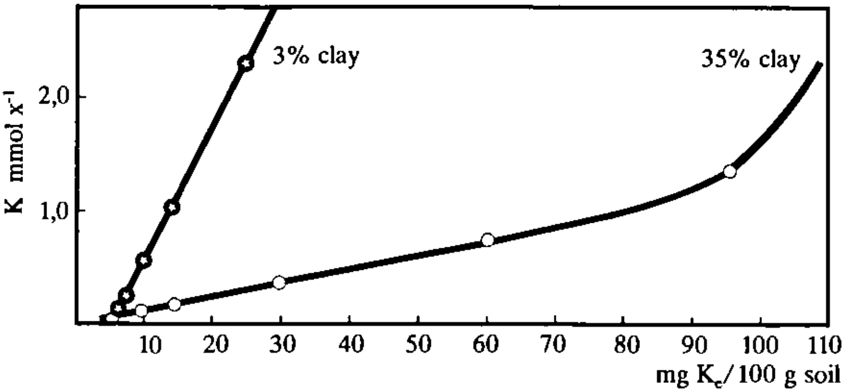
This can be seen from the Ø/I relationship shown in Figures 1 and 2, and is demonstrated once more by a comparison made with data adapted from *Grimme et al. [1971]* and *Németh [1971]* in Figure 3.

As far as we know, most countries use only one rating system for evaluation of exchangeable potassium without taking into account the variability of clay composition of soils. This may be due to two circumstances:

1. Most of the temperate climate countries with high input agriculture are small and at the same time from the point of view of soil mineralogy uniform enough to neglect variations in clay composition.
2. The determination of clay composition is expensive, time consuming and not suitable for routine analysis.

With regard to the first factor the situation is quite diffrent in the tropics, particularly in the humid and subhumid tropics where we can find soils of consistently different clay

Ⓐ Soils different in clay content but equal in clay composition



Ⓑ Soils equal in clay content but different in clay composition

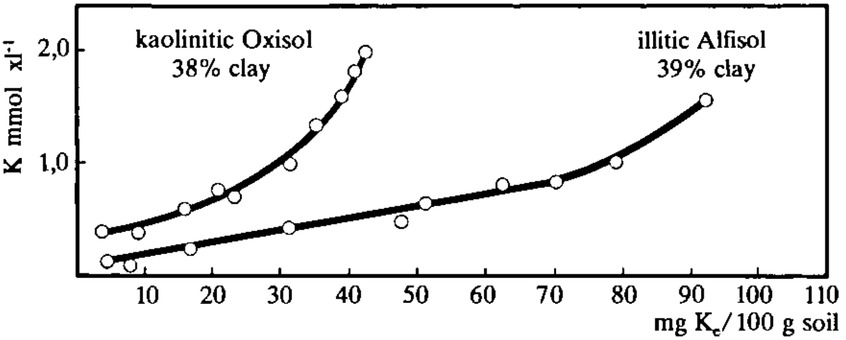


Fig. 3 Influence of clay content (A) and clay composition (B) on quantity/intensity relationship of soils (adaptet from Gimme et al 1971 and Németh 1971)

compositions side by side, or in large countries with areas in different climatic regions. Here we must take into account clay composition. The mistakes we can make by neglecting clay composition may be demonstrated by data obtained with different soils in several potassium exhaustion experiments.

Table 2 shows the main results obtained in these experiments. The amount of practically non available exchangeable potassium increases significantly in the order

kaolinite < montmorillonite < illite.

With the same threshold values for all soils we may overestimate the potassium supply to crops in one case and thus lose yield by using too little fertilizer for optimum growth, or waste fertilizer due to leaching losses in another. Probably the difficulties in direct determination of mineralogical composition of clay cannot be overcome, if ever, in the near future. This determination will never be a matter of routine analysis and must remain a field of research work. In addition to the cost of mineralogical analysis many important peculiarities of soil clays cannot yet be detected by present day techniques as has been proved for illitic clays, for example *Niederbudde [1978]; Mutscher [1980]).* Thus we have to resort to indirect methods. The best way seems to be the determination of Q/I relationships and hence to derive threshold values for the soils. This takes into account the influence of texture and clay composition simultaneously. Another way is grouping soils according to classification taxa with correlated medium clay composition.

This approach has been adopted by *Boyer [1982]* in proposing his rating system for ferrallitic soils with clay dominated by kaolinite-type minerals.

Table 2 Relationship between the mineralogical composition of the clay fraction and the residual exchangeable potassium remaining in the soil after exhaustion by ryegrass with the corresponding K concentration in the saturation extract

	Dominant clay mineral in the clay fraction	Cuts of rye grass taken	Residual exchangeable potassium		Final K concentration
			mg/100 g soil	mg/100 g clay	mmol/l
Smectitic alluvial soils and vertisols Egypt, Algeria, Cuba	Montmorillonite	5-8	12.2	26.1	0.040
Subtropical fersiallitic soils, brown calcareous soils and redbrown subaridic soils Algeria, India	Illite	5-7	20.4	44.4	0.033
Tropical ferrallitic and fersiallitic soils Congo, Tanzania, Cuba	Kaolinite	3-7	3.5	6.2	0.079

2. Variable charge clays and transformation of labile potassium

One of the most important mineralogical conditions in the humid tropics is the widespread occurrence of soils with clay fractions dominated by variable charge constituents. As has recently been stated by *Uehara [1982]* we dispose of sufficient information to understand the interpretative value of information on cation exchange capacity, base saturation and properties which covary with them of soils with permanent surface charge, but this is not yet the case for soils with variable charge characteristics. Until now, due to the lack of data, we treat the latter soils with regard to the evaluation of the exchangeable potassium status in the same manner as high base status soils of the dry tropics or of the temperate region. The question has to be asked whether this approach is justified or not. Actually, it seems not yet to be possible to give a definite answer to this question, but during the last decade our knowledge about the exchange behavior of variable charge soils has increased to such an extent that we are able to define the basic lines of research work to be executed in the near future in order to find a solution to the problem.

Principally, our requirements concerning potassium in variable charge soils are the same as for soils with permanent charge which have been outlined above.

Virtually the problem of variable charge soils consists in the much higher instability of the charge of the clay with the extreme complexity of factors influencing the actual state of charge and consequently the ionic environment for the roots in the soil solution. Thus monitoring and management of the ionic composition of the soil solution and of the ion flux to the roots becomes much more difficult than in soils with 2:1 layer silicate clays. There are several aspects of the problem to be taken into account:

1. The variable charge characteristics of a given soil are not only dominated by mineral constituents, but also by organic matter. Under tropical conditions organic matter content may change over relatively short intervals. The action of inorganic clay constituents on the overall charge of soil may be masked by the organic matter as has been proved by *Uehara [1982]* with the example given in Table 3.

Table 3 Influence of free iron and organic matter on ΔpH in an oxisol according to *Uehara* [1982]

Depth (cm)	C_{org}%	free Fe %	pH (H_2O)	pH (N KCl)	ΔpH
0-28	6.04	13.0	5.1	4.3	−0.8
28-46	2.04	12.9	5.0	4.4	−0.6
46-71	1.33	16.5	5.0	4.7	−0.3
71-97	0.86	19.2	5.2	5.7	+0.5
97-122	0.72	23.1	5.5	6.1	+0.6
122-157	0.52	25.7	5.7	6.4	+0.7
157-178+	0.19	27.3	5.8	6.7	+0.9

2. The various clay constituents not only possess different variable charge characteristics but also their spatial arrangement may vary infinitely. For example, kaolinite and oxides may exist in one case side by side as separate grains or in another, metallic oxides and silica as weathering products may cover the surface of kaolinite grains. Thus the overall charge of clay fractions with similar mineralogical composition may be rather different.

3. Changes in actual charge conditions may be caused by weather conditions, biological activity fluctuations and by agronomic measures like fertilizer application or liming also.
   This is the consequence of the dependence of charge on pH dynamics and electrolyte concentration in the soil solution.
   Unfortunately, we do not yet dispose of sufficient data about charge dynamics under different cropping conditions and its impact on potassium availability.

4. In the first place, management of soil pH is directed to the elimination of aluminium and manganese toxicities though by far not all low base status soils show toxicity constraints. If there are free aluminium ions they compete strongly with potassium and cause shifts in the relationship between the exchangeable and watersoluble forms of potassium in favour of the latter, in this way lowering the buffering of potassium concentration and increasing the risk of leaching losses.

5. There are very few data permitting a clear understanding of occurrence and extent of potassium selectivity and, in close connection with this, of potassium fixation; up to now they are not conclusive. Principally, kaolinite-like layer silicates do not show any sterically caused potassium selectivity. Unfortunately, the work done by *Mohinder Singh [1970]* on Malaysian soils and often quoted by others, has not encouraged further research in this field. According to his findings there is evidence for K selective and Al selective sites as well. It is now fairly certain that most highly weathered soils

still contain small amounts of residual 2:1 layer silicates in the clay including illite. Consequently, the observed selectivity to potassium may equally be due to these admixtures. In any case the influence of these 2:1 layer silicates on the potassium status has not yet been elucidated and still needs to be quantified. Practically, the same can be stated with regard to potassium fixation, particularly as to the role of porous amorphous materials. Concerning the latter the publication of *Reenwijk and De Villiers [1968]* has been quoted repeatedly but apparently the investigations have not been continued.

For all these reasons the interpretative value of exchangeable potassium content in variable charge soils is much less meaningful and reliable according to the dynamics of potassium supply to crops than in soils with permanent charge clays. But even in permanently charged soils we have tried to improve our understanding by additional values and determinations like potassium saturation or Q/I relationship isotherms. Though Q/I determination has not been introduced to routine work the method has brought an essential contribution to our present day understanding of transformation of labile potassium in high and medium base status soils. *Tinker [1964]* tried to adapt this approach to low base status soils in Nigeria but still on the basis of the original concept by *Beckett [1964]* with the adsorption ratio as a measure of intensity. Actually, most researchers agree about the limited importance of AR with regard to potassium supply *(cf. Van Diest [1978]; Grimme and Németh [1978])*. But obviously there has been little work on potassium concentration as intensity value.

Figures 4 and 5 show Q/I relationships obtained with kaolinite and oxisols with high content of free iron under different conditions. Figure 4 demonstrates the influence of

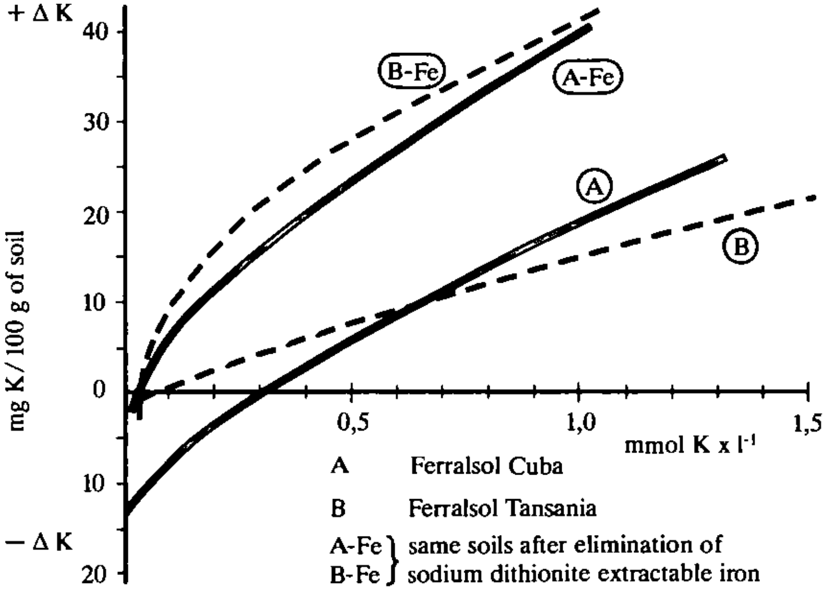


Fig. 4 Q/I relationship without and with elimination of dithionite extractable iron of two highly weathered soils

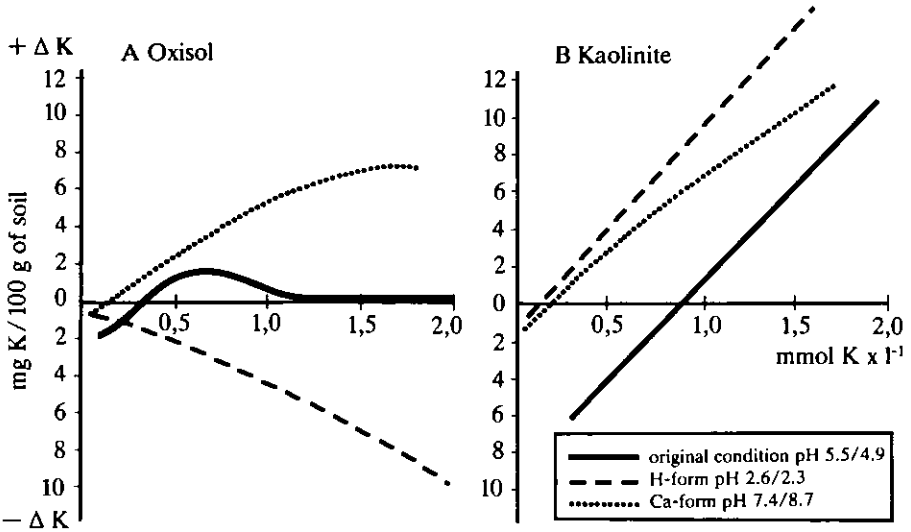


Fig. 5 Q/I relationship of an oxisol and deposite kaolinite in different ionic formes and with different pH

accumulated free iron on the shape of the curve and figure 5 the relationship under different pH conditions with different cations adsorbed. These examples demonstrate a possibility for studying the influence of various factors and the nature of the exchange complex on the dynamics of labile potassium. In our opinion the Q/I relationship should be used to a larger extent for low base status soils in order to qualify our understanding of the dependence of Q/I relationships on factors like pH, ionic strength, aluminium competition and, least not least, of the relation kaolinite: oxides in the clay fraction. The ultimate aim of all research in this field should be a scientifically well supported decision whether and how rating systems for exchangeable potassium could be improved considering pH_O, ΔpH *Mekaru and Uehara [1972]* interval pH_O to pH_{actual} or parameters expressing the particular dynamics of these values. One of the most urgent needs seems to be a thorough comparison of soils with kaolinitic and oxidic clays, respectively, in order to know how the interpretation of exchangeable potassium values in the two groups of soils should differ.

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Potassium Availability in the Soils of Thailand

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Summary

Features of the main soil groups *(Dudal and Moormann [1964])* are briefly described. High potassium contents are found in lowland alluvium and other lowland soils with high clay content (Grumusols, Non calcic Brown Soils) and in most upland soils. Low potassium contents are found in sandy soils – Low Humic Gley, Gray Podzolic and Regosols. Central Highlands, Rendzinas and Grumusols are dominated by montmorillonite; the soils in the North, Northeast and South are mainly dominated by kaolinite. Field experiments testing K fertilizer have been made in all parts and, while response to K is somewhat infrequent, the soils being comparatively well supplied with K, it is found that Low Humic Gleys, Regosols, Gray Podzolic and Latosols tend to be low in K. Low K soils occur in the northeast, parts of the central plain and parts of the south. Calibration of soil analysis with field crop tests indicates critical exchangeable K levels to be in the range 30-120 ppm according to crop.

1. Introduction

The total area of Thailand is approximately 514 000 km² lying between 5° 40' and 20° 30' N and 97° 70' and 105° 45' E. *Moormann and Rojanasoonthon [1966]* divided Thailand into 6 physiographic regions: Central Plain, Southeast Coast, Northeast Plateau, Central Highlands, North and West Continental Highlands and Peninsula (Figure 1). There are three main seasons: rainy from May to October, cool dry from November to February and hot, humid from March to May, but the South and Southeast Coast have no pronounced dry season. Temperature is even throughout the country (26-28° C) except in the north and at high altitude. Most of continental Thailand is tropical savanna («Koppen-Aw»), the northern mountains and higher altitudes humid subtropical (Cw); the easternmost part of the southeast coast, western mountains and peninsular Thailand where rainfall is very heavy has tropical monson climate (Am). Though vegetation on the Western coast of the peninsula approaches true rainforest, it does not fit the classification Af as there are 2 to 3 dry months with rainfall below 60 mm.

2. Soils

Though soils are now classified according to *US Soil Taxonomy* the data quoted here follow *Dudal and Moormann's [1964]* great soil groups. The two systems are compared in Table 1. Notes on the soils as follow:

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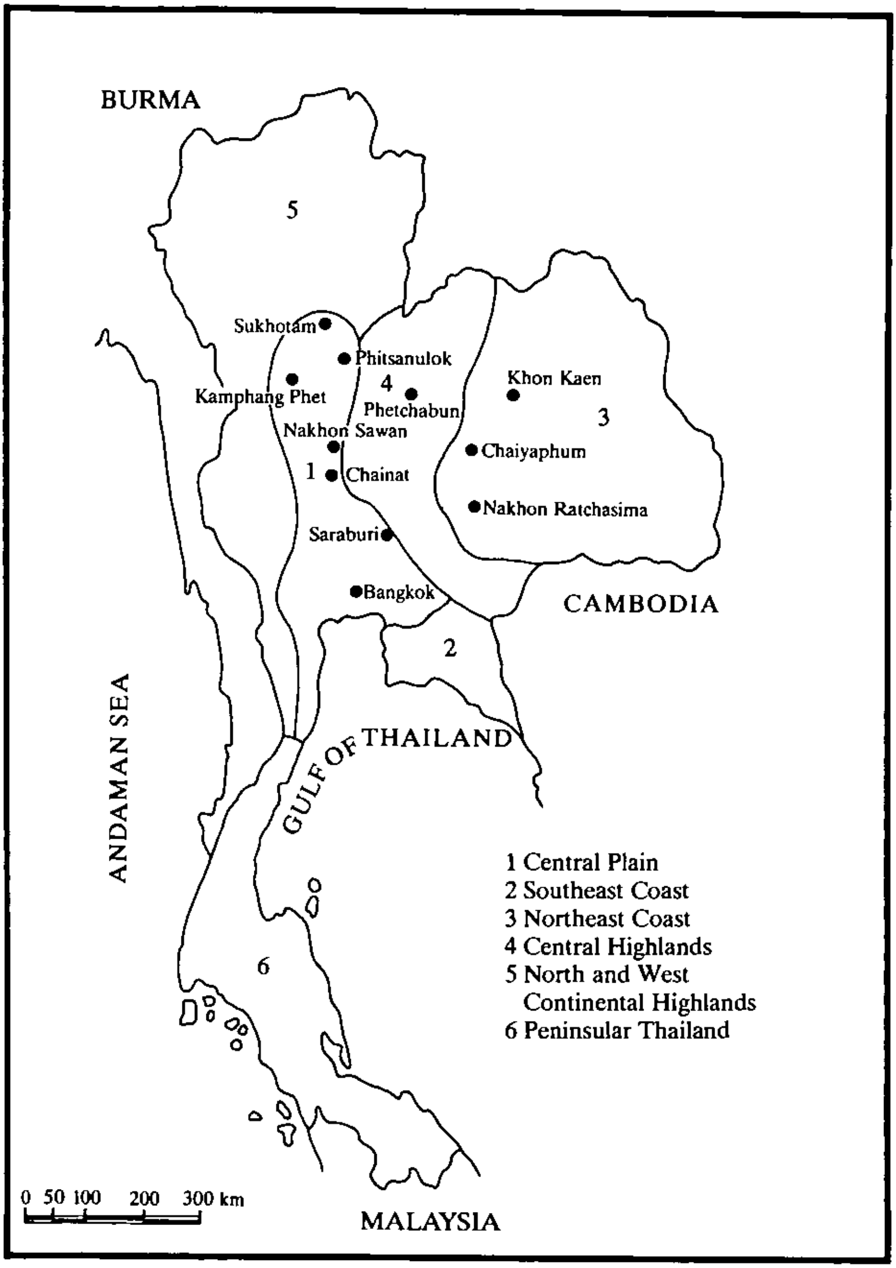

Fig. 1 Physiographic Regions of Thailand

Table 1. Comparison of soil classifications in great groups based on the U.S. Soil Taxonomy 1974 and the old classification of *Dudal and Moormann [1964]*

U.S. Soil Taxonomy 1974	*Dudal and Moormann [1964]*
Paleaquults, Plinthaquults, Tropaquults.	Low Humic Gley Soils
Fluvaquents, Haplaquolls, Tropaqualfs, Ustifluvents.	Alluvial Soils
Haplustults, Paleudults, Paleustults, Plintustults Tropudults, Dystropepts, Eutropepts, Ustropepts.	Red Yellow Podzolic Soils
Paleudults, Paleustults, Haplustults, Tropudults Dystropepts, Eutropepts, Ustropepts.	Gray Podzolic Soils
Plintustults, Paleustults, Haplustults Paleudults, Tropudults, Palehumults	Reddish Brown Lateritic Soils
Paleustalfs, Haplustalfs	Non Calcic Brown Soils
Quartzipsamments	Regosols
Calciustolls	Rendzinas
Haplustolls	Brown Forest Soils
Chromuderts, Pelluderts	Grumusols
Haplorthox, Paleustults, Haplustults Paleudults, Tropudults	Latosols
Rhodustalfs, Tropudalfs	Red Brown Earths

Regosols. Excessively drained on beach and dune sands. A-C_1, A-Cg horizons with little development. Mainly on coastline with patches on older fine sands. Whitish to light gray on coast, others reddish to yellow-red in sub-surface. Being agriculturally poor — some cassava and coconut are cultivated.

Alluvial. Poorly drained on recent water deposited material. A-C, A-Cg, A-(B)-C. Mostly clay, loam, clay-loam or sandy-clay-loam in texture. Subdivided into fresh, brackish and marine water sediments. Those in Central Plain are suitable for paddy and give relatively high yields. On those derived from brackish water sediments (particularly acid sulphate soils) yield is lower. Marine alluvial soils grow good paddy provided salt is leached from surface. Much of the latter has been developed for fruit and vegetables. Alluvial soils in Northeast Plateau are derived from sandstones and leached terrace sediments and are poor in nutrients.

Grumusols. Rich clayey parent material associated with limestone, marl and limestone-derived alluvium — a few from basalt or andesite. A-C, A-Cg soils with heavy clay dominated by montmorillonite. Surface layer is black or very dark gray-brown to considerable depth. Irregular surface with *gilgai* relief is a characteristic of this soil. Generally the soil is fertile, being high in bases and with free $CaCO_3$ in subsoil. Low lying mainly used for paddy, higher-lying mainly for maize, sorghum, cotton, mungbeans, groundnuts and tobacco.

Rendzinas. Formed from marls and weathered limestone fragments. Typically black to very dark brown in surface. Free lime throughout profile (A-C or A-B-C soils). Fertile upland soils mainly for maize, sorghum, mungbeans, peanuts and cotton.

Low Humic Gley soils. The soils derived mainly on older alluvial sediments and typical of alluvial terraces in lower lying areas throughout the country (A_1-A_2-Bt profile). Characterised by gleying throughout or starting immediately below surface horizon. Surface sandy-loam to loam soil is shallow and low in organic matter. Most of rainfed paddy require fetilizer for high paddy yield.

Non calcic Brown soils. Formed from semi-recent alluvium and associated with moderately to highly saturated Low Humic Gley soils. Flat to slightly undulating, texture usually clayey, silt loam to silty clay loam (A_1-A_2-Bt profile). It is brown in topsoil, yellowish-brown to reddish-yellow in subsoil. It is medium to high base saturation being increased with depth. Mostly in drier parts of the country the soils are used for sugarcane, cotton, pineapples. K status is high.

Red Brown earths. Formed from residuum and colluviated residuum associated with limestone and basalt. Clayey texture throughout, dark red to dark reddish brown in colour. Base saturation is medium to high and increasing with depth. Mostly used for maize, sorghum and cotton and give good yields.

Reddish Brown Lateritic soils. A_1-A_2-Bt soils formed from residuum and colluvium from intermediate rocks. Well drained with clayey texture throughout, though upper layers may be loamy. There may be mottled clay with or without laterite. Distinguished from Red Brown earths by low base saturation and constant or decreasing pH. Used for a variety of arable crops and orchards. Depletion of soil nutrients is rapid under continuous mono-cropping and subject to occasional severe drought.

Red Yellow Podzolic soils. A_1-A_2-Bt soils formed from a range of parent material (intermediate to acid rocks and older alluvium) on various land forms mainly in hilly areas. Normally well drained with distinct horizon differentiation. In the northeast, laterite concretions are abundant. Base saturation of sub-surface low, pH 4.5 to 5. In Southeast Coast and Peninsula they are used for rubber, coconut and oilpalm. They are characterised by shifting cultivation in hilly areas of Upper North.

Gray Podzolic soils. A_1-A_2-Bt soils formed from open terraces of major rivers and streams and coastal terraces of South and Southeast Coasts of the Peninsula and on Northeast Plateau. Texture is sandy loam or loamy sand in surface and sandy loam to clay loam below. Surface colour is light gray changing to grayish brown when moist. There are low fertility and limited cropping possibilities. In Northeast Plateau and Southeast Coast, the soils are mostly used for cassava and kenaf but rubber is grown in the Peninsula.

Latosols.

Reddish Brown Latosols formed from residuum and colluvium from basalt in limited areas in Chantaburi Province, Southeast Coast. Deep clay soils are dark redish brown with excellent structure and highly fertile. They are used for rubber, pepper and various fruit trees.

Red-Yellow Latosols formed from old alluvium on old terraces on Northeast Plateau. Red to yellowish red throughout profile. Texture is sandy and frequently with surface degradation. Low natural fertility and much is still under forest. Used for cassava.

3. Potassium status of soils

3.1 Clay mineral composition

Clay mineral composition is of dominat importance in affecting the extent of soil K reserves. Studies in this field have been made by *Motomura et al. [1984]* and *Ogawa et al. [1975]*. Main features of this work are given in Tables 2-5. Mica is dominant in alluvial soils around Bangkok; kaolinite in soils of Pitsanulok, Saraburi, Nakhon Nayok, Chacherngsao and Kamphaengphet derived from sandstone and shale. Montmorillonite dominates in limestone soils of Lopburi. In North-eastern, kaolinite is dominant in sandstone-derived soils (Nakhon Ratchasima, Khon Kaen, Ubon Ratchathani) and mica in alluvium derived soils (Nongkai and Nakhon Phanom). Northern soils are dominated by mica or kaolinite depending on parent material. Kaolinite is abundant in southern soils.

Table 2. Clay mineral composition of surface paddy soils in the Central Plain.

No.	Location (Province)	Relative abundance (%)			
		7 Å	10 Å	14 Å	
1	Bangkok	30	45	25	(Mt, Ver)
2	Samut Prakan	30	50	20	(Mt, Ver)
3	Pathum Thani	40	40	20	(Mt, Ver)
4	Pitsanulok	60	15	25	(Ver, Al-int)
5	Petchabun	20	15	65	(Mt, Ver, Ch, Int)
6	Sukhothai	25	60	15	(Ver, Mont, Al-int, Ch)
7	Saraburi	65	10	25	(Ver, Mont, Al-int, Ch)
8	Nakhon Nayok	65	15	20	(Ver, Mont, Al-int)
9	Chachengsao	45	25	30	(Ver, Al-int, Mt)
10	Kamphaeng Phet	55	40	5	(Ver)
11	Suphanburi	45	50	5	(Ver, Al-int, Ch)
12	Nakhon Pathom	30	65	5	(Mont, Ver)
13	Lopburi	15	0	85	(Mont)

Composition 7 Å, kaolinite; 10 Å, mica; Mt, montmorillonite; Ver, Vermiculite; Al-int, Aluminum interlayer; Ch, Chlorite; Int, interstratified mixed layer.

Source: *Motomura et al. [1984]*

Table 3. Clay mineral composition of surface paddy soils in the Northeastern region.

No.	Location	Relative abundance (%)			
		7 Å	10 Å	14 Å	
1	Nakhon Ratchasima	80	0	20	(Al-int, Ver)
2	Nong Khai	30	55	15	(Ch, Ver)
3	Khon Kaen	50	5	40	(Ver, Al-int, Int)
4	Nakhon Phanom	30	45	25	(Ch, Ver, Al-int)
5	Ubon Ratchathani	50	5	45	(Al-int, Ver, Int)

Source: *Motomura et al. [1984]*

Table 4. Clay mineral composition of surface paddy soils in the Northern region.

No.	Location	Relative abundance (%)			
		7 Å	10 Å	14 Å	
1	Chiang Mai	65	30	5	(Ver)
2	Nan	35	50	15	(Ver, Mt, Al-int)
3	Chaing Rai	55	35	10	(Mont, Al-int, Ver)
4	Phrae	20	60	20	(Mont, Ver, Ch)
5	Lampang	45	25	30	(Mont, Ver)

Source: *Motomura et al. [1984]*

Table 5. Clay mineral composition of surface paddy soils in the Southern region.

No.	Location	Relative abundance (%)			
		7 Å	10 Å	14 Å	
1	Phattalung	75	10	15	(Al-int, Ver)
2	Satun	60	35	5	(Ver)
3	Pattani	75	20	5	(Ver)
4	Narathiwat	80	15	5	(Ver)

Source: *Motomura et al. [1984]*

Minerals of upland soils are similar (Table 6), the podzolic soils, lateritic soils, latosols, regosols and low humic gley soils with kaolinite, grumusols and rendzinas with montmorillonite. Alluvial and Non Calcic Brown soils show a mixture of clay minerals.

Table 6. Some chemical and physical properties of upland soils in Thailand

Great Soil Group	pH (1:1)	C.E.C. me 100 g^{-1}		Total K %		Exchangeable K me 100 g^{-1}		Dominant
	Range	Range	Mean	Range	Mean	Range	Mean	Clay Minerals
Regosols	5.9-6.7	0.5-1.8	1.0	0.015-0.025	0.018	0.026-0.077	0.055	Kaolinite
Alluvial Soils	6.3-7.5	6.5-15.8	10.8	0.588-1.375	1.038	0.103-1.030	0.502	mixed
Low Humic Gley Soils	4.5-6.5	1.0-4.0	2.0	0.070-0.480	0.259	0.110-0.646	0.231	Kaolinite
Grumusols	7.9	—	43.0	—	0.105	—	0.510	Montmorillonite
Rendzinas	7.4-7.5	25.7-48.7	37.2	0.070-0.300	0.185	0.256-1.999	1.128	Montmorillonite
Non Calcic Brown Soils	5.1-7.8	2.0-14.6	8.8	0.067-1.400	0.902	0.032-1.430	0.586	mixed
Red Brown Earths	5.7-7.1	7.6-26.2	16.9	0.052-1.250	0.487	0.513-1.087	0.652	Illite and Halloysite
Gray Podzolic Soils	4.2-6.6	0.6-5.7	2.4	0.005-0.383	0.094	0.050-0.684	0.163	Kaolinite
Red Yellow Podzolic Soils	4.3-7.7	1.1-23.9	6.8	0.032-1.262	0.415	0.077-0.564	0.277	Kaolinite
Reddish Brown Lateritic Soils	4.7-5.3	6.8-11.0	8.2	0.052-0.168	0.099	0.256-0.947	0.652	Kaolinite
Red Yellow Latosols	4.9-6.4	1.2-5.6	2.8	0.025-0.120	0.046	0.036-0.474	0.191	Kaolinite

3.2 Total and available potassium in soils

Motomura et al. [1984] published detailed analyses of lowland soils according to soil group. Their results are given in Appendix Tables 9 and 10 and data from *Ogawa et al. [1980]* in Appendix Table 11. Alluvial soils are generally high in K but sandy soils (Regosols) are low. Total K is high in Central Region lowland soils with available K from 74-372 ppm. It is low in Northeastern Region with available K from 15-77 ppm. Alluvial soils with high clay content are high in available K. Low humic gley, hydromorphic Gray Podzolic soils and hydromorphic Regosols derived from sandstone in Northeastern Region are low in total and available K. Among the upland soils, high K is found in alluvial soils being high in clay and low values in Regosols. Most groups show a wide variation in K content. Upland soils in Southeastern and Northern Regions are comparatively low (available K = 23-114 ppm).

4. Response of crops to potassium fertilizer

Rice. Some 52% of arable land in Thailand is devoted to rice and fertilizers must be applied for high yield. Nitrogen and phosphorus are required everywhere, soil levels being deficient. The effect of potassium fertilizer has been investigated by *Kirithavip et al. [1966], Suthdani et al. [1967], Seetanun and Sawasdee [1968] and Mongkolporn et al. [1978-1982].* The results of the earlier work showed no response to K fertilizer regardless of the rates of N and P applied (Table 7) but later work with two cultivars in long term experiments showed good response by RD 2 to 75 kg/ha K but no response by «Niew San pa Tong» (NSPT), a somewhat lower yielding cultivar (Figure 2).

Table 7. Response of rice cultivars to potassium fertilization grown on four locations in 1966-1968

Nutrient rates kg/ha	Average yield of rice cultivars (kg/ha) in 1966-1968				
($N - P_2O_5 - K_2O$)	Location	BKN	PMI	SRN	KSR
	Rice cultivar	Chao Leung II	Kao Pahk Maw 17	Kao Pahk Mau 17	Khao Pahk Mau 17
0-0-0		1713	1594	1644	1156
37.50-37.50-0		2856	3044	2400	2300
37.50-37.50-18.75		2738	3256	2125	2025
37.50-37.50-37.50		2763	3181	2213	2063
37.50-37.50-56.25		2894	2963	2444	2150
37.50-37.50-75.00		2806	2831	2381	2019
75.00-75.00-0		3556	3394	2594	2775
75.00-75.00-18.75		3469	3450	2581	2938
75.00-75.00-37.50		3463	3388	2513	2744
75.00-75.00-56.25		3375	3481	2694	2913
75.00-75.00-75.00		3388	3525	2600	2881

Remarks:

BKN — Bangkhen Rice Experiment Station.
SRN — Surin Rice Experiment Station.
PMI — Phimai Rice Experiment Station.
KSR — Kok Samrong Rice Experiment Station.

Maize. This is an important crop on heavy soils of the Central Highlands. There was no response to K in early investigations *(Anon., 1964-1966)* on Reddish Brown Lateritic soils. However, *Meesawat et al. (1981-2)* recorded significant response to 31 kg/ha K at Pitsanulok (Gray Podzolic soil) but no response on Rendzinas and Reddish Brown Lateritic soils (Figure 3).

Sorghum. The sorghum crop often succeeds maize. *Meesawat et al. [1982]* found that sorghum responded to up to 62 kg/ha K on Gray Podzolic and Brown Forest soils (Figure 4), response being 9-19%.

Cotton. Experiments have been widespread in the cotton-growing areas but no response to K was demonstrated. In collaboration with FAO, *Somanas et al. [1981-2]* obtained the results shown in Figure 5 with response in the range 6.1-8.6% on Red Yellow Podzolic soils and 8.2-25.3% on Gray Podzolic soils but no response on Brown Forest soils.

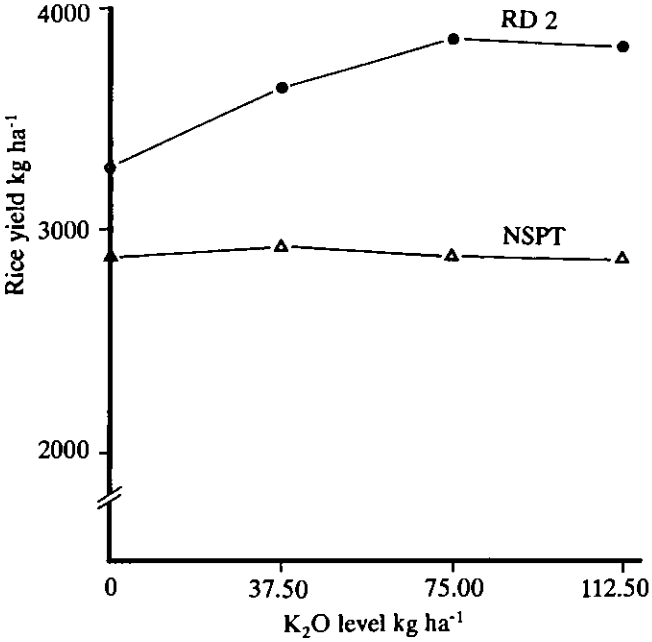

Fig. 2 Average yield of two rice cultivars responded to K fertilization at Surin Rice Expt. Sta. (Northeastern 1978-1982)

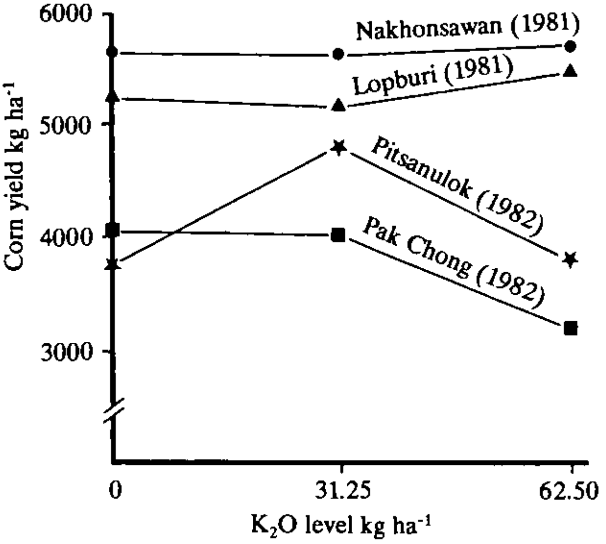

Fig. 3 Response of corn to K fertilization grown in Reddish Brown Lateritic soils at various locations in 1981-1982

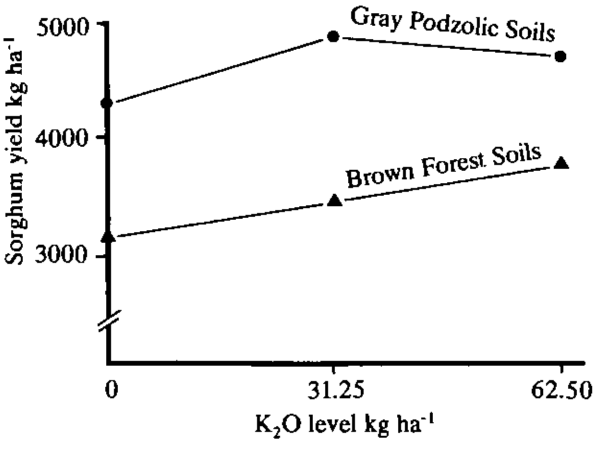

Fig. 4 Response of sorghum cultivar U-Thong 1 to K fertilization in Gray Podzolic and Brown Forest soils

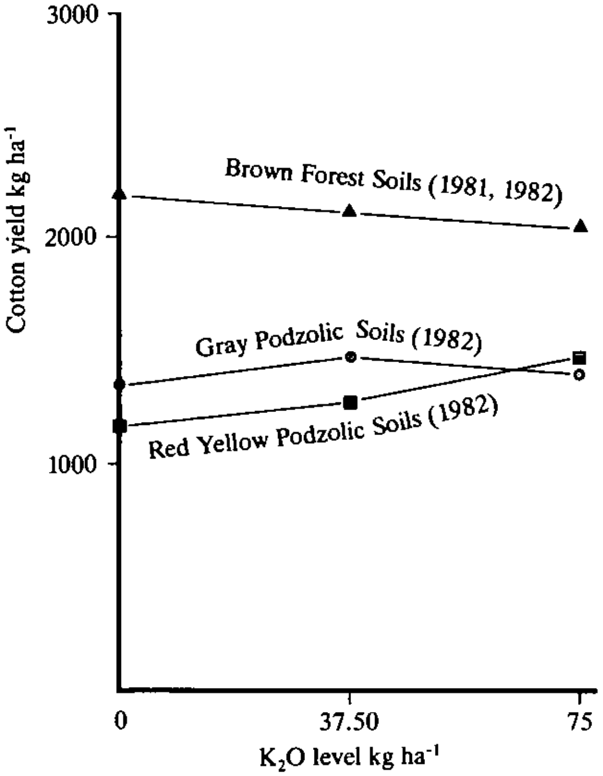

Fig. 5 Response of cotton to K fertilization grown on three soil groups in 1981-1982

Cassava. Cassava is a suitable crop for low fertility soils with low water holding capacity and is extensively grown in Southeast Coast, Northeastern and parts of the Central Plain. It is an exhaustive crop. Long-term experiments have been done on Gray Podzolic and Red Yellow Latosol soils in Northeastern from 1976 to 1983 *(Sittibusaya et al. [1984])*. No K response was recorded on Gray Podzolic soils in Northeastern but there were large responses on Yasothon soils at Khon Kaen (Figure 6).

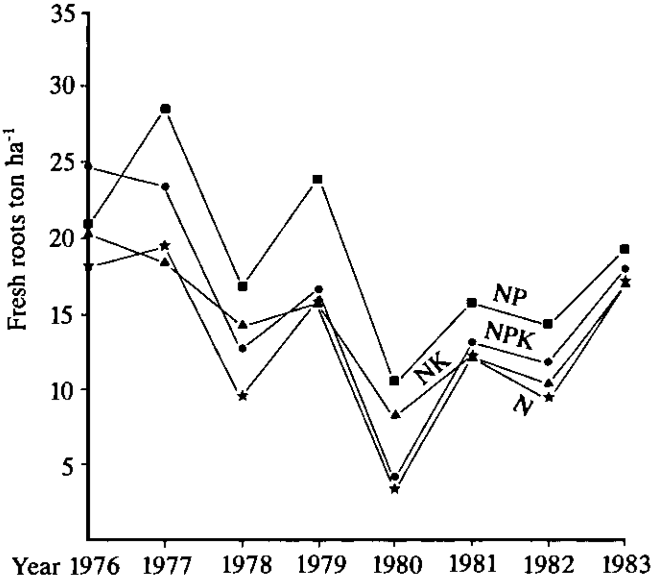

Fig. 6 Long term effect of fertilization on cassava yield in Korat soils Nakhon Ratchasima, Gray Podzolic Soils

4.1 Nutrient uptake by field crops

Available data are listed in Table 8. The heaviest K removal is by sugarcane and it should be noted that the bagasse is seldom returned to the field. Maize, soybeans, groundnuts and kenaf take up appreciable amounts of K but the residues are normally returned to the field.

4.2 Calibration of soil tests and K fertilizer recommendations

Exchangeable K is normally estimated by extracting with 1 *N* ammonium acetate at pH 7 and these values are well correlated with K extracted by 0.05 *N* HCl *(Cholitkul [1977]*. Though it is recognised that good correlations have been obtained between exchangeable K content and crop response, the matter is complex and requires full investigation of the response curve for each crop. *Suwanwaong et al. [1985]* found that the critical soil K level for response by rice on sandy soils of Northeastern and Southern Regions was 80 ppm K extracted by 0.05 *N* HCl.

Table 8. Nutrient uptakes of field crops

Crops	Yield	Total uptake of nutrients kg ha^{-1}							
	kg ha^{-1}	N	P	K	Ca	Mg	S	Mn	Zn
Corn									
Grains	3,669	58	14	18	3	7	—	0.06	0.17
Stovers		28	4	59	19	19	—	0.38	0.15
Cassava									
Roots	31,750	31	19	47	—	—	—	—	—
Stems		31	12	21	—	—	—	—	—
leaves	18,125	11	0.88	4	—	—	—	—	—
Soybeans									
Seeds	1,231	66	5	16	—	—	—	—	—
Stems & leaves		69	5	30	—	—	—	—	—
Peanuts									
Seeds	1,963	96	4	19	0.69	3	5	—	—
Shells	725	7	0.25	4	0.19	0.69	1	—	—
Stems, leaves and roots	2,750	52	3	56	43	19	11	—	—
Mungbeans									
Seeds	1,025	43	4	14	—	—	2	—	—
Shells	—	—	—	—	—	—	—	—	—
Stems	538	7	0.81	7	—	—	2	—	—
leaves	869	18	2	5	—	—	2	—	—
roots	188	2	0.19	0.56	—	—	0.56	—	—
Sugarcane									
Fresh stems	103,356	77	21	121	—	—	—	—	—
Leaves	—	—	—	—	—	—	—	—	—
Kenaf									
Stems & leaves (Fresh)	42,681								
(dry)	11,812	132	20	82	—	—	—	—	—
Fibers	2,738	—	—	—	—	—	—	—	—
Cotton									
Stems & leaves (dry)	2,963	53	5	—	—	—	—	—	—
Cotton balls	1,331	—	—	—	—	—	—	—	—

Ho and Sittibusaya [1984] have reported on the *FAO/Thai Fertilizer Project* for field crops. This work included calibration of soil tests from 1980. There was no correlation between percent response and soil values for maize and sorghum. For soybeans it was found that the critical value for exchangeable K was 55 ppm on Low Humic Gleys and Non Calcic Brown soils. They recommended K application as follows:

Exchangeable K ppm	Recommendation kg/ha K_2O
< 35	30
35-54	25
> 54	0

It was found that maximum yield of groundnuts on soils lower than 35 ppm K required 47 kg/ha K_2O. For cassava no K fertilizer is recommended at over 50 ppm exchangeable. The recommended rates are:

Exchangeable K ppm	Recommendation kg/ha K_2O
< 30	100
30-50	0-30
> 50	0

The critical level for cotton was 120 ppm K for 90% maximum yield. The critical value for kenaf was 45 ppm.

Recommendations are as follows:

Exchangeable K ppm		Recommendation kg/ha K_2O
	Cotton	
< 60		90
60-120		40
> 120		0
	Kenaf	
< 30		75
30-45		50
> 45		0-50

Appendix with Tables 9, 10 and 11 see pages 182-184

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Appendix

Table 9. Some chemical properties of lowland paddy soil in Thailand

Soil group	pH (H_2O)		C.E.C. me 100 g^{-1}		Total K mg 100 g^{-1}		Exchangeable K ppm	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
1. Marine Alluvial Soils	5.26	0.47	29.76	5.20	1066	266	422	139
2. Brackish Water Alluvial Soils	4.38	0.31	25.25	5.64	932	328	199	85
3. Fresh Water Alluvial Soils	5.66	0.93	16.73	8.29	727	471	114	75
4. Low Humic Gley Soils	5.25	0.64	8.53	5.78	437	382	103	80
5. Humic Gley Soils	7.75	0.10	20.66	0.88	690	9	102	—
6. Regosols	4.80	0.64	1.72	1.43	76	119	29	27
7. Gray Podzolic Soils	5.35	1.12	4.86	1.91	329	190	69	42
8. Non Calcic Brown Soils	6.09	1.32	13.06	6.32	489	247	76	33
9. Grumusols	6.65	0.74	45.43	10.81	250	126	193	50

Table 10. Total and available K in lowland soils.

Regions	Soil Group	Average values of total and available K in lowland soils		
		No. of Sites	Total K	Available K
			ppm	
Central plain	Marine Alluvial Soils	11	10167	372
	Brackish Water Alluvial Soils	6	9628	216
	Fresh Water Alluvial Soils	18	8214	121
	Low Humic Gley Soil Soils	13	4710	219
	Hydromorphic Non-Calcic Brown Soils	3	4929	74
	Grumusols	4	2500	194
North Eastern	Fresh Water Alluvial Soils	6	3757	77
	Low Humic Gley Soils	24	1026	50
	Hydromorphic Regosols	8	221	15
Northern	Fresh Water Alluvial Soils	8	6571	90
	Low Humic Gley Soils	24	6413	115
	Humic Gley Soils	2	6892	102
	Hydromorphic Gray Podzolic Soils	1	1768	55
Southern	Marine Alluvial Soils	2	594	264
	Brackish Water Alluvial Soils	1	8390	157
	Fresh Water Alluvial Soils	3	3142	55
	Low Humic Gley Soils	13	6479	59
	Hydromorphic Gley Podzolic Soils	2	5075	94
	Hydromorphic Regosols	1	3627	90
	Hydromorphic Non-Calcic Brown Soils	1	4946	46

Table 11.Total and available K in upland soils.

Regions	Soil Group	Average values of total and available K in upland soils		
		No. of Sites	Total K	Available K
			ppm	
Central Plain	Regosols	2	199	22
	Alluvial Soils	3	10376	199
	Rendzinas	2	1851	441
	Grumusols	1	1053	199
	Non-Calcic Brown Soils	6	11038	233
	Red Yellow Podzolic Soils	6	3551	117
	Reddish Brown Lateritic Soils	1	523	199
North Eastern	Red Brown Earths	3	4874	302
	Gray Podzolic Soils	18	519	40
	Red Yellow Podzolic Soils	1	10124	246
	Reddish Brown Lateritic Soils	1	871	101
	Red Yellow Latosols	5	435	56
South Eastern	Regosols	1	149	23
	Gray Podzolic Soils	8	811	106
	Red Yellow Podzolic Soils	1	1402	78
	Reddish Brown Latosols	1	448	113
Northern	Gray Podzolic Soils	2	2659	28
	Red Yellow Podzolic Soils	11	5702	114
Southern	Gray Podzolic Soils	7	1682	91
	Red Yellow Podzolic Soils	23	3584	112
	Reddish Brown Lateritic Soils	2	1278	361

Potassium Availability in Soils of Indonesia

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Summary

Among the major soil groups of Java, those that tend to have higher base status, K content and levels of 2:1 clays — grumusols, regosols and mediterranean soils — predominate in East Java and some of Central Java. More highly weathered soils, primarily composed of 1:1 clays or amorphous material and generally containing lower levels of K such as latosols and podzolics, are more common in West Java. Podzolics are the most common soils on the outer islands, followed next by alluvial soils and organic or humic gley soils. Most of these soils are highly weathered and contain relatively low levels of K.

Recent research indicates that many paddy soils which were unresponsive to K are now responding. Fertilization with K has been shown to increase N and P efficiency and decrease Fe and Mn toxicity in some soils. Straw application can substitute for K in some K deficient soils, while levels of K in irrigation water can be substantial and important as well.

Intensive upland cropping over a long period of time has been shown to draw K levels down to deficient levels, even in soils originally high in K. Although much of the literature reports variable results, recent work in Sumatra indicates substantial responses to K can be expected on acid, infertile podzolics.

Comparisons have been made among K extractants for predicting response to K on paddy soils. Several seem to work quite well with similar soils, but not as well if a wide range of soils are analized.

1. Introduction

Mineral fertilizers in Indonesia have, until recently, been utilized almost exclusively on industrial or export crops, while relatively smaller amounts have been applied to food crops. With the introduction of the higher yielding varieties, use of N and P fertilizers increased dramatically for food crops, but use of K fertilizers increased only slowly (Table 1). This imbalance, with relatively large amounts of K being removed from the soil in crop yields over a period of time, is graphically illustrated in Figure 1. Thus many soils which previously had sufficient K supplying power are now becoming deficient and responding to K fertilization.

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Another reason that increased response to K is being observed in Indonesia is that in the last few years greater emphasis has been placed on agriculture on the outer islands of Sumatra, Kalimantan, Sulawesi and Irian Jaya. In general, soils on these islands are more highly weathered, more acid and infertile, and contain lower levels of K than do soils in Java *(Middelburg [1955]; Sudjadi [1984])*.

Table 1. Total fertilizer application for Indonesia from 1968-1984 in 1000 tons (from: *Ministry of Agriculture [1983]*)

Year	For Food Production			For Non Food Production		
	N	P	K	N	P	K
1968	95.1	10.7	0.3	6.1	3.6	9.2
1969	155.2	16.1	0.8	16.1	2.9	10.5
1970	162.1	13.9	3.0	21.8	6.1	12.1
1971	194.6	13.0	7.0	17.1	2.6	3.6
1972	228.0	9.4	1.7	27.3	5.2	31.1
1973	312.0	28.7	1.6	16.9	2.7	12.0
1974	290.8	42.1	5.6	25.6	3.8	2.2
1975	311.3	48.5	0.8	27.5	4.2	20.9
1976	313.3	43.7	2.5	39.0	5.1	15.9
1977	443.4	46.1	8.1	43.4	3.7	33.1
1978	478.9	65.8	9.8	70.1	4.9	53.8
1979	550.9	57.2	14.9	69.5	9.4	55.1
1980	787.3	92.8	11.6	53.1	9.1	65.7
1981	946.0	131.6	12.4	51.1	9.4	71.6
1982	1060.0	156.0	35.9	23.8	6.2	30.7
1983	973.4	139.6	45.2	75.7	18.2	44.6
1984	1070.7	153.6	49.7	83.3	20.0	49.1

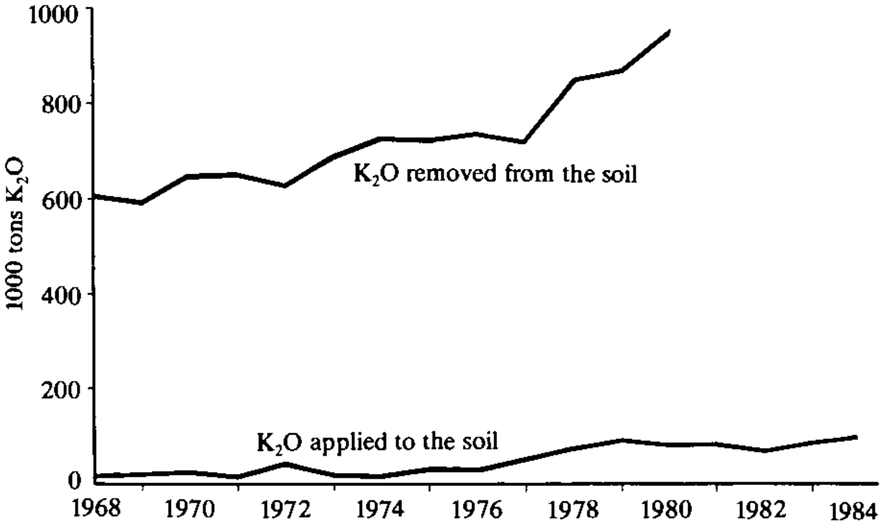

Fig. 1 Removal of K in crop harvests and K fertilizer application in 1000 t of K_2O in Indonesia from 1968-1984 from: *Ministry of Agriculture, [1983]*

2. Soils of Indonesia and their K status

Javanese soils have been studied longer and characterized better than soils on the outer islands. An estimate of the areal extent of various soil types in Java and Madura has been made from the soil map for that region *(CSR [1969b])* and can be seen in Table 2, along with the range in pH and 25% HCl extractable K for these soils. Although values for K are highly variable, in general, grumusols, regosols and mediterranean soils have higher K levels than do latosols, andosols and podzolics. Several volcanoes in East and Central Java have deposited material with significant quantities of leucite which, combined with the longer dry season resulting in less weathering, has given these soils relatively higher K levels *(Middelburg [1955])*.

Table 2. Soils of Java and Madura, their distribution, pH and 25% HCl extractable K levels (adapted from *CSR* [1969], and *Parwoto* [1978])

Soil Types	Soil Taxonomy Equivalence	Area 1000 ha	% of Total	pH Range	K Range ppm
Latosol	Oxisol/Inceptisol	2361	18	4.5-6.4	33-1170
Alluvial	Entisol/Inceptisol	2323	18	4.3-7.9	8-1187
Grumusol	Vertisol	2229	17	6.3-8.0	58- 689
Regosol	Entisol/Inceptisol	1833	14	5.5-7.6	42-2175
Red Yellow Mediterranean	Alfisol	1800	14	6.1-7.6	66- 274
Andosol	Andosol	1240	10	4.3-6.5	80- 340
Red Yellow Podzolics	Ultisol	1160	9	4.1-6.1	33- 250
Others		31	< 1		
Total		12977	100		

Parwoto [1978] compiled data from over 4000 locations on Java in developing a K map for paddy soils of Java *(CSR [1977])*. The map is divided into 5 levels of K and results are summarized in Table 3. Over 50% of the paddy soils in West Java, often highly weathered latosols or podzolics made up predominantely of 1:1 clays, were ranked in the low or very low K classes, while those from Central and East Java had a much higher percentage in the high and very high classes. Based on work by *Soepardi [1976]* that found a Bray 2 critical level for K in paddy soils of 124 ppm, *Partohardjono et al. [1977]* collected data and soil samples from many areas of Java to develope a map of paddy rice soils in Java with 2 categories — areas potentially responsive to K (Bray 2 extractable K < 124 ppm) and areas not responsive to K (Bray 2 K > 124 ppm). Based upon this map, they calculated that about 2.2 million hectares of paddy soils in Java required K fertilization at that time.

Soils on the outer islands have not yet been as extensively mapped as those on Java; however, the potential for agricultural expansion on these islands is great. Estimates of the amounts of soils with less than 10% slope on the major islands has been made by *CSR [1969a]*, and more recently, estimates of the distribution of soil types for all soils on Sumatra has been made *(Scholz [1983])*. Table 4 gives a summary of these estimates. The soils which cover the greatest area on these islands are alluvial, organic or humic gley and podzolic soils. The alluvial soils are highly variable, depending on source and duration of deposition. Organosols and humic gley soils generally found in coastal areas, are low in plant nutrients and require a high degree of management to become productive. The podzolics, which have been estimated by *Driessen and Soepraptohardjo [1974]* to cover 30% of Indonesia, are generally highly weathered, easily eroded, acidic and have low base status, often with very low levels of K *(Dudal and Soepraptohardjo [1957]; Sudjadi [1984])*. Significant areas of South Sulawesi, the Lesser Sundas and the Malukus have rendzinas, grumusols and mediterranean soils, most of which are relatively higher in bases due to their parent material, their recent and their relatively pronounced dry season which favors slower weathering *(Middelburg [1955])*.

Table 3. Distribution of paddy rice soils in Java based on 25% extractable K (adapted from *Parwoto [1978])*.

		Areal Distribution in Java in 1000 hectares							
		WEST		CENTRAL		EAST		TOTAL	
Class	K extracted ppm	ha	%	ha	%	ha	%	ha	%
Very low	0- 80	192	22	14	2	8	1	214	8
Low	80-160	313	37	177	20	213	24	703	27
Average	160-320	176	21	327	36	335	37	838	32
High	320-480	124	14	165	18	252	28	541	20
Very High	480 +	51	6	212	24	93	10	356	13
Total		856		895		901		2652	100

Table 4. Percentage of the soil area of each major outer island distributed according to soil types for soils with less than 10% slope only (adapted from *CSR [1969]*; except that data for Sumatra is for all soils, from *Scholz [1983]*

Soil group	Sumatra	Kalimantan	Sulawesi	Lesser Sundas	Maluku	Irian Java
1. Organosol/Humic Gely	22	28				36
2. Alluvial	10	17	24	37	26	36
3. Regosol			1			
4. Renzinas			1	24	36	1
5. Grumusol			7	15		
6. Mediterranean			24		17	
7. Latosol	14					
8. Podzolic	47	45	43	24	21	27
9. Podzol		10				
10. Andosol	5					

Recently, an attempt to study variability of various soil parameters, including K, was completed in the Sitiung region of West Sumatra *(Trangmar et al. [1984])*. This study involved intensive sampling of an area in the piedmont/peneplain of Sumatra of approximately 1200 km^2 and analyzing the samples for many physical and chemical parameters. Analysis of the data was performed using geostatical methodology. It was found that texture and P levels were related to geomorphic unit, type of deposition (volcanic or alluvial) and age of material, while levels of Ca, Mg and K were apparently not. Isotropic semivariograms for different parameters were made; and it was reported that many (texture, pH, extractable P, Al and Al saturation) had a certain distance between sampling sites where spatial variability was random. At sampling distances less than that range, values obtained were related to values of nearby sampling sites. However, for Ca, Mg and K, no quantifiable spatial dependence was found. Spacial variation for these parameters was considered to be essentially random at the sampling distances used in this study.

3. Potassium in paddy soils

Although K fertilization of paddy soils in Indonesia has been considered to be unimportant, research within the past few years indicated that K deficiencies are becoming more widespread *(Ismunadji et al. [1973a]; CSR [1977]; Sri Adiningsih [1976])*. In areas with low soil K levels, yields were more than double with 100 kg K/ha *(Ismunadji et al. [1976])*. *Partohardjono et al. [1977]* found that during the dry season, 50-75 kg K/ha were sufficient to achieve maximum yields, while during the wet season 100-125 kg K/ha were required.

Recently, an investigation of the effects of continuous cropping on the K supplying power of latosols in West Java has been undertaken. *Sri Adiningsih [1984]* selected 9 latosols with clay minerals dominated by kaolinite and some halloysite and grew 8 cycles of rice continuously in pots containing 7.5 kg of soil. Initial exchangeable K levels ranged from 47-550 ppm, and by the end of the eighth cycle, K levels ranged from 4-62 ppm, fell below the critical level of 140 ppm. Plant levels of K fell below the critical level of 2% with all soils by the fifth crop, even for the soil which had begun with 550 ppm.

A long term field study, begun in 1982 by CSR, was initiated to study K fertilization on a latosol with a high K content (430 ppm) in West Java. During the first season, no response to K was observed. By the second crop, a slight, though significant response was obtained and the most recently harvested crop showed an even higher response.

Use of K has been shown to be important in increasing N and P efficiency in Indonesia. Research contucted by *Sri Adiningsih [1984]* for 4 seasons both in the greenhouse and in the field using a latosol with low initial exchangeable K (78 ppm) showed a negative response to increasing N and P levels. More than half of both the N and P taken up was found in the straw and was not translocated to the grain. Potassium fertilization not only increased grain yields dramatically, but it increased the grain: straw ratio and increased N and P usage significantly. Treatments with applied K had 70% of the N and 85% of the P taken up in the grain.

Iron toxicity is a problem in several regions of Indonesia. *Ismunadji et al. [1973]*, found that Fe toxicity symptoms were seen on plants with only 0.35% K. When K was applied to the soil, foliar K levels increased to 1% and Fe levels dropped. A more recent experiment conducted on a latosol with poor drainage and high Fe levels studies the effects of K fertilization, straw incorporation and percolation rates on yields and N, P, K and Fe uptake. Results can be seen in Table 5. Percolation of 1 cm/day was superior to no percolation. Increase aeration in the reduced layer due to percolation increase root growth and nutrient uptake. Both K and rice straw incorporation increased N, P and K uptake and decreased Fe uptake *(Sri Adiningsih [1984])*. *Sismiyati and Yazawa [1977]* speculated that bronzing symptoms found in some regions of Java were actually a combination of Fe and Mn toxicities. Using nutrient solution culture, they showed that increasing K levels were quite effective in decreasing Mn uptake and increasing yields in Mn toxic solutions.

An integral part of K management in paddy soils is rice straw disposal. In Indonesia straw disposal consists primarily of burning or incorporating it, often from piles formed around the threshing site, although minor uses exist *(Ismunadji [1978]; Ponnamperuma [1984]). Ismunadji et al. [1973b]* found that incorporation of 3 tons straw/ha was effective in increasing yields by 600 kg grain/ha, as well as increasing N, P and K uptake. Burning and incorporation of 10 tons/ha to a grumusol both gave significant yield increases over no straw application in another experiment *(Ismunadji [1978]).* Studying the effects of straw incorporation in a soil with low K in the greenhouse, *Sri Adiningsih [1984]* found that straw was as effective as K in increasing rice yields, N and P uptake and improving chemical and physical fertility (Table 6). Another experiment conducted over 4 seasons in the field had a treatment of 5 tons straw/ha as part of a K study on a latosol with low K levels *(Sri Adiningsih [1984]).* Straw application gave the same or even higher yields than all other treatments, including the treatment with 166 kg K/ha (Figure 2). Higher yields with straw are perhaps due to improvement of soil physical parameters, to addition of nutrients other than K within the straw or because K is released more slowly and leaching is decreased.

Table 5. Effects of percolation rates, straw incorporation and K fertilization on uptake of N, P, K and Fe of rice grown on a latosol paddy soil from West Java.

	Without Percolation				With Percolation (1 cm/day)			
	without straw		with straw		without straw		with straw	
	OK	+K	OK	+K	OK	+K	OK	+K
Grain yld. (g/pot)	g/pot							
	28.2	47.1	43.3	47.2	43.1	53.3	53.8	59.2
Uptake	mg/pot							
N	603	854	800	809	830	042	943	1052
P	58	90	92	98	80	92	103	116
K	327	508	712	888	386	811	781	1049
	ppm							
Fe	774	546	564	474	459	402	332	325

Table 6. The effect of straw application on some chemical and physical soil fertility factors after 4 seasons on Latosol paddy soil from West Java.

	$C_{org.}$	N	P	K	Mg	CEC	Si	Agregat
	----%----		mg/100 g		me/100 g	soil	ppm	Stability
Without straw	2.40	0.28	17	0.13	0.50	18	50	60
With straw (5 ton/ha/seasion)	3.90	0.33	18	0.35	0.75	20	150	80

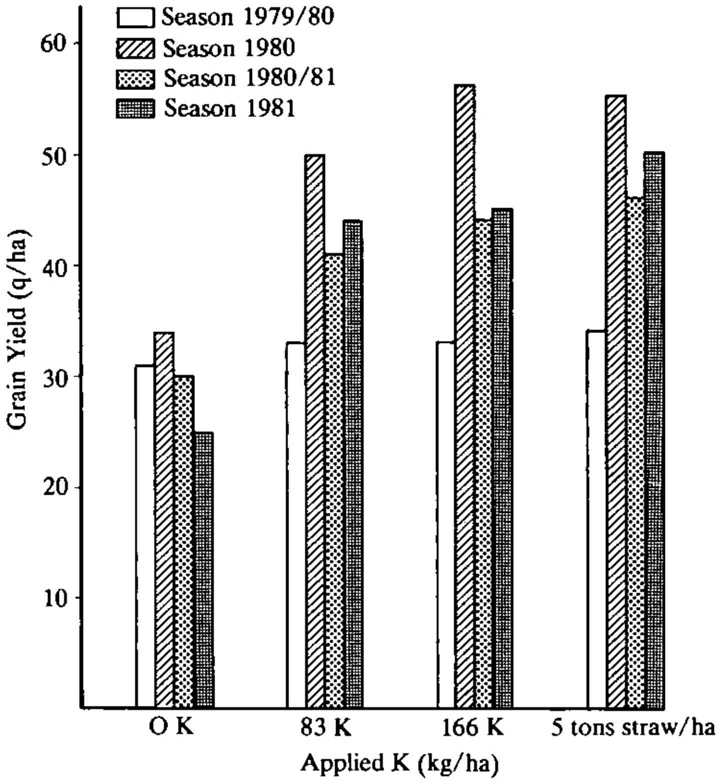

Fig. 2 Rice grain yield response to applied K and 5 ton straw/ha during 4 seasons (1979/80-1981) on Latosol paddy soil, West Java

Improving K fertilizer efficiency by split applications has been investigated. On a highly K deficient, well drained soil, *Ismunadji et al. [1976]* found that splitting K applications gave 20% greater yields than simply applying K at transplanting. *Santoso and Moersidi [1976]* conducted experiments in 2 locations, on a grumusol and on an alluvial soil. The grumusol did not respond to K, while for the alluvial soil, splitting K applications improved yields relative to basal application during the rainy season but not during the dry season. Perhaps this is due to less leaching of K during the dry season or because of higher K in irrigation water in dry season.

Levels of K in irrigation water contribute significantly at times to the nutritional needs of a rice crop. *Van Dijk [1951]* examined levels of K in Javanese waters and found that concentrations in East and Central Java were greater than those in West Java. He also found that K levels in the dry season were higher than during the wet season. He calculated that K concentration was sufficient to provide from 53 kg K/ha in wet season in West Java to 90 kg K/ha in dry season in East Java. Differences in irrigation water content help explain results obtained by *Partohardjono et al. [1977]* who found rice responses to peak at 50-75 kg K/ha in the dry season, but at 100-125 kg K/ha in the wet season.

Ongoing research at CSR is investigating concentrations of nutrients in irrigation and river water around Indonesia. Potassium has so far been determined in 415 samples, and results are seen in Table 7. Levels of K in water tend to correspond to soil levels of K, with levels in Sumatra, Kalimantan and Sulawesi in general lower than those in Java and the Lesser Sundas. Some areas in Sumatra and Kalimantan contain extremely low levels of K, reflecting the paucity of nutrients in the soil these water flow through. As also observed by *Van Dijk [1951],* there is a trend for K concentrations to decrease going from east to west across Java. In each Javanese province, there was a significant increase in K concentration in the dry season, with levels in rainy season averaging 80% of those in dry season. If a rice crop utilizes 1000 mm of irrigation water, it follows that some areas of Sumatra and Kalimantan receive less than 4 kg K/ha/crop, while West Java averages 26 kg K and East Java averages 52 kg K/ha/crop in the irrigation water.

Table 7. Concentration of K in river & irrigation water in several areas of Indonesia

Island	Province	K concentration mg K/l	K Range mg K/l	Samples
Sumatra	Lampung	0.4	0- 1.2	7
	South Sumatra	0.7	0- 1.6	5
	Bengkulu	0.4	0- 0.4	3
	West Sumatra	0.4	0- 0.4	9
Kalimantan	West Kalimantan	0.4	0- 0.4	5
	East Kalimantan	1.2	0.4- 2.3	8
	South Kalimantan	0.4	-	1
Sulawesi	Southeast Sulawesi	1.0	0- 2.0	17
Timor	East Timor	4.6	3.5- 5.5	3
Madura	Madura	1.5	0.9- 2.0	4
Java	East Java	5.2	1.5-33.4	185
	Central Java	3.1	1.3-14.5	42
	West Java	2.6	0.2- 7.6	126
				415

4.Potassium in upland soils

Investigation of upland crop response to K fertilization has been conducted for some time in Java. *Van Dijk [1951]* reported on a study of cassava on a grumusol in Central Java from 1929-1941. During the first 4 years, there was no response to K. However, after that, response to K increased as soil K levels were drawn down. Another study with sugarcane from 1931-1934 concluded that K was unimportant and thus not recommended for sugarcane production. By 1957 however, K deficiency in sugarcane was widespread in Java and K fertilizer significantly improved yield and quality *(Schuylenborgh and Sarjadi [1958]).*

Research on K fertilization of upland food crops has been conducted in the last decade, but reports often do not adequately characterize the site, *i. e.* soil type, K status, texture, etc. This limits conclusions which can be drawn from these experiments. *Djatijanto et al.*

[1976] in their review of K use in upland crops in Central Java found crops to be unresponsive on many soils. Maize responded to K at only 2 of 11 sites, while other crops were reported to respond at approximately half the locations studied. *Ismunadji et al. [1976]* concluded that upland crop response in Java was variable and when it did occur, it was only slight. *Santoso and Al-Jabri [1977]* reported that corn required 25-50 kg K/ha in Lampung, Sumatra, but the following year *(Santoso [1977]),* no response was obtained on a similar soil which had been in fallow for 15 years.

Several experiments have recently been initiated as part of the Tropsoils Project in West Sumatra, a collaborative soil management research endeavor between *CSR, University of Hawaii* and *North Carolina State University*/USA. Soils in this transmigration settlement region are podzolics characterized by low pH, high Al and low base status, with exchangeable K averaging less than 78 ppm *(Trangmar et al. [1984], Sudjadi [1984]).* Partially in response to the large governmental liming for soybeans program, experiments to study the interaction of K with lime have been implemented.

Since most farmers in the area grow a rotation of upland rice followed by soybean, an experiment using this rotation was conducted on a typic Haplorthox cleared by bulldozers 7 years earlier, cropped briefly and abandoned. Original K level by Mehlich 1 was 20 ppm, and after applying 3 rates of lime (0.4, 1.5 and 5 t/ha), Al saturation was 70, 59 and 4%, respectively. Yield response of rice to applied K at the 3 lime levels can be seen in Figure 3. While the rice did not respond to lime due its high Al tolerance, it reached a maximum of 2.3 t grain/ha between 120 and 240 kg K/ha. Before soybeans were planted, lime was reapplied to bring the middle rate of lime down to 40% Al saturation and K was reappli-

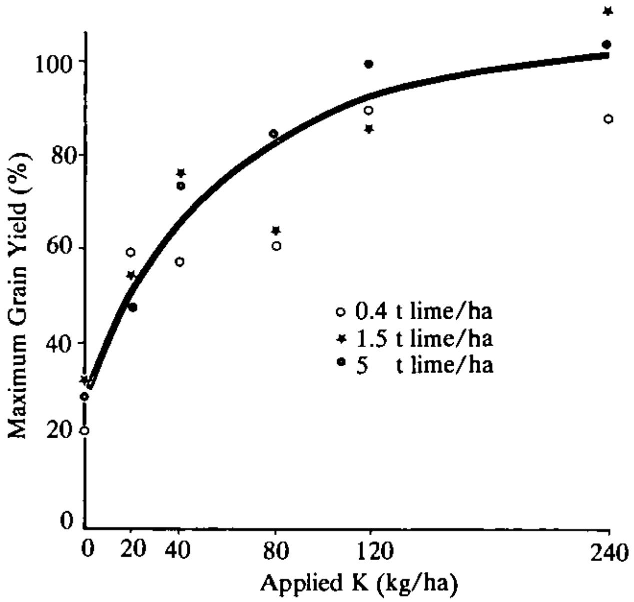

Fig. 3 Response of upland rice on a Typic Haplorthox to applied K rates at three limit levels in West Sumatra

ed. Soybean yield results are in Figure 4. Being less Al tolerant, soybean responded to lime, while K response increased with increasing K rates. Soil samples taken between the two crops showed that soil K levels were higher than the ${}_0$K plots only in treatments which had received 80 kg K/ha or more. Considerable leaching is occurring and attemps are being made to quantify this by sampling various depths of soil and establishing a soil crop K budget. Another similar experiment with a corn — peanut rotation has shown dramatic responses to both lime and K for these crops on an acidic, low K (40 ppm) Typic Dystropept.

Another experiment in the same area on a Paleudult with 25 ppm K has examined the K response of an upland rice — soybean rotation under 3 residue management systems: straw removal, incorporation of straw from the previous crop, and straw incorporation + 10 t/ha (wet weight) of *Calopogonium* sp. Top yields for both crops were obtained with 120 kg K/ha when previous crop residues were not utilized, a common farmer practice in this area. With straw from the previous crop incorporated, soybean yields were higher at the ${}_0$K rate and almost 2.5 t/ha at 80 kg K/ha. The 10 t/ha of *Calopogonium* supplied 60.1 kg K/ha and was sufficient to achieve maximum yields without K additions.

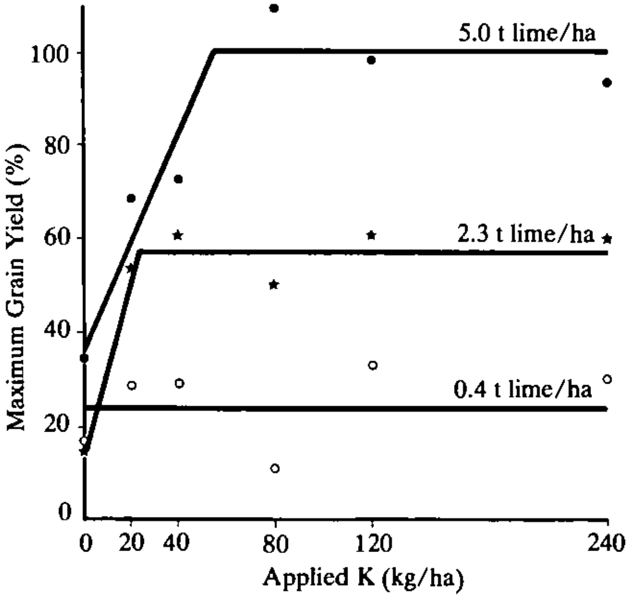

Fig. 4 Response of soybeans to applied K rates at three lime levels in West Sumatra

5.Soil testing for potassium

Attempts have been made for years to develop soil tests for prediction of crop response to K fertilization in Indonesia. In his review of K research in Indonesia, *Middelburg [1955]* found that 2% citric acid, 25% HCl and Morgan-Venema (10% Na acetate + 3% acetic acid) extractable K were inversely related to K fertilizer requirement of sugarcane, tea and tobacco in Java. Little effort was made to develop soil tests for food crops until the late 1960's when greater governmental priority was placed upon overcoming food deficits and increasing agricultural research *(Sudjadi [1973]). CSR* staff *(TPUT [1976])* found NH_4 acetate, Olsen, Bray 2 and 25% HCl to all have high potential for use as K extractants in Indonesia soils. *Soepardi [1976]* claimed that, for paddy soils in West Java, Bray 2 was correlated more closely with yield and K uptake than were NH_4 acetate, Bray 1 or Mehlich 1. *Sri Adiningsih [1976],* working with samples from many areas of Java, reported that no extractant was significantly correlated with rice yield, but that several were correlated somewhat with K uptake. In comparing the response of corn yield and K uptake at forty days to 25% HCl, Olsen and NH_4 - acetate extractable K, *Sri Adiningsih [1976]* found all 3 to be well correlated to dry weight and K uptake, but NH_4- acetate gave the best correlation with dry weight and Olsen best predicted K uptake.

Soil tests for K involving a variety of soil types is generally less successful than those involving similar soils, due to differences in secondary minerals, clay and organic matter content, etc. *(Chang [1978]).* Using 25 paddy soils from around Indonesia, *Sri Adiningsih and Sudjadi [1983]* compared 5 extractants for predicting 2 month old rice yields and K uptake. Only 25% HCl extractable K did not correlate well with yields and K uptake, while Bray 2 had the highest correlation, and Bray 1, Olsen and NH_4 acetate were intermediate. *Purwanto and Sri Adiningsih [1980]* reported that over a fairly wide range of soils, hot 1 $\underline{N}$ HNO_3 had the highest correlation with rice yields and K uptake, while Morgan-Venema gave correlations almost as high. Olsen, 25% HCl and NH_4 - acetate correlations were considerably lower. Working only with latosols, *Sri Adningsih [1984]* found that all extractants which were compared provided high correlations with crop yields and K uptake. With other soils (alluvial, grumusols and regosols), however, much lower correlations were obtained. Thus it appears that good prediction of K response is possible on soils with similar characteristics. The challenge for the future is to develop some soil testing methodology for K that is widely applicable over large areas and different of soil types.

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The Potassium Status of Soils in South China

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Summary

Most of the K-bearing minerals in South China soils have been degraded by strong weathering and eluviation. Both total and slowly available K contents are low. Investigation has shown that supplies of K readily available to plants are limited. As agriculture is intensified and crop yields rise, soil supplies of potassium plus that contained in organic manures is proving insufficient to support good harvests. There is an increasing need for potassium fertilizer in this region.

1. K-bearing minerals and soil potassium content *[1-5]*

The K-bearing minerals constitute a reserve of potassium while the potassium adsorbed to clay minerals is the main source of K supply to plants. The main minerals containing potassium are the micas and feldspars. As Table 1 shows, the K content of the feldspars is lower than that of the micas. Latosols derived from basalt or marine deposits contain the least K-bearing minerals and the purplish soils the highest (up to 34.6%). Paddy soils on lacustrine deposits are intermediate.

The amount of K-bearing minerals in the soil depends solely on parent material and degree of weathering. Purplish sandy shale contains much mica, while purplish soil, an entisol derived from this material, is rich in mica and hydrous micas. Table 2 shows the distribution of K-feldspars and micas in the various particle size fractions. Micas are found mainly in the < 2 μ and 2-10 μ fractions with feldspars mainly in the 5-10 μ fraction.

Hydrous micas are the dominant K-rich minerals in soil clay. The higher their content, the greater the K content of the clay. For instance, the red earths on the phyllite of Xingjiang (Jiangxi Province) is rich in hydromica, with about 3% K_2O, in the < 5 μ fraction. With increasing weathering, K is increasingly removed from the hydromica and there is a shift in particle size distribution; the soil K content is reduced. For instance, in the 4 m deep profile, which is the subject of Table 3, the clays (< 5 μ) in the weathered body contain about 18 times as much K as the surface soil; in the highly weathered body clay K content is 5.5 times that of the surface layer. In the surface soil, the K reserve is less than 50 mg/100 g soil.

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Table 1. Potassium-bearing minerals in the soils of red earth regions

Soil	Parent materials	Locality	K-bearing minerals (%)				Dominant clay minerals
			K-feldspar		Micas		
			< 10 μ	Total soil	< 10 μ	Total soil	
Latosol	Basalt	Xuwen, Guangdong	Trace	Trace	1.6	2.0	K.G.
	Marine deposits	Zhanjiang, Guangdong	0.2	0.2	1.0	1.0	K.C.
Lateritic red soil	Granite-gneiss	Huazhou, Guangdong	Trace	0.2	2.9	3.6	K.G.
Paddy soil	Granite	Guangzhou, Guangdong	Trace	0.6	2.3	3.3	K.H.
		Guangtze, Fujian	0.8	10.8	15.8	21.7	K.H.
Purplish soil	Purplish shale	Hengyang, Hunan	0.8	1.8	28.0	32.8	H.C
		Chongqing, Sichuan	—	—	15.8	28.1	H.M.
Paddy soil	Limestone	Liuzhou, Guangxi	Trace	Trace	1.0	1.0	K.V.
		Yichun, Jiangxi	—	—	9.2	23.3	K.H.
		Shaoyang, Hunan	0.4	0.7	13.5	14.4	K.H.
	Red sandstone	Yujiang, Jiangxi	0.3	0.9	5.7	6.2	K.C.H.
	Red clay	Jenxian, Jiangxi	0.7	1.2	9.7	10.9	K.C.H.
		Xiangtan, Hunan	0.1-0.9	0.2-2.4	12.7-14.8	13.7-17.3	K.C.H.
		Chuxian, Zhejiang	0.5	1.6	8.4	10.0	K.V.H.
	Lacustrine deposits	Hanshou, Hunan	0.48	3.0	17.1	22.2	H.C.K.
	Alluvial deposits	Lianyuan, Hunan	0.3	0.7	13.2	14.4	H.C.K.
		Xiangtan, Hunan	0.5	1.0	11.4	12.5	H.C.K.

K: Kaolinite
C: Chlorite
M: Montmorillonite
H: Hydromica
V: Vermiculite
G: Gibbsite

Table 2. Content of K-bearing minerals in different soil particle size fractions

Parent materials	< 2 μ		2-10 μ		10-50 μ		50-100 μ		Total content	
	K-feldspar	Micas	K-feldspar	Micas	K-feldspar	Micas	K-feldspar	Micas	K-feldspar	Micas
Lacustrine deposit	0.19	11.44	0.29	5.66	2.27	4.89	0.24	0.20	2.99	22.19
Lime stone	0.06	11.40	0.27	2.14	0.38	0.81	<0.01	<0.01	0.71	14.35
Purplish shale	0.11	28.03	0.55	4.77	0.55	1.65	<0.01	<0.01	1.21	34.45
Red clay	0.04	10.66	0.24	2.08	0.48	0.95	0.05	0.03	0.81	13.72
Alluvial deposit	0.26	9.36	0.35	2.01	0.68	1.04	0.04	0.07	0.98	12.48
Sand shale	0.69	10.25	0.21	4.40	0.28	2.46	0.03	0.18	1.21	17.29

Table 3. Potassium content in different particle size fractions of lateritic red soil and its parent materials of granite-gneiss (Huazhou, Guangdong)

Depth	< 1 mm	Clay fraction (<5 μ)		Silt fraction (5-50 μ)		Fine sand fraction (0.05-0.1 mm)	
	K %	%	K (mg/100g)	%	K (mg/100g)	%	K (mg/100g)
Surface soil (0-20 cm)	0.154	30.5	47	18.2	0.60	51.3	0.41
Highly weathered materials (170-240 cm)	0.454	56.2	259	19.2	1.59	24.6	0.62
Weathered materials (240-400 cm)	0.919	63.0	857	9.3	2.60	27.4	1.12

In the tropical regions, the proportion of hydrous mica and vermiculite in clay minerals is reduced and the content of kaolinite increased as compared with the warm temperate zone. In central subtropical zones, kaolinite predominates with a little hydromica and vermiculite, while in the southern subtropical and tropical areas the soils contain gibbsite in addition to well crystallised kaolinite, some of them with less hydromica and vermiculite. These soils' K supplying potentials reflect their clay mineral composition.

Table 4 reports contents of total, slowly available and available soil K in the main soils of South China. The latosols derived from basalt and tuff show serious soil weathering, with a thick soil solum and heavy clayey texture. They are very low in K-bearing primary minerals, with kaolinite, gibbsite and iron oxide as main clay minerals. Thus, this kind of soil shows the lowest potassium level in the zonal soil types of China. The coastal sandy loam developed on marine deposits is also one of the lowest K level soils. Red soils derived from limestone, red sandstone and red clay on the rolling hills of South and central China are generally low in K. Soils derived from neutral calcareous purplish shale show the highest K in South China. The K contents of paddy soils developed on the alluvial and lacustrine deposits along the alluvial plains delta are determined essentially by the origin of soil-forming substance. Generally, they have a medium content of soil K.

Table 4. K content of main soils in South China

Soil	Parent materials	Total K (%)	Slowly avail. K (mg K/100 g)	Avail. K (mg K/100 g)
Latosol	Basalt, tuff	0.20	3.7	5.5
	Marine deposits granits	0.31	4.2	4.4
	Metamorphic rocks	1.43	46.3	14.8
Lateritic red soil	Granite-gneiss	0.38	6.4	6.5
Red soil	Red clay	0.95	16.3	6.6
	Red sandstone	0.77	7.0	3.2
	Granite, phyllite	2.72	19.8	7.6
Yellow soil	Sandy shale, granite	1.06	7.5	9.8
Limestone soil	Limestone	0.94	14.8	6.3
Purplish soil	Purplish shale	1.86	48.3	13.2
Paddy soil	Alluvium of the Pearl River	1.84	26.5	6.1
	Lacustrine deposit of of Taihu Lake	1.43	31.5	8.2
	Alluvium along Yangtze River	1.64	48.3	6.6
Yellow-brown soils		1.28	36.2	8.1

2. The release of soil potassium

Studies have been made in relation to K-releasing ability of different types of soils by means of drying, cation-exchange resin, successive extraction with HNO_3 and by pot culture.

2.1 Effect of drying

Table 5 shows the effect of drying at various temperature on release and fixation of K in soils with different clay minerals [6]. As we can see, in the case of air drying, the soils (whose parent materials are lacustrine, alluvial deposits, granite, and basalt respectively) with kaolinite as the dominant clay mineral only release little K, while those with hydrous mica as the principal clay mineral release more. When oven-dried at 105° C, the soils with kaolinite as the principal clay mineral have the ability to fix potassium ions, while those with montmorillonite and hydrous mica as the principal minerals release considerable amounts of K. When oven-dried at 200° C-400°C, most of the soils release K in varying amounts, but on the whole the soils with kaolinite as the dominant clay mineral in South China tend to release less potassium.

Table 5. The effect of drying at various temperature on release and fixation of K in soils with different clay minerals

Dominant clay minerals	Parent materials	Increase in exchangeable K (%)			
		Air-dried soil (based on moist soil K)	Oven-dried soil by 105°C (based on air-dried soil K)	Oven-dried soil by 200°C (based on oven-dried soil K by 105° C)	Oven-dried soil by 400°C (based on oven-dried soil K by 200° C)
Kaolinite	Lacustrine deposits	2.1	− 19.9	2.6	82.2
	Alluvial deposits	3.8	− 3.7	26.9	113.2
	Granite	9.2	− 28.5	− 2.2	17.6
	Granite	3.0	− 11.8	50.0	17.7
	Basalt	35.9	− 1.9	94.2	11.9
Montmorillonite, hydrous mica	Loess	23.0	50.7	45.2	106.1
	Purplish shale	16.1	34.1	65.5	114.6
	Basalt	61.0	110.6	43.9	45.0
Hydrous mica	Lacustrine deposits	116.2	76.9	76.4	202.3
	Loess	81.3	50.7	78.0	177.2
	Loess	69.6	38.5	75.2	153.8
	Alluvial deposits	91.7	46.7	91.1	166.3
	Alluvial deposits	23.8	38.5	122.2	200.0
	Purplish shale	30.5	12.4	70.2	210.4
	Alluvial deposits	8.3	15.4	93.3	132.8

2.2 Resin extraction

The results of extraction of K from different types of soils using a cation-exchange resin are shown in Table 6. The four types of soils in South China (whose parent materials are limestone, red clay, alluvial deposits and lacustrine deposits respectively) are all low in both available and slowly available K. The amount of K extracted in one resin extraction is close to that of available K, and the total amount of K extracted in six extractions is larger than the amount of available K but smaller than the amount of slowly available K. This means that the total K removed in six extractions represents the more active portion of slowly available K, still the soils in South China have lesser amounts of potassium extracted *[7]*.

Table 6. Estimation of K in soils by a cation-exchange resin

Parent materials	Available K (mg K/100 g)	Slowly available K (mg K/100 g)	Resin exchange K One extraction	(mg K/100 g) Six extractions
Limestone	2.5	2.3	2.8	5.0
Red clay	2.9	7.3	3.0	4.8
Alluvial deposits	7.1	50.2	8.5	10.6
Lacustrine deposits	10.7	39.9	12.0	16.9
Loess	22.0	84.7	20.8	33.1
Loess	31.2	122.3	40.3	71.1

2.3 Available potassium

The adequacy of a soil to supply a crop's K requirements over a season's growth depends mainly on the level of available K. If the available K is close to or lower than what is needed for the season's growth, the rate of release from less readily available sources assumes importance. The content and rate of transformation of this reserve K must be taken into account in appraising the long-term K supplying potential.

Although there have been quite a number of suggestions as to the methods of determining the K-supplying potential of soil, extraction with 1 N boiling nitric acid for ten minutes is still the most common method *[8]*. Figure 1 lists the results of releasable soil potassium by 6 successive extractions with boiling 1 N HNO_3.

In the given six soil types, the amount released is the lowest for latosols, next for red earths and the highest for grey fluvo-aquic soils, indicating that the K-supplying potential of latosols and red earths in red earth region is very low. The purplish soils, with their higher rate of release are the soils having the highest K-supplying potential in South China.

2.4 Pot culture experiments

Pot culture experiments were conducted on 26 soils with a wide range of slowly available potassium (from 1.8 mg to 130 mg). Rice was used as the test crop. For the soils without KCl treatment, the potassium uptaken by 6 successive crops of rice varied noticeably with the soil, with the lowest uptake of only 1.7 mg for latosols and the highest for warp soil (derived from alluvial deposits), amounting to 43.9 mg. In South China regions, with the exception of purplish soils, the soil K-potential is low. It can be seen from Figure 2

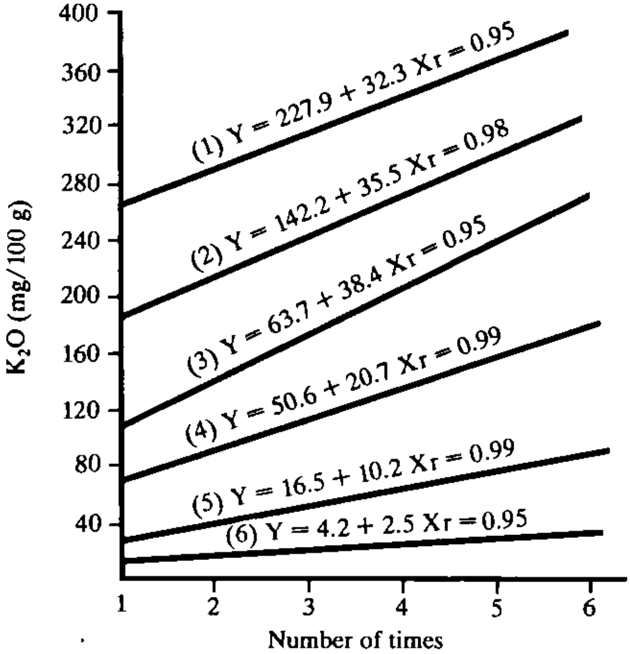

Fig. 1 Rate of release of potassium from different soils
(1) Gray fluvo-aquic soil; (2) Fluvo-aquic soil; (3) Purplish soil; (4) Paddy soil derived from lacustrine deposits; (5) Paddy soil derived from red earth, and (6) Latosol.

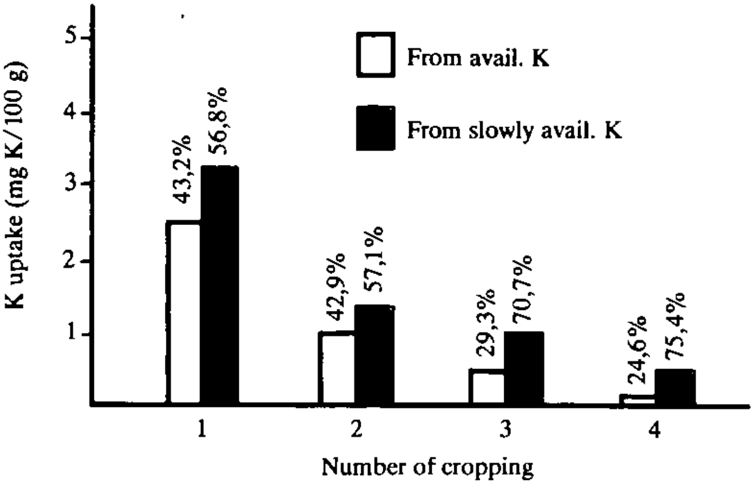

Fig. 2 K uptake by successive rice crops (pot experiment, average of 26 soils).

that in soils receiving no K-fertilizer, the amount of potassium taken up from the available potassium by rice was relatively low, but relatively high from the slowly available potassium. The total amount of potassium taken up by the rice plants was significantly correlated with the slowly available potassium of the soils before cultivation ($r = 0.897$). The total K-uptake by rice was better correlated with the slowly available potassium ($r = 0.983$) than with the available potassium ($r = 0.852$), showing that in the long run the slowly available soil potassium is the chief source of potassium for rice.

Another series of pot culture experiments was conducted on 35 soils with different levels of slowly available soil potassium, grouped into 7 classes from <6.6 mg to >116 mg *[5]*. Responses to potassium fertilizer by 3 successive crops of rice vary with the content of slowly available potassium, *i.e.* the lower the slowly available potassium, the greater the effect of potassium fertilizer. Such effects will increase in successive crops as the soil K-potential is lowered by the consumpiton of previous crops. Results also indicate that the content of slowly available potassium reflects both the soil K-supplying potential and the requirements for K-fertilizer.

3. The K-supplying potential and K fertilizer requirements of the chief soils

The main soils of South China can be classified for K-supplying potential as follows:

1. Very low: In general, the content of the slowly available potassium is lower than 6.6 mg. The deficiency in potassium has currently become a restricting factor to crop yields and the response to potassium fertilizer is most conspicuous. Among the dominant soils are the allitic red earths, the coastal sandy loam and the lateritic soils in South China and those derived partly from limestones in Guangdong and Guangxi provinces. Such soils were found to be the most K-deficient in our country. Heavy applications of potassium fertilizer began with these soils.

2. Low: This soil group contains slowly available potassium about 6.6-16.6 mg. In the areas of such soils there has already been a significant potassium deficiency and, what is more, it is becoming even more serious. The soils of this group are mainly distributed in the subtropical region of Central China, including the hilly land of Jiangxi, Hunan and eastern Zhejiang. They include the red soils derived from Tertiary sandstone and Quaternary red clay, the paddy soils developed on these red soils, and also the badly eroded red soils derived from granite. In Hunan Province, a significant response of rice to K fertilizer has been found in large areas of paddy soil developed on the red soil originated from limestone and red clay. The permanently waterlogged paddy soils occurring in low lying basins of red soil areas in Jiangxi and Hubei provinces show serious K deficiency.

3. Moderate to low: The content of slowly available potassium in this soil group is about 16.6-33 mg and the K-supply is becoming increasingly deficient, especially for high-yield crops. Among the dominant soils are the soils in Zhujiang Delta and the paddy soils along the valleys of the Xiang River of Hunan and the Gan River of Jiangxi. In the Zhujiang Delta, for example, some soils especially the paddy soils derived from alluvial materials in the old polder areas, show severe potassium deficiency. Application of K-fertilizer in these areas markedly improves rice production.

4. Moderate: The content of slowly available potassium in this soil group is about 30-50 mg. The steady increase in crop production necessitates applying K-fertilizer. Among the principal types of soil are the paddy soils derived from the lacustrine deposits of Dongting Lake and Poyang Lake and the purplish soils of South China.

5. Moderate to high: As a rule, the slowly available potassium in this soil group is more than 50 mg and no K-fertilizer will be needed in the near future. Among the dominant soils are purplish soils, and also the red and yellow earths occurring on the high hills under natural vegetation. They inherit soil K from their parent materials of granite and phyllite in the regions of South and Central China. For instance, the siallitic laterite spreading over the higher hilly region between terraces and mountainous areas in Hainan Island was mostly either the secondary monsoon rain forest or the mixed shrubby forest before planting rubber trees. The trees grown on this kind of soil receive excellent potassium nutrition.

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Potassium Availability in Soils of Southern India

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Summary

The major soil groups of Southern India — black, red, alluvial and laterite — cover 52.4, 31.9, 7.0 and 1.2 million hectares respectively. Kaolinite is the dominant mineral group in laterites and most red soils whereas montmorillonite dominates in black and some red soils. While laterites are low in exchangeable, non-exchangeable and total K, black soils have higher exchangeable and non-exchangeable K with red soils occupying an intermediate position. K fixation and release are influenced by moisture regimes, added K and period of incubation. Available and reserve forms of K tend to increase with fineness of texture.

Conventional estimates of K availability, EUF fractions and Q/I parameters broadly indicate a general need for K fertilizers in the red and laterite soils and for smaller applications of K in some black soils.

A large number of experiments on cultivators' fields indicate very profitable response to K in all cereals whether grown under irrigated and assured rainfall conditions or under rainfed dryland conditions. Pulses and oilseeds were less responsive to K but groundnut and sorghum showed considerable response.

Ammonium acetate K is a poor predictor of crop response to K fertilizer. As agriculture intensifies, the pattern of crop response to K is changing, probably due to negative K balance caused by K applications being less than crop removals.

Introduction

Soils of Peninsular India are largely sedentary. Hence, their fertility depends on the chemical composition of rocks and minerals from which they are derived. Black, red, alluvial and laterite soils constitute 56, 34.5, 7.6 and 1.3 per cent of the geographical area in South India, covering 52.4, 31.9, 7.0 and 1.2 million hectares, respectively (Figure 1).

1. Soils of South India

1.1. Black Soils

Black soils, also known as regur or black cotton soils, are generally derived from the Deccan trap basalt. At places, these have originated from granite and gneiss containing lime and soda feldspars, which are basic in character. Soil depth is variable. According to Soil Taxonomy, shallow soils are classified as orthents and associated suborders and

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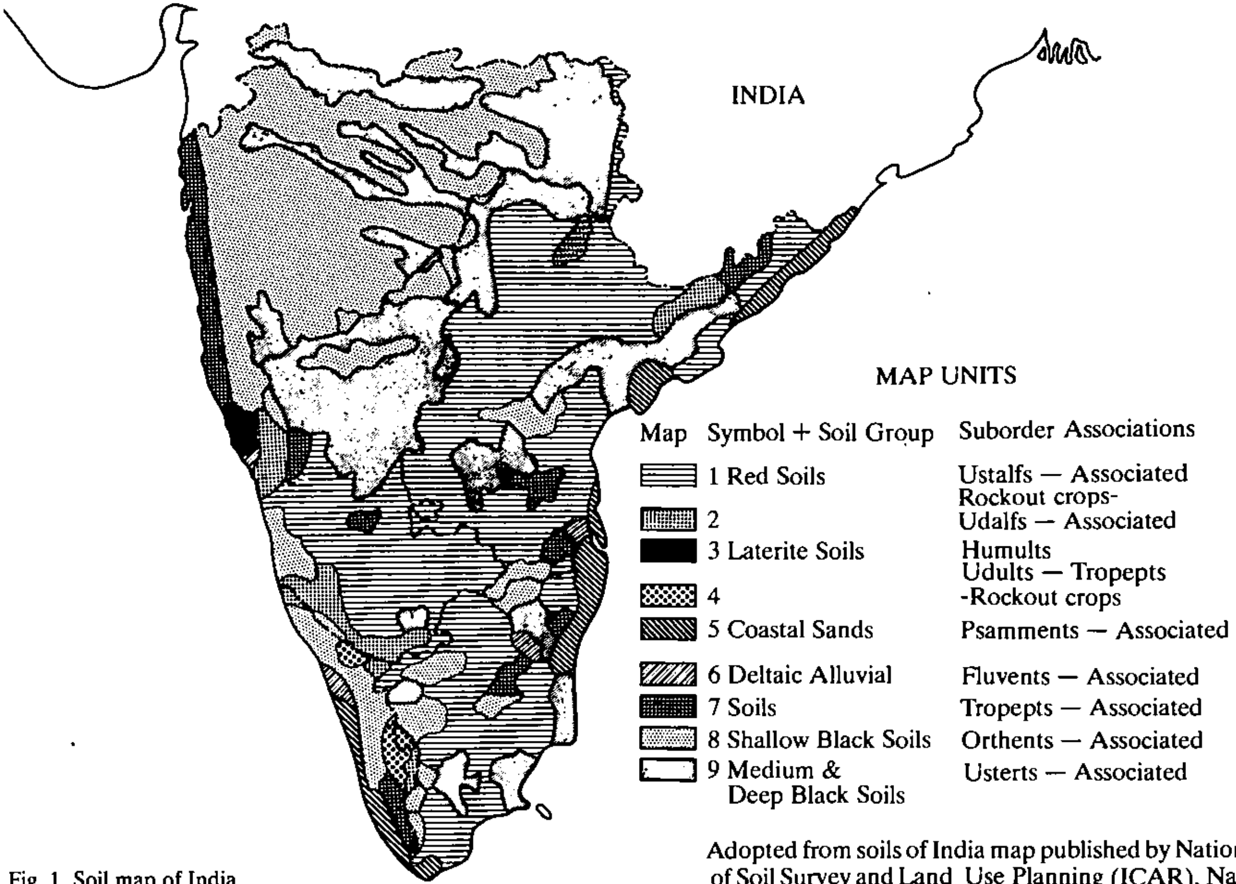

Fig. 1. Soil map of India

Adopted from soils of India map published by National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur.

medium to deep soils under Usterts and associated suborders. In South India, they predominate in Maharashtra (94%), Karnataka (54.8%), Andhra Pradesh (32.5%) and Tamilnadu (25.7%). These are heavy textured with clay content ranging from about 35 to more than 70 per cent. They are plastic and sticky when wet, and have marked tendency for swelling and shrinkage. Organic carbon is less than 1.5 per cent. In shallow black soils pH ranges from 7.2 to 7.6 whereas in medium to deep soils it ranges from 7.5 to 8.5. Calcium carbonate content ranges commonly from 0.5 to 3.0 per cent with extremes from 0.1 to 20 per cent. Cation exchange capacity ranges between 25.0 and 36.0 me/100 g in shallow, and 50 to 75 me/100 g medium to heavy textured black soils.

1.2 Red Soils

Red soils are derived mostly from granite, gneiss and schists and are rich in feldspars, micas and hornblende. According to Soil Taxonomy, these soils are classified under Ustalfs and associated suborders, Rockout crops-Udalfs and associated suborders. These are the major soil groups in Andhra Pradesh (62.9%), Tamilnadu (52.5%) and Karnataka (43.8%). Red soils are either sandy or loam. Red sandy soils are mildly acidic (pH 5.5) to very slightly alkaline (pH 7.5). In general, they are deficient in organic matter. The cation exchange capacity of the soils generally ranges from 3.0 to 15.0 me/100g, depending on the amounts of clay and organic matter present. In red loams also organic matter content is low. The reaction is almost neutral (pH 6.7 to 7.5). Base saturation ranges from 88 to 93 per cent.

1.3 Laterite soils

Laterite soils have developed on a variety of rocks, both basic igneous rocks such as basalt, norite and diabase and acid rocks such as granite, granulite and schists. According to Soil Taxonomy, these are classified as humults, Udults-tropepts-rockoutcrops. They occur in the hills of Western ghats in Kerala, Karnataka and Coastal Maharashtra, and are the predominant soil group (21.7 per cent) in Kerala. These are very acidic with pH 4.5 to 5.5, with low organic matter and nitrogen contents. The cation exchange capacity ranges from 5 to 7 me/100 g. Owing to intense leaching, the soils are very poor in bases.

1.4 Alluvial soils

These soils have developed either on the river alluvium or on the sea coast. In soil taxonomy, they are classified as Psamments-associated suborders, Fluvents-associated suborders and Tropepts and associated suborders. They are relatively more frequent in Tamilnadu (21%) and Kerala (17.7%). The texture of coastal alluvium is extremely variable and ranges from sandy to silty clay. Sands are prominent along the coast in Tamilnadu, Andhra Pradesh and Kerala. These are poor in fertility and often affected with salinity. In coastal alluvium pH ranges from 4.2 to 5.5. The coastal sands have extremely low water holding capacity. Deltaic soils occur in the deltas of Krishna, Godavari and Kavery. Godavari and Krishna delta soils are silty clays whereas Kavery delta alluvium contains a high proportion of dark silt clay. The CEC is quite high. The pH varies from 7 to 8.2.

Table 1. Some characteristics of surface soils of selected soil series from South India *[12]*

Soil Group	State/ Distt.	Soil Series	Climate	Rainfall	Clay Minerals	Depth of Surface Soil (cm)	Clay Content %	Org. Carbon %	Carbonate as $CaCO_3$ %	pH 1:2.5 H_2O	Ca+ Mg	K	CEC	CEC/ Clay
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
I. Black	*Maharashtra*													
	Amraoti	Jambha	Sub-humid Trop.	975 mm	Mont.	0-20	59.7	0.46	1.9	8.6	54.0	1.0	55.2	0.92
	Nagpur	Linga	– *do* –	1125 mm	– *do* –	0-16	74.6	0.51	1.9	8.3	53.7	0.6	59.3	0.76
	Solapur	Barsi	Semi Arid Trop.	740 mm	– *do* –	0-12	65.9	0.53	0.4	8.5	67.6	0.8	70.1	1.06
	Karnataka													
	Dharwar	Achmatti	– *do* –	660 mm	– *do* –	0- 4	54.6	1.25	16.2	8.3	41.1	1.1	64.6	1.09
	Dharwar	Hungund	– *do* –	660 mm	– *do* –	0- 9	35.2	0.62	10.0	8.7	53.8	0.8	56.2	1.60
	Gulbarga	Kagalgomh	Semi Arid Trop.	760 mm	– *do* –	0-10	52.0	0.63	5.7	8.5	57.2	0.8	67.6	1.30
	Raichur	Raichur	Semi Arid Trop.	750 mm	– *do* –	0-12	64.6	0.97	3.4	8.0	62.5	1.4	71.8	1.11
	Tamilnadu													
	Coimbatore	Coimbatore	Semi Arid Sub-Trop.	570 mm	– *do* –	0-15	43.0	0.35	6.9	8.7	36.9	0.9	39.1	0.91
II. Red.	*Karnataka*													
	Bijapur	Jamkhandi	S.A.S.T.	575 mm	Sand Stones & Quartzites	0-16	20.1	1.03	1.2	8.2	13.1	0.9	16.6	0.82
	Bangalore	Tyama-gondalu	SAT	750-850 mm	Weathered gneiss	0-13	12.8	0.50	—	6.8	2.3	0.3	2.9	0.2
	Bangalore	Vijayapura	SAT	900-1000 mm	Weathered granite gneiss	0- 7	16.6	0.44	—	5.6	2.3	0.2	3.0	0.18

Condt.. 2/-

Table 1. *contd.*

Soil Group	State/ Distt.	Soil Series	Climate	Rainfall	Clay Minerals	Depth of Surface Soil (cm)	Clay Content %	Org. Carbon %	Carbonate as $CaCO_3$ %	pH 1:2.5 H_2O	Ca+ Mg	K	CEC	CEC/ Clay
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
II.														
Red.	Bangalore	Chama Sandra	SAT	730 mm	Weathered granite gneiss	0-17	8.5	0.53	—	6.7	4.3	0.2	4.5	0.42
	Andhra Pradesh													
	Medak	Kadirabad	SAT	730 mm	Mont.	0- 2	36.7	0.71	2.2	8.0	36.8	0.7	40.5	1.10
	Medak	Chinnaloni	SAT	730 mm	*— do —*	0- 2	55.2	0.91	6.2	7.8	59.8	1.5	61.9	1.12
	Medak	Kasireddipalli	SAT	760 mm	*— do —*	0-20	53.7	0.73	5.3	8.8	52.6	0.7	57.2	1.06
	Medak	Patancheru	SAT	760 mm	Weathered granite gneiss	0-12	17.9	0.84	—	6.5	7.7	0.3	8.1	0.45
III.														
Laterite	*Kerala*													
	Idduki	Thekkadi	HT	4000 mm	Kaolinite	0-27	41.2	3.29	—	6.0	13.1	0.7	15.9	0.39
	Trivandrum	Trivandrum	HT	1840 mm	*— do —*	0- 9	51.6	1.39	—	4.5	2.1	0.2	6.7	0.13
	Calicut	Kunnamangalam	HT	3280 mm	*— do —*	0-13	27.6	1.63	—	5.4	0.8	Tr.	3.2	0.12
IV.														
Alluvial	*Tamilnadu*													
	Thanjavur	Kalathur	SAT	870 mm	Mont.	0-14	39.7	0.90	8.2	9.1	37.0	0.4	38.9	1.01

2. Potassium status of soils

Different groups of workers have examined these soils. Table 1 gives some characteristics of surface horizons of a few bench-mark soils *[12]*. One will note that with the exception of laterites which have developed in humid tropics, all others-black, red and alluvial-have generally developed in the semi arid or sub humid tropics or sub tropics. *Mukherjee, Das and Raman [10]* and *Ghosh and Kapur [5]* have discussed the mineralogy of Indian soils. While kaolinite is the dominant mineral group in the laterites and red soils of Karnataka and Tamilnadu, montmorillonite is dominant in black and even some red soils of Andhra Pradesh.

Black soils and red soils, having montmorillonitic clay minerals, also have higher clay content, cation exchange capacity and exchangeable potassium than other red soils and laterites. Potassium saturation of the exchange complex in these soils ranges from 1.0-2.3 in black soils, 1.2-3.7 in red soils, having montmorillonitic clay minerals, 4.4-10.3 in other soils and 3.0-4.4 in laterites.

2.1 Exchangeable, non-exchangeable and total potassium

Ekambaram et al [2], *Kadrekar [7]* and *Ranganathan* and *Satyanarayana [21]* have reported on potassium distribution in some profiles of these soils in the states of Tamilnadu, Maharashtra and Karnataka, respectively. *Sidhu [22]* has examined some soil series of Andhra Pradesh and Karnataka. Extracts of results from their studies on the surface soils are given in Table 2. These indicate that laterite soils are low in all forms of potassium-exchangeable, non-exchangeable and total. Black soils have higher exchangeable and non-exchangeable potassium than red soils but their total potassium content is often less than that of red soils and is quite low in some soils of Karnataka and Tamilnadu.

2.2 Potassium supply characteristics

At the *Potash Research Institute*, Gurgaon, we are studying the supply characteristics of bench-mark soils. Samples of soils from 5 soil series were collected and analysed for estimates of K availability by various methods. *[15]*. Table 3 summarizes these data. The amounts of water soluble K are only slightly less than EUF_{10}-K. NH_4OAc extractable K and EUF_{35}-K give similar estimates of available K, although the latter estimate is always slightly less than the former. In general, HNO_3-K and ratio of $EUF_{30\text{-}35}$-K to EUF_{30}-K give similar estimates of the K-buffer capacity of soils, although there are some differences in detail. Comparisons of these estimates with those of plant available K obtained from growing crops in these soils should be useful.

Figure 2 gives K-desorption curves for the 5 soils. *[15]*. Apparently, the two red soils (Vijayapura and Tyamagondalu) and the laterite soil (Nedumangad) bahave fairly similarly. The amount of K-desorption at each successive interval is the highest in Noyyal and intermediate in Pemberty. All laboratory estimates point towards the need for a sufficient application of potassium fertilizer in the red and laterite soils, for a small application in Pemberty soil, at least in the long run, and for no potassium in Noyyal series for a considerable length of time.

Table 2. Forms of potassium in some soils of Southern India

Soil group	State	Soil Series	Depth of Surface soil (cm)	Potassium in indicated forms in the surface soil			Reference
				Exchangeable (mg K/100 g)	Non-Exchangeable (mg K/100 g)	Total %	
I. Black	Maharashtra Akola	—	0-23	19.1	77.2	1.04	*Kadrekar [7]*
	Andhra Pradesh	Kasireddipalli	—	14.3	62.0	1.05	*Sidhu [22]*
	Karnataka	—	0-15	28.1	66.0	0.41	*Ranganathan & Satyanarayana [21]*
		Telgi	—	19.0	34.1	0.52	*Sidhu [22]*
	Tamilnadu Peelamedu		0-15	25.0	62.0	0.56	*Ekambaram et al [2]*
II. Red	Karnataka	—	0-20	11.9	48.5	1.69	*Ranganathan & Satyanarayana [21]*
		Chamasandra	—	11.8	42.7	1.70	*Sidhu [22]*
		Tyamagondalu	—	7.7	26.3	1.70	*Sidhu [22]*
III. Laterite	Maharashtra	—	0-24	3.9	17.4	0.63	*Kadrekar [7]*
	Karnataka	—	0-15	5.5	30.5	0.63	*Ranganathan & Satyanarayana [21]*
IV. Alluvial	Karnataka	—	0-26	7.0	24.0	0.63	*Ranganathan & Satyanarayana [21]*
	Tamilnadu	—	0-15	32.0	64.0	0.34	*Ekambaram et al [2]*

Table 3. Some estimates of K availability by conventional and Electroultrafiltration methods for five Bench mark soil series of South India *[15]*

Soil Series	Classification	K mg/100 g*					
		Water soluble	EUF_{10}	EUF_{35}	NH_4OAc	HNO_3	$\frac{EUF_{30\text{-}35}}{EUF_{30}}$
1. Pemberty (Andhra Pradesh)	Vertic Ustochrept	1.98	2.25	20.6	21.2	70	0.77
2. Noyyal (Tamilnadu)	Udorthentic Chromustert	7.89	11.80	58.0	64.8	228	0.53
3. Vijayapura (Karnataka)	Oxic Haplustalf	1.62	2.26	5.4	7.1	14	0.28
4. Tyamagondalu (Karnataka)	Oxic Pleustalf	2.05	2.62	6.3	8.1	38	0.30
5. Nedumangad (Kerala)	Oxic Dystropept	1.27	2.05	5.9	8.4	14	0.37

*Average Of 25 samples

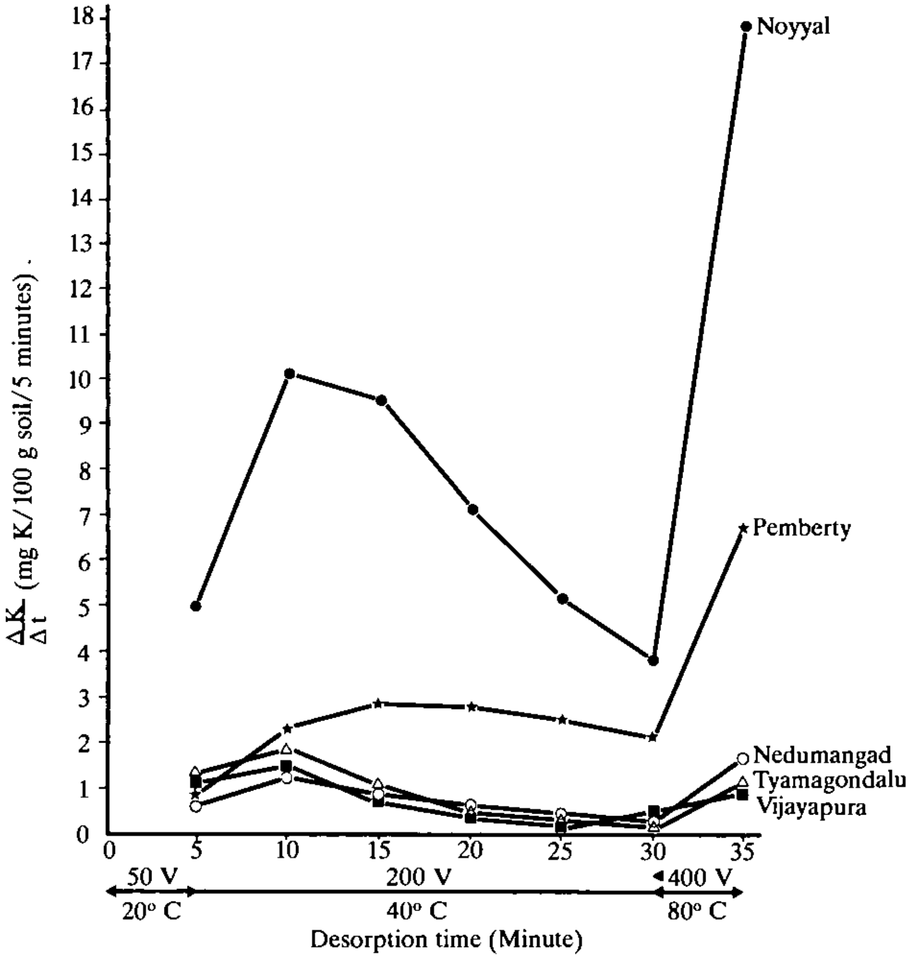

Fig. 2. Desorption of potassium in selected soils from five soil series of South India *[15]*

Some quantity-intensity parameters of potassium availability in a few soils of South India are given in Table 4. The labile pool of K is generally higher in black soils as compared to red soils. According to *Sidhu [22]* this difference is due mainly to more K being held on non-specific sites in black soils. Otherwise, potassium held on specific sites is more in red soils than in black soils. The potential *Buffering Capacity (PBC)* of black soils is higher than red soils indicating their higher potential to replenish K concentration in the soil solution as compared with the red soils. The equilibrium activity ratio of red soils, on the other hand, is higher than that of black soils so that immediate availability of K will be higher in these soils, although they may not be as effectively buffered against K depletion.

Table 4. Some parameters of potassium availability in a few soils of South India

State/Soils	Series	Equilibrium activity ratio $AR^K_e \times 10^{-3}$ $(M/L)^{1/2}$	K_L	K_O	K_X	Buffer capacity $\Delta Q/\Delta I$	Authors
			me/100 g				
Black Soils							
Andhra Pradesh	—	1.50	0.17	—	—	132	*Ramakrishnayya & Chatterjee [16]*
	Kasireddipalli	2.60	0.62	0.53	0.09	207	)
		2.80	0.42	0.33	0.09	120	) *Sidhu [22]*
		2.00	0.48	0.42	0.06	210	)
Karnataka	Telgi	1.2	0.39	0.36	0.03	313	)
		1.2	0.32	0.28	0.04	233	)
		1.9	0.36	0.33	0.03	174	)
Red Soils							
Tamilnadu		7.72	0.45	—	—	59.6	*Ramanathan [17]*
Andhra Pradesh		3.65	0.14	—	—	59.8	*Subba Rao et al [23]*
– do –	Patancheru	3.7	0.23	0.17	0.06	44.6	) *Sidhu [22]*
		6.5	0.26	0.12	0.14	18.5	)
Karnataka		9.90	0.13	—	—	14.6	*Ramakrishnayya & Chatterjee [16]*
	Tymagondalu	19.3	0.28	0.18	0.10	9.4	)
		11.5	0.19	0.04	0.15	3.5	) *Sidhu [22]*
		11.3	0.30	0.18	0.12	15.6	)
Laterite soils							
Kerala		1.2	0.11	—	—	92	*Padmaja [13]*
Tamilnadu		0.43	0.10	—	—	34.1	*Ramanathan [17]*

2.3 Potassium supply from non-exchangeable and mineral lattice sources

Haylock [6] proposed step K and constant rate K as measures of plant utilizable non-exchangeable K and K release from mineral lattice structures, respectively. Cumulative K release curves for five soils obtained by repeated extractions with boiling $N HNO_3$ are shown in Figure 3 (15). Noyyal and Pemberty series from black soil region released more K than the series belonging to red and laterite soils. Step K and constant rate K values were also higher for the former series (Table 5). In black soils the presence of micaceou

Table 5. Step K and constant rate K values of five series of Southern India *[15]*

Soil Series	Step	Constant Rate
	K in mg/100 g	
Noyyal	520.0	3.15
Pemberty	171.5	1.05
Tyamagondalu	77.5	1.40
Vijayapura	24.2	0.37
Nedumangad	17.2	0.37

minerals like hydrous mica (illite) and biotite in clay and silt fractions contributes to their high K release whereas in weathered red and laterite soils, the contents of these micaceous minerals are rather small. However, in those red soils like the Tyamagondalu series where micaceous minerals occur in moderate amounts they contribute considerably to K supplying capacity.

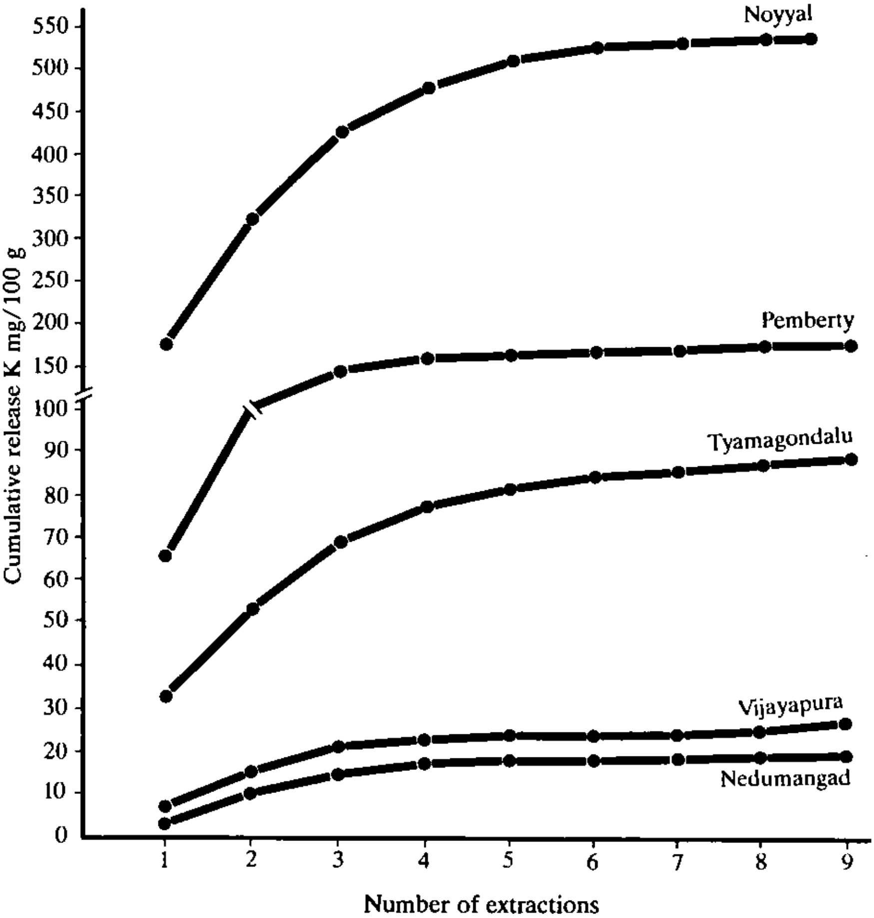

Fig. 3. Potassium release from non-exchangeable and mineral lattice in selected soils from five soil series *[15]*

2.4 Release and fixation of potassium

Some soils release sufficient K from reserve sources because they have a good buffering capacity to supply modest amounts of exchangeable and soil solution K over a growing season. Other soils have a low capacity to release slowly available K to maintain K con-

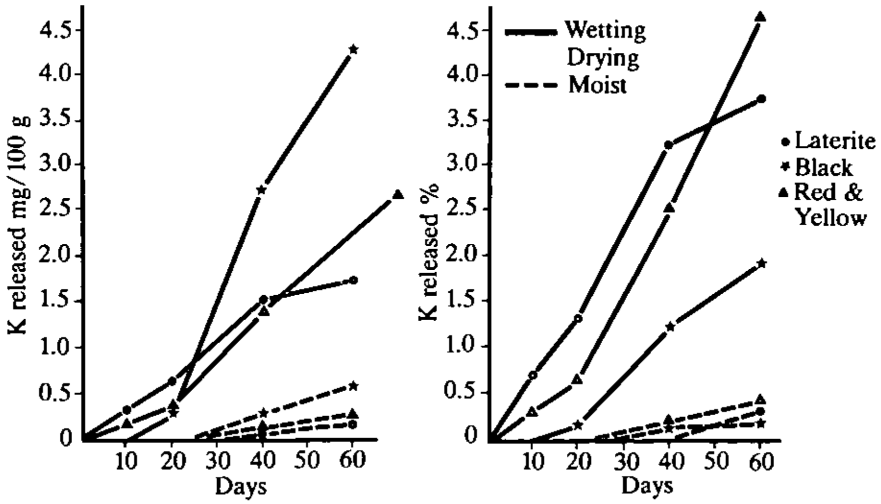

Fig. 4a. Potassium release due to wetting and drying in soils maintained at 50% moisture equivalent *[8]*

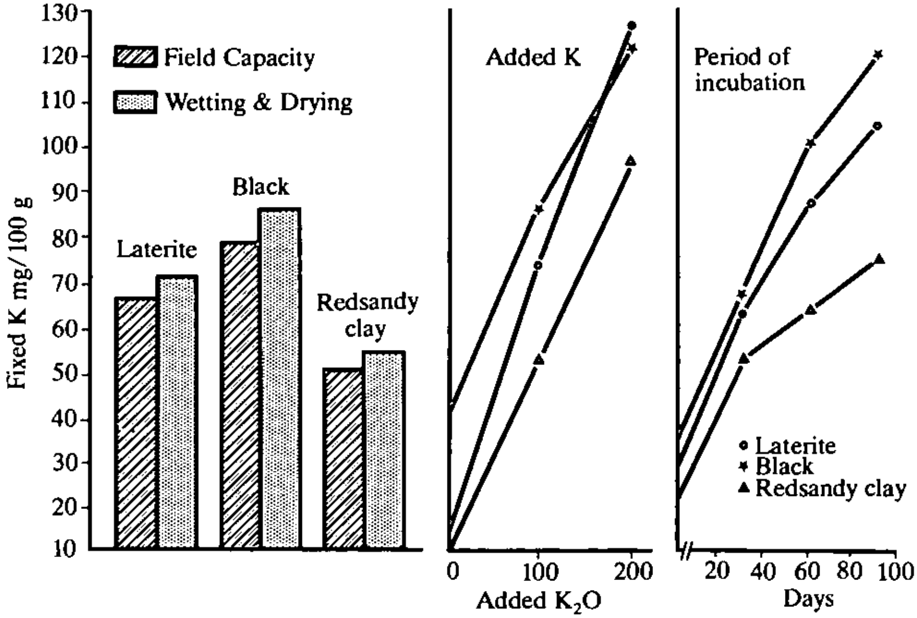

Fig. 4b. Potassium fixation as affected by moisture, added K and period of incubation *[18, 19, 20[*

centration of the soil solution well enough during the growing season, owing to their poor buffering capacity.

Yet other soils fix K when soluble K is added to them. Such soils have been depleted of K through previous cropping or weathering. The added K is trapped in the inter layer positions and blocks further release of such K. Consequently, large amounts of K must be added before estimates of readily available K show a perceptible increase. K thus fixed is held within the system and is subsequently released to crops, though at a rate too low for high levels of crop production.

Kadrekar and Kibe [8] examined the release of soil potassium in Black (Poona), Red and yellow (Dongargaon) and Laterite (Dapoli) soils of Maharashtra. Their results are reproduced in Figure 4a. Black soils of Poona released most potassium and laterite soils of Dapoli, the least. Red and yellow soils of Dongargaon were intermediate in this respect. K release was much higher when the soils were intermittently wetted and dried than when they were kept moist throughout. Moistening the soil to one-half of its moisture equivalent was better than moistening it to double this amount. It took 40-60 days for the soils to show perceptible K release. After 60 days of wetting and drying cycles, the release was 4.23 mg/100g (19% of the initial amount of Exch. K) in black soil, 2.66 (46%) in red and yellow soil and 1.74 (37%) in laterite soil.

Ramanathan et al [18, 19, 20] made similar studies on K fixation with samples of Tamilnadu soils belonging to these three groups. Their results are summarized in Figure 4b. Laterite soil of Coonoor fixed more potassium than the black and red sandy clay loam soils of Coimbatore. K fixation was pretty much the same whether the soil was kept at field capacity or was intermittently wetted and dried. The fixation appears to start instantaneously and tends to decrease with time. Within the limits of applied potassium, fixation appears to increase almost linearly with the amount of applied potassium.

2. 5 Other soil factors affecting potassium availability

Besides the mineralogical composition of clay and other particle size fractions, the other most significant soil factor that may affect K availability is the amount of clay. The miner-

Table 6. Ammonium acetate and boiling nitric acid extractable and EUF potassium in textural classes of different soil series of South India *[15]*

Soil series	Textural Class	No. of soils	NH_4OAcK ppm		*N* HNO_3K ppm		$EUF_{35}K$ ppm	
			Range	Mean	Range	Mean	Range	Mean
Noyyal	Loam	6	443- 750	581	1870-2400	2102	400-614	488
	Silty loam	4	238- 675	525	1140-2500	2030	225-658	491
	Clay loam	4	463- 713	610	1780-2570	2285	420-645	550
	Silty clay loam	8	525-1000	749	2020-2840	2475	478-941	676
Vijayapura	Sandy loam	11	24- 85	49	50- 220	120	19- 64	34
	Sandy clay loam	11	30- 149	65	70- 220	146	23-105	52
Tyama-gondalu	Loamy sand	7	38- 71	55	235- 370	320	31- 62	45
	Sandy loam	14	33- 138	83	295- 395	359	21-116	70

alogy and particle size distribution together influence the cation exchange capacity of the soils, their ability to hold exchangeable and non-exchangeable K, fix applied K or release the intrinsic or previously fixed K. Soil physical factors which may influence K availability to plants, to a lesser extent, are soil temperature, soil moisture and tilth. Within the constraints of regional climate and the availability or lack of irrigation water, particle-size distribution very considerably modifies these physical factors.

Table 6 gives estimates of K availability in various soil types in three soil series from South India. Heavier textured soils have higher average amounts of NH_4OAc-K, N HNO_3-K and EUF_{35}-K. However, the ranges of these estimates, frequently overlap. Owing to the variation in the per cent saturation of CEC, sufficiency levels of exchangeable K for maximum crop production, should be higher in heavier textured soils having similar estimates of available K.

3. Crop responses to applied K in soils of South India

Table 7 summarizes the results of a large number of single replicate experiments involving various combinations of N, P and K, done in cultivators' fields under irrigated and assured rainfall conditions *[14]*. These show that among cereal crops, the response to K was much more in rice than in sorghum or finger millet. Yield increase with an application of 20 kg K_2O/ha ranged from 13.5-22.5 kg grains per kg K_2O in paddy, against 10.5-22.5 in sorghum and 5-18 in finger millet. It was large in Kerala and Karnataka in rainfed rice, in Karnataka and Tamilnadu in monsoon sorghum and in Maharashtra, Karnataka and Tamilnadu in winter grown finger millet. The magnitude of crop response to K tended to decrease with amount of applied K but 60 kg K_2O per hectare appeared to be profitable. The grain yield of rice, sorghum and finger millet in unfertilized plots averaged 30.1 q/ha in rainfed rice in Kerala and Karnataka, 11.5 in monsoon sorghum in Karnataka and Tamilnadu and 15.8 in winter grown fingermillet in Maharashtra, Karnataka and Tamilnadu, while the corresponding average yield with an application of 60 kg K_2O in addition to 120 kg N and 60 kg P_2O_5 per hectare was 51.8, 26.2 and 33.6 q/ha, respectively. This amounted to an increase of 21.7, 14.7 and 17.8 q/ha due to fertilizer, out of which net contribution from an application of 60 kg K_2O/ha was 5.3, 5.1 and 4.7 q/ha, representing a net contribution of 24, 34 and 26 per cent of the observed increase in grain yield.

Table 8 summarizes the results of experiments under rainfed conditions *[14]*. In cereal crops, a modest application of 30 kg K_2O per hectare appeared to be the optimum everywhere. Yield increase was about 8 kg grain per kg K_2O in monsoon rice in Maharashtra, monsoon sorghum in Maharashtra and Andhra Pradesh and winter sorghum in Andhra Pradesh: it was 11 kg grain per kg K_2O in monsoon finger millet in Karnataka.

Pulses and oilseeds showed relatively less response to K but groundnut in Andhra Pradesh, Tamilnadu and Karnataka and sesamum in Andhra Pradesh showed considerable advantage from an application of 40 and 60 kg K_2O/ha.

Ammonium acetate K, the method generally used to estimate soil K status, does not predict crop response to K well. Wide variations in crop response are found at similar levels of soil K. However, as agriculture has been intensified, the pattern of crop response to K has changed, as evidenced by the general profitability of K fertilizer for most crops of the region.

Table 7. Response to potassium in experiments on cultivators' fields under irrigated/assured rainfall conditions.
(AICARP data for the period, 1977-78 to 1982-83) *[14]*

Season/Crop	State	No. of trials	Av. grain yield of unfertilized plots (t/ha)	Response to K with an application of indicated amount of fertilizer K_2O/ha in addition to indicated amount of N and P_2O_5			Average yield with an application of given amount of fertilizer N + P_2O_5 + K_2O
				20 K_2O	40	60	120 + 60 + 60
				N + P_2O_5 40 + 20	N + P_2O_5 80 + 40	N + P_2O_5 120 + 60	
					t/ha		
Monsoon Rice (irrigated)	Andhra Pradesh & Orissa	740	2.61	0.27	0.35	0.51	4.97
	Karnataka, Kerala & Tamilnadu	666	3.41	0.33	0.38	0.53	5.48
Monsoon Rice (Rainfed)	Kerala & Karnataka	477	3.01	0.45	0.40	0.53	5.18
Winter Rice (irrigated)	Andhra Pradesh	409	2.35	0.29	0.37	0.50	4.80
	Tamilnadu	268	3.23	0.38	0.54	0.68	6.21
Monsoon Sorghum	Maharasthra	208	1.38	0.21	0.19	0.28	2.57
	Karnataka & Tamilnadu	58	1.15	0.45	0.45	0.51	2.62
Monsoon Finger millet	Andhra Pradesh, Orissa & Madhya Pradesh.	5	0.48	0.10	0.06	0.13	1.86
	Karnataka & Tamilnadu	8	0.84	0.13	0.21	0.01	2.15
Winter Finger millet	Andhra Pradesh, Orissa & Madhya Pradesh	52	1.18	0.11	0.14	0.16	2.08
	Maharashtra, Madhya Pradesh	40	1.23	0.36	0.40	0.62	3.06
	Karnataka & Tamilnadu	80	1.76	0.22	0.32	0.40	3.51

Table 8. Response to potassium in experiments on cultivators' fields under rainfed dryland conditions.
(AICARP data for the period, 1977-78 to 1982-83) *[14]*

Season/Crop	State	No. of Trials	Average yield of unfertilized plots (t/ha)	Response to K with an application of indicated amount of fertilizer K_2O/ha in addition to indicated amount of N and P_2O_5		Average yield with an application of given amount of fertilizer
				30 K_2O	60	N + P_2O_5+K_2O
				N P_2O_5 60 + 60	N P_2O_5 90 90 90	60 60
					(t/ha)	
Monsoon rice	Madhya Pradesh & Maharashtra	300	0.82	0.24	0.17	2.07
Monsoon sorghum	Andhra Pradesh	44	0.63	0.23	0.17	1.69
	Maharashtra, Madhya Pradesh	507	1.51	0.25	0.20	2.80
	Karnataka, Tamilnadu	169	0.80	0.14	0.13	1.48
Winter Sorghum	Andhra Pradesh	150	0.65	0.25	0.22	2.00
	Maharashtra	170	0.45	0.10	0.08	0.92
	Tamilnadu, & Karnataka	234	0.66	0.12	0.13	1.28
Monsoon Finger millet	Karnataka	228	1.15	0.33	0.32	2.70
				20 K_2O		
				N P_2O_5 20 40		20— 40 —20
Monsoon black gram	Andhra Pradesh	131	0.18	0.04		0.57
	Karnataka	141	0.25	0.02		0.55
Winter black gram	Andhra Pradesh	215	0.39	0.09		1.20
	Tamilnadu	70	0.44	0.06		0.73
Summer black gram	Karnataka	17	0.40	0.09		0.90
Winter gram	Andhra Pradesh	47	0.22	0.04		0.74
	Maharashtra	351	0.49	0.05		0.88
	Karnataka	255	0.58	0.06		1.07
Monsoon green gram	Andhra Pradesh	117	0.27	0.03		0.68
	Maharashtra	142	0.14	0.04		0.43
	Karnataka	145	0.27	0.02		0.53
Winter green gram	Andhra Pradesh	105	0.32	0.06		0.87
Monsoon Pigeon pea	Andhra Pradesh	56	0.33	0.11		1.22
	Karnataka	104	0.34	0.07		0.83

Contd.. 2/

Table 8. Condt.

Season/Crop	State &&	No. of trials	Average yield of unfertilized plots (t/ha)	40 K_2O N P_2O_5 20 60	20 — 60 — 40
Monsoon groundnut	Andhra Pradesh	174	0.52	0.12	1.40
	Maharashtra	495	0.63	0.07	1.18
	Tamilnadu	266	1.16	0.12	1.83
	Karnataka	310	1.01	0.12	1.74

				20	40	60	
			N + P_2O_5 60 40				60 ± 40 + 60
Winter Linseed	Maharashtra	274	0.23	0.03	0.01	0.01	0.47
Monsoon Sesamum	Andhra Pradesh	36	0.09	0.03	0.06	0.01	0.44
Winter Sesamum	Andhra Pradesh	100	0.19	0.04	0.09	0.14	0.58

4. Input-output balance of K in soils of South India

When K continues to be removed from a soil, season after season, by growing crops, or through leaching to the layers beneath or by soil erosion, without replenishment, the soil will have a depleted K balance and crop responses to applied K will progressively increase. Table 9 gives estimates of K removal per tonne of produce, average K removal per hectare of crop land, generalized fertilizer K recommendation and actual fertilizer K usage. Clearly, fertilizer usage every where is less than the recommended amount and falls far short of the nutrient removal. Even after taking into account the additional quantities of N, P and K which may become available through the addition of organic manures *[1]* nutrient imbalance still persist. The results of some long-term experiments, reproduced in Table 10 furnish an estimate of the difference between K addition through fertilizers and manures and K removal by crops. These show K imbalances even when a little more potassium than what is recommended (on the basis of soil tests) is applied, with or without farm yard manure. Evidently, recommended amounts of fertilizer potassium are usually a fraction of that removed by crops during growth, because a substantial part of the K needs of crops is expected to be met from the intrinsic supply within the soil. Unfavourable nutrient balances, caused by low rates of fertilizer application in relation to crop removal of K may partly explain, the developing crop responses to potassium.

Table 9. Average K removal, Generalized fertilizer recommendation and actual fertilizer use for some major crops in South Indian States.

1	K removal (kg/tonne) /9/ 2	State 3	Average Crop yield /4/ 4	Average K removal 5	Generalized K recommendation /3/ 6	Actual K use /4/ 7
			(t/ha)	(kg/ha)	(kg/ha)	(kg/ha
A. Rice	44.8	Maharashtra	1.6	72	50	4.9
		Andhra Pradesh	2.1	94	(50) for light soils only	6.0
		Karnataka	1.9	85	50-87	9.3
		Tamilnadu	1.9	85	37-50	18.6
		Kerala	1.7	76	20-45	12.7
B.Sorghum	77.0	Maharashtra	0.72	55	62	
		Andhra Pradesh	0.56	43	–	
		Karnataka	0.87	67	37	*– do –*
		Tamilnadu	0.78	60	0— 45	
		Kerala	—	—	—	
C.Ground-nut	27.1	Maharasthra	1.03	28	25	
		Andhra Pradesh	1.04	28	30	
		Karnataka	0.89	24	25-37	*– do –*
		Tamilnadu	1.01	27	45-52	
		Kerala	0.87	24	75	
1	2	3	4	5	6	7
D. Sugarcane	3.3	Maharashtra	90	297	170	–
		Andhra Pradesh	69	228	(50 to soils analysing less than 159 kg K_2O/ha.	
		Karnataka	73	241	75-187	
		Tamilnadu	92	304	112	
		Kerala	–	–	75-90	
E.Cotton	142	Maharashtra	0.07	10	25-50	
		Andhra Pradesh	0.35	50	50	
		Karnataka	0.10	14	25-75	
		Tamilnadu	0.25	35	30-60	
		Kerala	–	–	–	

Table 10. Difference between potassium addition and crop removal in some long-term fertilizer trials. *[11]*

Soil/Location	Under conditions of application of fertilizer nitrogen alone or in combination with other nutrients. (kg K/ha)				Under conditions of application of different amounts of fertilizer			
	N	N+P	N+P+K	N+P+K +FYM	None	50%NPK	100% NPK	150% NPK
Medium black								
Coimbatore	−86	−210	−194	−256	−65	−169	−194	−200
Red Loam								
Hyderabad	−143	−179	−126	−166	−86	−106	−126	−142
Bangalore	−12	−76	−16	−26	−27	−24	−16	−2

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Coordinator's Report on the 2nd Working Session

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Dynamics of Potassium in Soil/Plant Systems

In this session, six papers were presented of which two covered the behavior of potassium in soil, and the remaining four dealt with research on the use of potassium in Asian countries.

Grimme pointed out the difficulties involved in defining the term «available potassium». Any boundary line drawn between the fraction called «available K» and the one called «non available K» is an arbitrary one. The quantity of soil K available to a crop is to some extent determined by the crop species involved. Some crops are much more effective in mining a soil for K than are others.

Grimme also emphasised the importance of soil water in determining the quantity of soil potassium available to plants. Water is the substance through whose movement toward a plant root a certain quantity of K is carried to the root. He also showed, however, that soil water is more important as a medium through which K ions can diffuse toward absorbing plant roots.

Although the boundary line between exchangeable and nonexchangeable K is a vague one, *Grimme* could show that yields decreased when a substantial portion of the absorbed K had to come from the pool of nonexchangeable K. Such data point out the importance of the use of potash fertilizer to stock the supply of easily available K when this supply has been strongly depleted by crops having a high K demand.

For phospate it is wellknown that quantities present in a dry topsoil are unavailable to plants. *Grimme* showed that also for K the water content of a soil is an important factor in determining the availability of soil K to plants.

The widespread presence in the humid tropics of the so-called «low-activity clay» soils is a mixed blessing. On the one hand, these soils have low K-capacity values, but on the other hand they form no obstacle to the availability to plants of recently added fertilizer-K. A disadvantage is that these soils offer little protection against leaching losses of K in situations of heavy rainfall. Split application of K fertilizer should therefore be considered.

In the next presentation, *Mutscher* pointed out that a precise understanding of the transformation behavior of clay constituents is all the more important when we deal with impoverished soils whose potassium management is difficult due to the specific contents and nature of these clay constituents.

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Mutscher also mentioned that most research on quantity-intensity relationships with respect to K has been conducted in temperate regions with soils having permanent charges, and that similar investigations with tropical soils having variable charges so far have been rare. He recommended that research in the tropics on that subject be expanded.

In spite of the importance of clay minerals for the availability of K in soils, I would like to show with data on research conducted in Brazil (Table 1) how important the presence of organic matter in tropical soils is for the cation exchange capacity and thus for the presence of available K as well.

Table 1. Contributions of organic matter (O.M.) and clay to the exchange capacity of topsoils of the State of Sao Paulo, Brazil.

Soil characteristics							
				CEC*, me/100 g soil			%of CEC
Legend	pH-H_2O	% clay	% O.M.	total	of O.M.	of clay	in O.M.
			soils with an argillic B horizon				
PVIs	5.6	5	0.8	3.2	2.2	1.0	69
PMI	5.8	6	0.6	3.3	2.1	1.2	64
Pln	6.4	12	2.5	10.0	8.2	1.8	82
Pc	5.9	19	2.4	7.4	6.0	1.4	81
PV	4.5	38	2.3	6.3	4.3	2.0	68
PV	6.1	18	3.2	9.1	7.9	1.2	87
TE	6.8	64	4.5	24.4	15.0	9.4	62
			soils with a latosolic B horizon				
LR	6.8	59	4.5	28.9	16.1	12.8	56
LR	5.2	52	2.7	9.5	6.4	3.1	67
LEA	5.2	24	1.2	3.9	2.9	1.0	74
LVt	4.6	25	2.0	6.2	4.0	2.2	65
LVr	5.0	56	6.5	16.3	14.9	1.4	91

*CEC was determined with calcium acetate, pH7.
Source: *B. van Raij*, Bragantia *28*, 85-112 (1969)

In the paper presented by *Samnao et al.* it was made clear that in Thailand some soils are rich enough in K to sustain acceptable crop yields for a number of years to come. Yet, in other soils, mainly the latosolic soils, crops are already responding to inputs of K fertilizers. In this context, I would like to emphasize the importance of proper analytical methods for constructing input-output balance sheets. As soil scientists, we pay a great deal of attention to devising analytical soil-testing methods enabling us to make justifiable fertilizer recommendations. I think that, as soil scientists, we should also pay due attention to analytical methods used in plant analysis. I come to such a recommendation on the basis of a discrepancy between the data presented by *Cooke* (p. 22) and *Samnao et al.* (p. 177) on K content of cassava. From the former data, it can be calculated that the K content of cassava roots is 0.62%, whereas the latter data point to a K content of 0.15%. On the basis of other data presented in the literature I am inclined to think that the values presented by *Cooke* are proper estimates of K withdrawn by cassava which is a crop demanding large quantities of K.

One agricultural commodity through which my home country, the Netherlands, and Thailand have trade relations, is cassava. In 1982, the Netherlands imported 2491000 tons of cassava as concentrated feed from Thailand. With the K percentage, as derived from *Cooke's* table, it can be calculated that this quantity of cassava contains 15000 tons of K. From the paper of *Pushparajah,* still to be presented, I learned that in 1982 Thailand imported 31700 tons of K as fertilizer. This means that about 50% of K, imported as fertilizer in Thailand, is leaving the country in the form of just one commodity, namely cassava, to just one tiny European country, namely the Netherlands.

I think that on the basis of such data it would be useful for a country like Thailand, which exports a sizeable percentage of its agricultural produce, to pay attention to the existing discrepancy between import and export of potassium.

Sudjadi et al. showed that also in Indonesia a large discrepancy exists between K removed by crops and K applied in the form of fertilizer. In this presentation, mention was made of the frequently observed phenomenon that the response of crops, in this case rice, to N- and P-fertilizer application is much higher when the crop is not suffering from a shortage of K. It is perhaps not too farfetched to predict that in the not too distant future the efficiency with which fertilizer N- and P- is utilized by crops in South East Asia will decline due to shortage of available potassium and, for that matter, sulfur.

Mention was made by *Sudjadi et al.* of the function that K can play in reducing Fe toxicity in rice. The importance of straw in supplying K was also emphasized.

Next to K in fertilizer and in straw, K in irrigation water can also make a welcome contribution to the K nutrition of crops. It was shown by *Sudjadi et al.* that in Indonesia such contributions can vary from 52 kg K per ha per year in East Java with its young volcanic soils to only 4 kg in the older and nonvolcanic soils of Sumatra and Kalimantan. The recent eruption of the Nevado del Ruiz volcano in Colombia reminded us again of the fact that the much appreciated rejuvenation of soils through the influx of volcanic ash and lava can bring great tragedy to people living in areas where such rejuvenations take place.

An interesting interaction was presented by *Sudjadi et al.* between lime and potassium. It would be interesting to know whether the higher response of soybean to K fertilizer on limed soil arises from better growing conditions resulting from liming or from a reduction in availability of soil K due to liming.

In his presentation, *Xie* paid attention to the interesting question whether or not the extractability of soil K is affected by drying the soil prior to analysis. For purposes of soil testing, the issue is a very important one. *Xie* showed that for kaolinite-type soils there is no effect of drying upon K release, but that in hydrous-mica soils drying leads to more release of K.

It was further shown that the total K uptake by rice was better correlated with the slowly available potassium than with the readily available potassium, indicating that in the long run slowly available K is the main source of potassium for rice.

With Indonesia and China already covered, a consideration of the K-fertility status of soils of India, as dealt with by *Sekhon,* brings me to realize that in these three countries a little less than half of the world's population is living. In these countries, great progress has been made over the past 20 years in producing food for an ever growing population. It was not so long ago that food shortages in India frequently gave rise to shocking reports of millions of people living on the verge of starvation, or of people actually dying of starvation. This unfortunate situation was replaced by one in which nowadays India can feed its own people, and can even store food for any future years of low yields, or for export.

This improvement was primarily made possible by our fellow agricultural scientists in genetics and plant breeding. The resulting new varieties required additional inputs of nitrogen and phosphate with which the yields of many crops could be raised to levels previously unheard of in the tropics.

Man cannot live by bread alone, and likewise plants cannot live from just sunshine, water, nitrogen and phosphate. As *Sekhon* has shown, in South India there are many soils not supplying enough potassium to meet the K requirements of crops that were supplied with nitrogen- and phosphate fertilizers. Presently rather wide gaps exist between K removal by crops and K addition through fertilizer use. It is a challenge to *Sekhon and his coworkers* in the *Potash Research Institute of India* to make sure that high yields, materialized in India through the use of nitrogen and phosphate, can be sustained and even further improved through judicious use of potash fertilizers.

Chairman of the 3rd Session

Prof. Dr. *U. Kafkafi,* Institute of Soil and Water, Volcani Center, Bet Dagan/Israel; member of the Scientific Board of the International Potash Institute

3rd Session

Maintenance of Soil Fertility in Upland Farming Systems

Improvement and Maintenance of Soil Fertility in Tropical Upland Farming Systems

H. R. von Uexküll, Singapore*

Summary

Most of the land in the tropics not already under cultivation is under rainforest (or under anthropic savanna) on acid soils of low inherent fertility. In nature this forest is highly productive (25-35 t/ha dry matter per year) but under arable crops without fertilizer the limit of production is only 5-7 t/ha initially, falling off rapidly under continuous cultivation. Factors limiting productivity are discussed. Organic matter plays an important role in soil fertility. On Ultisols surface fertility could be maintained by non-burn clearing and growing of cover crops for two years with application of phosphate and dolomite to build up subsoil fertility. Such a system should replace the traditional slash-and-burn method. The aim of cropping systems should be to imitate natural forest conditions using:

Rotation between food and cover crops under which only half the area is under food crops;
Planting food crops into live mulch (non-creeping legumes);
Avenue cropping (side by side cultivation of food and tree crops).

Phosphate and lime are key requirements in the build up stage, but, at a later stage potassium becomes a key nutrient. Given sufficient fertilizer input such soils are capable of sustaining high crop yields. With correct management yields of 15 to 20 t/ha/yr grain in a maize-rice soybean rotation are possible but at that level the potassium requirement would be 500-600 kg/ha K_2O.

1. Introduction

For a number of reasons upland farming systems in the tropics will rapidly gain importance. This is especially true for rice growing Asia. In the past and up to the present day most of the efforts in improving agricultural production had been focussed on rice. Compared with other crops, wetland rice has a number of very significant advantages, most of which are related to the effect of water *(v. Uexküll [1985])*:

- The water cover in flooded rice protects the soil from the direct influence of the elements and acts in a similar way like the vegetation cover in the rain forest.
- It provides a good environment for biological nitrogen fixation.
- It preserves organic matter.
- It buffers the soil pH.

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- It increases availability of most plant nutrients.
- It reduces build up of soil pathogens, which largely explains the near-unlimited self-compatibility of wetland rice.
- It reduces weed problems.
- It makes the crop less dependent on the vagaries of climate and decreases risk in using fertilizer.
- It results in yields that are considerably higher than for other cereals at a comparable material input level.

Over long periods of time rice as a mono-culture can support far more people than any other crop.

Vis-a-vis other crops rice thus offered such an over-whelming advantage, that it pushed aside many other potential crops. As a result, we find in rice growing Asia a highly stable and dependable staple food basis, but at the same time there is very little diversity.

As a result of the «Green Revolution» rice production in Asia increased sharply and has outpaced population growth by a substantial margin. Many countries with a predominantly rice-based agriculture are therefore expected to face rice surplus problems.

While natural inertia in the system will continue to push up production, the rate of increase in consumption is expected to fall:

- Per capita rice consumption in most countries has peaked.
- Population growth rates are slowing down.
- Increases in per capita income will result in decreases in per capita rice consumption and increased demand for vegetables, fruit and animal products that are produced in upland farming systems.

Fortunately for mankind, the largest, so far largely untapped potential for future food production lies in the udic tropics with rain forest vegetation. Also fortunately, plant breeders have recently developed a wide spectrum of high yielding hybrids and strains of a variety of important food crops better adapted to acid soils and a tropical climate.

With climatic limitations to year-round crop production minimal, better technologies that not only prevent yield decline, but that also maintain and improve soil fertility over time are needed.

Most fertile soils with a high base saturation are already under cultivation. What is left are acid soils, mostly oxisols and ultisols of very low inherent fertility. The discussion on improvement and maintenance of soil fertility in tropical upland farming systems will therefore be largely limited to acid soils of which there about 600-830 million hectares or 41% of the total arable land available in the world *(Kellogg and Orvedal [1969], Thorne and Thorne [1979], Sanchez et al. [1983]).*

2. Fertility constraints in the acid soils of the tropics

Most of the acid soils in the tropics are still under primary or secondary forest. Their fertility is usually so low and fragile that successful permanent use for agriculture has so far largely been limited to tree crops, mainly rubber and oil palm. *Von Uexküll*

[1981] mentioned the following fertility constraints:

- — a low pH
- — a low cation exchange capacity
- — a low level of total and available nutrients
- — a low base saturation percentage
- — a high aluminium saturation percentage
- — a high, often toxic concentration of manganese
- — a high phosphorus fixation capacity
- — a clay fraction consisting of minerals with a low and partly pH-dependent surface charge density
- — a low water retention capacity
- — an organic matter fraction consisting largely of coarse, purely dispersed material
- — absence of stable organo-mineral complexes (exception: andepts)
- — a low level of micro-biological activity
- — sensitivity to compaction (especially Ultisols) and slow recovery from compaction
- — sensitivity to erosion

This catalogue of constraints could be expanded, but it is sufficient to explain why most acid soils have been left uncultivated.

Some of the major fertility problems related to soil acidity will be briefly discussed below:

2.1 Aluminium toxicity

Until the late 1950s it was generally believed that hydrogen was the dominant cation in acid soils. It was largely the work of *(Coleman and co-workers [1958])* that proved that aluminium rather than hydrogen was the dominant cation in the majority of soils with a pH below 5.0.

With the exception of peat soils the primary cause of poor crop growth in acid soils is usually aluminium toxicity.

Next to silica, aluminium is the most abundant element in the earth's crust. Low concentrations of aluminium appear to have a beneficial effect on the growth of most plants. Tea appears to require high aluminium concentrations for healthy growth and for good quality *(Chenery, [1955])*.

Aluminium in the soil solution is usually below 1 ppm as long as the aluminium saturation is below 60% but rises sharply at aluminium saturation levels beyond 60%. Conversely, growth of even aluminium tolerant plants diminishes sharply with an aluminium concentration exceeding 1 ppm.

Aluminium toxicicity manifests itself first in impaired root growth, thereby preventing plants from effectively utilizing soil water and nutrients.

2.2 Manganese toxicity

Solubility and availability of manganese increases sharply with decreasing pH. Manganese availability also increases with increasing soil moisture and decreasing soil aeration. Manganese toxicity frequently develops on soils high in secondary manganese bearing minerals like pyrolunite and manganite at pH levels below 5.5. At pH levels below 4.8 manganese toxicity may occur along with aluminium toxicity. High manganese concentrations in plants can induce iron deficiency. Calcium, and even more so, magnesium depress manganese uptake.

2.3 Phosphorus deficiency

Most acid soils in the tropics are generally low in total as well as in available phosphorus. Most of the plant available phosphorus is in organic form and thus concentrated in the Ap horizon.

The lower the pH, the higher is usually the concentration of iron and aluminium in the soil solution. Soluble phosphorus not only reacts with iron and aluminium in the soil solution, but also with aluminium in the exchange complex, forming compounds of the general formula $Al(OH)_2 . H_2PO_4$ *(Coleman et al [1960])*. While this process fixes phosphorus it also eliminates or reduces aluminium toxicity. Lack of phosphorus is often a cause for poor subsoil penetration of roots.

2.4 Calcium and magnesium deficiency

Although the primary cause of very poor crop performance on acid soils is usually aluminium toxicity and/or phosphorus deficiency, small additions of calcium often produce significant yield increases, indicating a deficiency of calcium as a nutrient. Similarly, there are also often very good responses to magnesium on strongly acid soils. This could be a direct effect of magnesium as a deficient plant nutrient, or an indirect effect of magnesium in improving tolerance of plants to aluminium *(Grimme [1984])*. Magnesium often becomes critically short once other constraints are removed and crop yields are increased with heavy use of NPK fertilizer.

2.5 Potassium deficiency

Soil pH has a definite influence on potassium availability *(Kemmler [1980])*. Low pH increases K availability and over time this results in loss of most available soil K due to leaching.

Although the vast majority of acid soils in the tropics are very low in both, available and reserve potassium, K is rarely a *primary* nutrient factor limiting yield. Potassium deficiency develops as a result of:

- increased K demand as yields increase due to liming, phosphate application, etc.
- decreased concentration of K in the soil solution due to increased ECEC resulting from lime application.
- increase in the number of K selective sorption sites in the exchange complex due to liming, which at a lower pH are occupied by aluminium hydroxo-polymers.

2.6 The role of organic matter

Maintenance of good supply of organic matter is central to the productivity of most infertile tropical upland soils, especially for ultisols (acrisols) *(Von Uexküll [1982])*.

The most drastic change that occurs when tropical rain forest is turned into agricultural land is:

- The *destruction of organic matter* during conventional land clearing and burning.
- The drastic decrease in organic matter deposited on and in the soil after the destruction of the forest.

Greenland and Dart [1972] have pointed out following benefits of organic matter for agriculture in which no fertilizer is used:

- Organic matter supplies most of the nitrogen and sulphur and half of the phosphorus taken up by unfertilized crops. The slow-release pattern of nitrogen and sulphur mineralization in organic matter offers a definite advantage over soluble fertilizers.
- Organic matter supplies most of the cation exchange capacity of acid, highly weathered soils. Rapid decreases in organic matter resulted in sharp reduction in the CEC.
- By forming complexes with organic matter, amorphous oxides do not crystallize. Phosphorus fixation by these oxides is decreased by organic radicals blocking the fixation charges.
- Organic matter contributes to soil aggregation, and thus improves physical properties and reduces susceptibility to erosion.
- Organic matter modifies water retention properties, particularly in sandy soils. In Ghana, the soil water-holding capacity decreased from 57% to 37% when the soil organic matter decreased from 5% to 3%.
- Organic matter may form complexes with micro-nutrients which prevent their leaching. The availability of micro-nutrients is also improved.

In addition, the following other effects are of importance:

- Organic matter forms complexes with aluminium and manganese, thereby decreasing their concentration in the soil solution.
- Organic matter stimulates activity of the soil flora and fauna. This in turn further improves physical properties through the formation of more stable soil aggregates and aeration channels.
- By keeping the soil surface covered, organic matter prevents the build-up of high temperatures in the topsoil, and stimulates root development in the topsoil. Because of rapid decomposition, and because clay minerals with low surface charge (like kaolinite) do not form stable organo-mineral complexes*, the effect of the bulk of the organic matter is rather short-lived. Under forest there is a continuous supply of organic matter. Clearing the forest and cropping the land interrupts the supply of organic matter, while at the same time often speeding up its decomposition.

In East Asia, (China) where population pressure has forced people to make use of soils with low base saturation and where intensive cropping has been going on for centuries, the central role of organic matter is well understood. In most parts of the

*Allophane on the other hand reacts with organic radicals to form complexes with organic complexes that remain relatively resistant to mineralization. The same applies to some other amorphous sesquioxide compounds.

tropics, where so far only the fertile soils with high base saturation have been intensively utilized, organic matter as a key element in the management of poor acid soils is still grossly under-estimated. In too many cases the short-term effect of organic matter as as source of nutrients has been improperly compared with the effect of mineral fertilizer. What has been neglected in those comparisons is the direct and indirect effect of organic matter in improving the root environment (chemical as well as physical) and thus the potential for plants to make better use of both the indigenous soil fertility and applied fertilizer. What makes organic matter so important is the fact that it is the only soil amendment that can be largely preserved and produced on or around the farm.

3. Forest growth on acid soils

To the present day, man had difficulties in using the acid soils for crop production. Where man usually failed, nature seems to have little trouble in maintaining a forest vegetation that produces 25-35 m.t. of dry matter per year.

When cropped to arable crops without fertilizer, total dry matter production in the first two years rarely exceeds 5-7 tons and usually drops even lower if the land is cultivated for longer periods of time. Obviously nature is doing something right that man so far has not been able to copy effectively.

To maintain soil fertility and vigorous plant growth in the humid tropics, the soil should be permanently, or at least most of the time, under some cover. Such cover can be a forest canopy, the canopy of a crop, live or dead mulch or water. Forest and paddy rice are so far the only two systems that provide a good protective cover of the soil and that thus offer stability *(Figure 1)*.

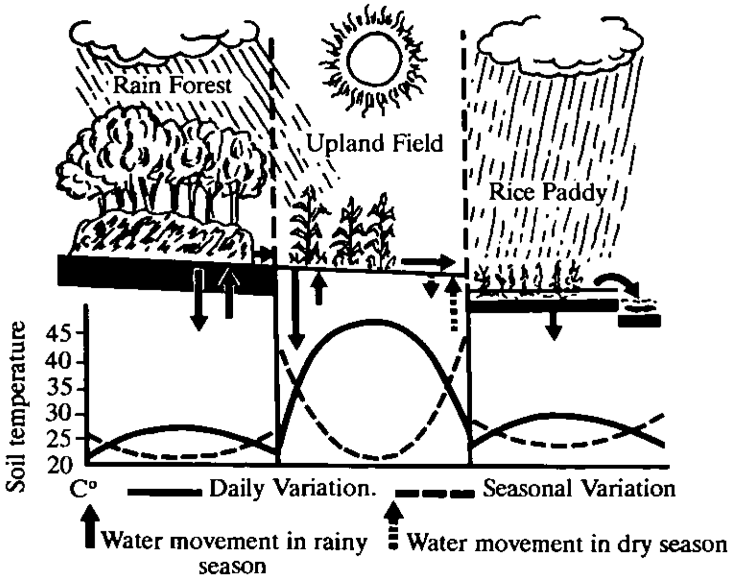

Fig. 1 Soil cover and soil fertility in the tropics.

Rooting depth in most acid soils in the tropics is restricted by aluminium toxicity, manganese toxicity, phosphorus deficiency, a pH near or below the zero point of charge and temporary periods of stagnant water (Ultisols only). The effective rooting depths of most plants grown on acid soils (withouth amelioration) is therefore usually limited to the top 10-30 cm. In the undisturbed rain forest, most of the active roots are found in, the upper part of the Ap-horizon, in the decaying wood and leaf litter.

Under forest cover many roots can stay alive and active above the mineral soil because the ground remains shaded, moist and cool. Big quantities of nutrients are in rapid circulation (Table 1) and with water rarely in deficit, the shallow rooting forest vegetation can largely depend on the nutrients in the cycle. As most of the nutrients are absorbed from or within the decomposing organic matter, and the topsoil, the vegetation depends very little on the subsoil as a source of nutrients, provided that the topsoil maintains conditions favourable for root growth.

Table 1. Nutrient cycle in high forest at Kade, Ghana

	Wt. of material (oven dry) kg/ha	Nutrient elements (kg/ha/annum)				
		N	P	K	Ca	Mg
Rainfall in open — (1854 mm in 12 months)		15	0.4	18	12	11
Rainfall under forest — (1575 mm in same period)		27	4.1	238	41	29
Rain wash from leaves		12	3.7	220	29	18
Timber fall	11.210	36	2.9	6	82	8
Litter fall (on 12 months' records)	10.540	200	7.3	68	206	45
Total addition to soil surface		248	13.9	294	317	71

Source: Calculated from *Nye and Greenland [1960]*

4. Problems in fertility maintenance

Based on past experience in many parts of the humid tropics, the view is widely held that permanent use of acid soils for arable crops invariably leads to soil degradation *(Friedman [1977], Goodland and Irwin [1975], Sioli [1980])*. And there is ample evidence to support such view. Throughout the tropics thousands of hectares of land that at one time carried a dense and productive tropical rain forest are abandoned annually to anthropic savanna after producing only a few crops.

At present shifting cultivation is the predominant «farming» system for acid tropical soils. It is practiced by about 240-300 million people *(Dove [1983])*.

Shifting cultivation makes use of fertility accumulated in the primary or secondary forest vegetation and released to the soil after clearing and burning. According to *Sanchez [1977]* the high supply of nitrogen left in the topsoil after burning, plus the large amounts of phosphorus, potassium, calcium, magnesium and micro-nutrients in the ash almost insures no (major) fertility limitation to the first crop grown. The pH of the topsoil is (temporary) raised and the aluminium saturation is decreased.

Table 2. Selected topsoil (0-10 cm) properties of three fields prior to and 1 month after burning.

Chacra	Time	pH	Exchangeable Al	Ca	Mg	K	ECEC	Al sat.	Olsen P	Sand	Silt	Clay
			cmol (+) kg^{-1} (me 100 cc^{-1})					%	mg kg^{-1}	%		
I	Preclearing	4.0	2.27	0.26	0.15	0.10	2.78	82	5	65.3	23.0	11.7
	After burning	4.5	1.70	0.59	0.29	0.32	2.90	59	17			
II	Preclearing	3.9	2.18	1.13	0.35	0.33	3.99	55	14	63.6	24.6	11.8
	After burning	4.9	0.67	3.53	0.57	0.27	5.04	13	23			
III	Preclearing	4.1	1.70	1.60	0.50	0.32	4.12	41	17	63.6	25.5	10.9
	After burning	4.6	1.30	2.78	0.86	0.57	5.51	24	31			

Source: *Sanchez et al. [1983]*

In Alfisols of Ghana ashes from the burned forest vegetation contributed 1.5-3.0 tons of Ca, 180 kg of Mg and 600-800 kg of K/ha *(Nye and Greenland [1964])*. Forests grown on low base status, acid Oxisols and Ultisols contain far less. According to *Sanchez [1976]* the corresponding amounts of Ca, Mg and K for Ultisols and Oxisols ranged from 275-600 kg/ha of Ca, 30-80 kg/ha Mg and 90-240 kg/ha of K. Topsoil properties as affected by burning are shown in Table 2.

As shown in Table 2 there was a very marked improvement on all soil fertility parameters as a result of burning. But on Oxisols and Ultisols this effect is usually short-lived. Within one or two years the soil properties revert to pre-burn levels — with the difference that most of the fertility contained in the original forest biomass is gone. *Mc Intosh and Suryatna [1978]* analysed soils from cassava plantations at the start and after two and respectively four years of cultivation (Table 3). All fertility parameters deteriorated with the drop in available potassium and calcium being most drastic.

Table 3. Soil test results from cassava plantations in Central Lampung, Indonesia, Cropping Systems Research, 1978

		Plantation I		Plantation II	
		New	4th yr	New	2and yr
pH H_2O		5.5	5.4	5.7	5.6
pH KCl		4.4	4.1	4.4	4.2
Extr. Al	me (in KCl)	0.09	0.30	0.17	0.32
Exch. bases					
Ca	me	3.1	1.3	0.5	0.8
Mg		1.1	0.4	0.5	0.5
K		0.5	0.3	0.3	0.1
CEC	me	10.1	10.8	7.6	8.9
% Base sat		25	19	18	17
Organic matter					
C — %		4.37	2.80	2.00	2.45
N — %		0.31	0.21	0.18	0.17
C/N		14	13	16	14
$Bray_1$ — ppm		32.1	13.3	10.1	8.5
$Bray_2$ — ppm		50.8	18.2	13.2	9.0
Extr. nutrients ppm (1N NH_4 OAC at pH 4.8)					
P		2	1	1	1
K		223	56	138	31
Ca		529	73	60	41
Mg		131	40	40	46
Mn		4	3	1	2
Fe		9	15	7	6

Source: *McIntosh and Suryatna [1978]*

Burning also exposes the soil surface directly to solar heat and the impact of raindrops. Heavy rains following the burn before a new canopy has been formed can result in very severe erosion and irreparable loss in soil fertility. Loss of topsoil due to erosion is probably the largest single factor responsible for the rapid decline in soil fertility frequently observed in the tropics. *Lal [1979]* has shown that a removal of 2.5 cm topsoil can result in yield losses of 40-50%.

Depending on the amounts of nutrients released on the burn of the vegetation, the quality of the soil, one to four crops are usually taken by shifting cultivators before the land has to be abandoned. As a result the yields of the second crop are about half of the first. *Moorman and Greenland [1980]* have shown that by fertilizer application and weeding high crop yields could be maintained whereas without fertilizer and weeding, yields within a span of four years dropped to nearly zero (Figure 2).

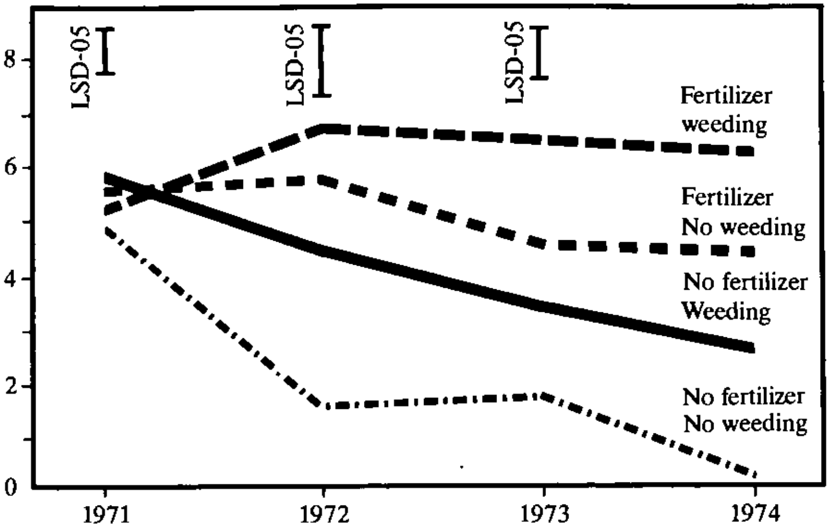

Fig. 2 Effect of cultural factors on maize yield in southern Nigeria.
(Moorman and Greenland, [1980]).

Unfortunately shifting cultivation is usually practiced in areas with poor infrastructure where fertilizer prices are high and fertilizers are often not available. Also, most farmers will avoid using «expensive» fertilizer as long as sufficient forested land is available where the forest vegetation can be used as a short-term source of «cheap» soil fertility. Shifting cultivation *can* be an efficient soil management system for subsistence agriculture — as long as population pressure is low and as long as the people practicing it have a long traditional experience in this system. But shifting cultivation can be a disaster if done by people new to this system. With increasing population pressure and decreasing forest resources, shifting cultivation has to give way to more intensive management systems that maintain soil fertility and thus permit continous use of the land.

5. Soil fertility maintenance and improvements

Maintenance and improvement of soil fertility of inherently poor, acid soils requires a set and sequence of management practices, whose main aims should be:

- preservation and maintenance of the original topsoil fertility.
- building up soil fertility, especially in the subsoil.
- long-term maintenance and improvement of soil fertility under intensive cropping.

5.1 Maintenance of the original topsoil fertility

Land clearing

A large percentage of the acid soils in the tropics is still under forest cover. Where this is the case, the method of land clearing can have a decisive influence on the initial performance of the crops grown and consequently also on the amount of money a farmer can spend to build up soil fertility.
Root growth of most plants grown on unimproved acid soils is restricted to the topsoil. As explained in chapter 3, the excellent performance of the rain forest, even on very poor soil, is mainly due to the rapid circulation of nutrients between the live vegetation and the topsoil, making the vegetation very little dependent on the subsoil as a source of nutrients.

Traditional methods of land clearing consist of cutting and burning the forest vegetation. They not only destroy the forest canopy as a constantly renewing source of organic matter and as a protective soil cover, but in the process of burning they also destroy most of the leaf litter, finally exposing the bare ground to the elements.
Burning the forest vegetation tends to destroy all one would like to retain (mulch layer, dry foliage, twigs and branches) and leaves behind the carbonized and sterilized tree trunks, which are the one item one really would like to burn.

Factors affected and permanently changed by cutting and burning the forest are:

	Before cutting	After cutting and burning
a.) Soil surface temperature	Uniform 24-28° C	Big variation 23-53° C
b.) Soil surface moisture	Uniformly moist	Extreme variation
c.) Leaching and surface erosion	Minimal	Considerable to very severe
d.) Microbiological activity	High	Low→Very high→Very low
e.) Soil structure	Stable	Variable
f.) Nutrient cycle	Closed	Broken
g.) Organic matter cycle	Closed	Broken
h.) Organic matter content	Constant	Declining
i.) CO_2 production and release	High and uniform	Low and irregular

Temporary changes in connection with traditional forest clearing and burning are:

- A single, large addition of plant nutrients.
- A temporary increase in pH and base saturation.
- A very irregular distribution of nutrients as a result of burning, restacking and reburning.
- A localized irreversible dehydration of soil colloids as a result of the high temperature during the burning.
- A steep decrease in microbial activity, due to partial «sterilization» after burning, followed by a short «flush» and a gradual decline in microbial population.

Zero burn techniques

To preserve as much as possible the original organic matter, *von Uexküll [1984]* suggested land clearing without burn. Land clearing is done in following steps:

— Underbrushing is done at the start of the rainy season.
— Commercial timber is removed.
— The cut undergrowth and branches of trees felled for commercial timber are cut up and stacked in rows that permit access to the land.
— A cover crop is planted while some big trees are still standing. As a cover crop free-seeding, large-seed cover crops such as *Mucuna utilis* or *Phsophocarpus palustris* or *P. tetragonolobum* (winged bean) are most suitable, but planting cuttings of *Purearia triloba* or *Calopogonium caeruleum* or seedling of other leguminous creeper can also give good results.
— About 200 kg/ha of soft rock phosphate (or 50-100 kg/ha triple super phosphate) and 300-500 kg/ha of finely ground dolomite is spread along the rows where the cover crop is planted.
— The remaining big trees are ring-barked and poisoned. Poisoning is done in order to trap moisture in the tree trunks and to speed up their decay.
— The poisoned trees should be felled at the first sign that the canopy is dying or they should be left standing until they collapse. It is dangerous to fell dead trees as branches of dead, poisoned trees soon become very brittle.
— The land is left for two years under the cover crop. After this period most wood other than the trunks of some hard-wood trees has decayed and the soil is covered by thick layer of dead and live mulch. The cover crop planted before the last big trees are removed takes over the protective function of the rain forest, while still offering easy access to the land. It serves following main purposes:

- It keeps the soil shaded and cool.
- It provides a thick layer of mulch.
- It prevents weed (grass) infestation.
- It prevents or minimizes soil erosion.
- It fixes atmospheric nitrogen.
- It covers the logs, speeds up their decomposition and prevents them from becoming breeding grounds for black beetles.
- A good cover crop contains about 130-180 kg of N, 8-12 kg of P, 80-120 kg of K, 15-20 kg of Mg and 40-70 kg of Ca.

Cropping under fertility regenerating systems

To maintain the fertility of acid soils under upland farming it is important to simulate forest conditions as much as possible. The aim should be to have the soil constantly covered, either through the canopy of a crop or through live or dead mulch or through shade trees. Following fertility regenerating management systems have been suggested:

— Rotation between a cover crop and food crop. Under this system about one half of the land is all the time under a cover crop and the other half is used for food production.
— *Live mulches* — In this system crops are directly planted into the live mulch. Legumes used are either non-creepers like *Arachis prostrata* and *Desmodium ovalifolium* or, if they are creepers, they are so managed as to minimize their competing with the planted crop and are prevented from climbing and stifling the crop.
— *Avenue cropping* — This agro-foresty technique integrates on a continuous basis the soil restorative attributes of the bush fallow with upland arable cropping through simultaneous culture of arable crops and fast-growing perennial trees side by side *(Wijewardene and Waidyanatha [1984]).*

The leguminous trees or shrubs are established in hedgerows 3-5 meters apart. At the time of seed-bed preparation the trees are lopped and loppings are used as fertilizer and mulch.

Among the many tropical leguminous tree species *Leucena leucocephala* and *Gliricidia maculata* are most widely used. *Leucena* on account of her fast growth, deep rooting and high nitrogen content in the leaves has received most attention. But *Leucaena* is sensitive to acid soil conditions and may require heavy liming and sometimes also a dressing with common salt for good establishment. *Gliricidia* is tolerant to acid soils and can be easily established from cuttings, but its shallow root system tends to compete with arable crops.

Table 4 compares the effect of «simulated forest» with conventional tillage. The mulch from the simulated forest doubled the yield of maize. It is also interesting to note that without mulch there was no response to P and K over N, whereas in the presence of the mulch the response to PK was very large.

Table 4. Effect of «simulated forest» and fertilizer on maize yields over two years (1980 and 1981) Sri Lanka

Treatment	Loppings added (1980, kg/ha)	Grain yield (1980, kg/ha)	Loppings added (1981, kg/ha)	Grain yield (1981, kg/ha)
A. Simulated forest (#)				
1 No added fert'er	561	1373	2811	1561
2 + 60N	—	—	3129	1921
3 + 60N, 60P, 60K	579	3002	2963	2728
B. Without *Simulated forest*				
1 No added fert'er	—	1163	—	680
2 + 60N	—	—	—	1385
3 + 60N, 60P, 60K	—	—	—	1354

Source: *Handawela [1983]*

Gliricidia planted 5 m × 3 m, and Maize grown in avenues between.

5.2. Building-up soil fertility

Fertility re-generating cropping systems based on leguminous herbs, creepers, shrubs and trees are very important to maintain soil productivity, especially at low input levels, but to be effective over longer periods of time such systems have to be supplemented by soil ameliorants like lime, phosphate and silicate fertilizer, with the aim to improve subsoil properties and thus to increase rooting depth. As subsoil properties improve the importance of fertility re-generating systems diminishes.

In fertility re-generating cropping systems *organic matter* is the main contributor to soil fertility. To build up soil fertility, *lime and phosphate* assume a central role. Usually it takes several years of continued lime and phosphate application to change subsoil properties to the extent that it becomes a good medium for root growth. Application of ammonium sulphate and potassium chloride promotes the downward movement of Ca^{++} and Mg^{++} which results in a more favourable environment for root development. Once yields have been increased as a result of topsoil and subsoil improvement, the organic matter of the root mass plus the organic matter from the crop residues is usually sufficient to maintain soil productivity and there is no need to sacrifice land for the sole purpose of producing organic fertilizer and restoring fertility.

5.3. Long-term maintenance and improvement of soil fertility under intensive cropping

Sanchez and co-workers [1982, 1983] have monitored crop yields, topsoil properties and nutrient balance over an 8 year period of continuous cropping (Figure 3 and Table 5 & 6). With complete fertilization they obtained long-term average yields of 9.4 t of grain/ha in a (upland) rice-maize-soybean rotation and 8.1 t/ha in a rice-peanut-soybean rotation. This represented a six to ten fold increase in per ha production as compared to shifting cultivation while avoiding the need to clear new land every year. Over time high yields could be maintained and even increased. But this could only be done at considerable fertilizer input. The fertilizer requirements for 3 crop/year rotations are shown in Table 7.

Table 5. Balance between fertilizer additions and crop uptake during 8 y in Chacra I (19 crops).

	N	P	K	Ca	Mg	Zn	Cu
				kg ha^{-1}			
Fertilizer additions	1480	850	1740	5235	289	11.0	15.0
Crop uptake	1916	279	1837	360	222	2.8	0.4
Balance	-436	571	-97	4875	67	8.2	14.6

Table 6. Changes in topsoil (0-15 cm) properties after 8 y of continuous cultivation and 20 harvests of upland rice-corn-soybean rotation with complete fertilization in Chacra I.

Soil property	Before clearing (September 1972)	94 months after clearing (May 1980)	Significance
pH (1:1 water)	4.0	5.7	*
Organic matter, %	2.13	1.55	*
Exchangeable Al, cmol (+) kg^{-1}	2.27	0.06	*
Exchangeable Ca, cmol (+) kg^{-1}	0.26	4.98	*
Exchangeable Mg, cmol (+) kg^{-1}	0.15	0.35	*
Exchangeable K, cmol (+) kg^{-1}	0.10	0.11	NS
ECEC, cmol (+) kg^{-1}	2.78	5.51	*
Al saturation, %	82	1	*
Available P, mg kg^{-1}	5	39	*
Available Zn, mg kg^{-1}	1.5†	3.5	NS
Available Cu, mg kg^{-1}	0.9†	5.2	*
Available Fe, mg kg^{-1}	650	398	*
Available Mn, mg kg^{-1}	5.3†	1.5	*

*Significant at the 0.05 level or less.
†30 months after clearing.
Source: *Sanchez et al [1983]*

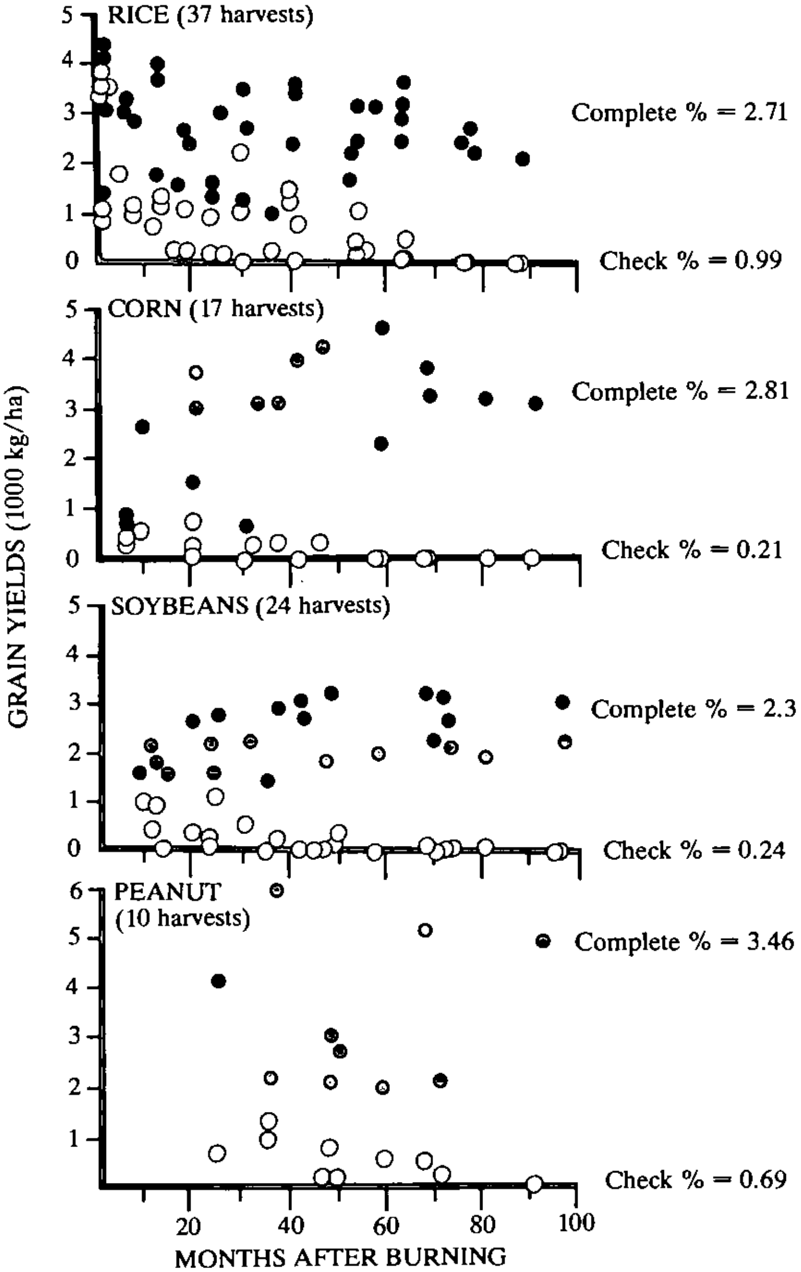

Fig. 3 Crop yields as a function of time after clearing with (●) and without (○) complete fertilization. Each point is mean of four replications. Yurimaguas (1972-1980).

Table 7. Fertilizer requirements for continuous cultivation of annual rotations of rice, corn, and soybeans or rice, peanuts, and soybeans on an acid Ultisol in Yurimaguas

Input*	Amount per hectare	Frequency
Lime	3 t	Once every 3 years
Nitrogen	80 to 100 kg N	Corn and rice only
Phosphorus	25 kg P	Every crop
Potassium	80 to 100 kg K	Every crop, split application
Magnesium	25 kg Mg	Every crop (unless dolomitic lime is used)
Copper	1 kg Cu	Once a year or once every 2 years
Zinc	1 kg Zn	Once a year or once every 2 years
Boron	1 kg B	Once a year
Molybdenum	20 g Mo	Mixed with legume seeds only

* Calcium and sulfur requirements are satisfied by lime, simple superphosphate, and magnesium, copper, and zinc carriers.

Source: *Sanchez et al. [1982]*

The 19 crops extracted more N than was added, probably reflecting symbiotic nitrogen fixation by soybeans. There was an accumulation of phosphorus, calcium, zinc and copper but a negative balance for potassium, in spite of the heavy potash dressings used.

6. Discussion

Contrary to common belief, the acid soils of the tropics can be used for continous crop production. Provided that sound soil management practices are employed, the soils can be considerably improved in this process. But such improvement in soil fertility and soil productivity comes at a price. There is no way to obtain and to maintain high yields with using a low or minimum input technology.

The most promising approach is probably to develop the productivity in three steps. The first step is preservation and maintenance of the original topsoil fertility, largely through preservation of organic matter and the use of fertility-regenerating legume fallow. At this stage organic matter is the most important fertility component.

The next step should be aiming at improving subsoil properties. Lime and phosphate become the dominant agents for soil amelioration.

Once the subsoil properties have been improved, intensive year-round crop production becomes possible. At this stage potassium moves into the most prominent position. With good agronomic care and proper soil management annual yields of 15 to 20 tons of grain in a maize-rice-soybean rotation or a maize-soybean-maize rotation can be within easy reach. To maintain yields at that level, potash requirements will amount to 500-600 kg/ha of K_2O. For a subsistence farmer producing 1 ton of grain from the same land once every eight years this may sound utopic. But it is not. With only marginal climatic limitations, the upland soils of the tropics represent the last and largest reserve potential to meet future food needs. But to tap this potential a *full* effort with high inputs is required.

Half-hearted efforts with minimum inputs will result in a deterioration or even a destruction of the valuable, so-far under-utilized land resources in the tropics.

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Potassium and Mixed Cropping Systems

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Summary

Mixed cropping is an important means of diversifying agriculture and producing more food. Use of fertilizers, including potassium, is very important to produce maximum yields in such cropping systems. The total uptake of nutrients is about twice as high in corn-soybean mixed crops than in either of these crops grown alone. There is a positive correlation between potassium absorption of corn and soybean yields in mixed cropping. In mixed cropping the combined grain yield of corn and soybean was 2.5 to 3.4 times that of sole crop corn and 1.9 to 2.5 that of sole cropped soybean.

1. Introduction

Mixed cropping systems are very popular among farmers in Indonesia, and have long been established in this country. They were introduced by farmers in Java, the most densely populated island in Indonesia. Farmers practise mixed cropping systems because their farms are small, to diversify their crops and to reduce the risk of crop failure, to intensify the use of their land, to maintain soil fertility, and to gain cash income as well as subsistence. As is the case in other developing countries, most farmers in Indonesia have low incomes; by practising mixed farming systems, they are able to plant crops partly for their own consumption, and can sell the remainder in the market to increase their income. Mixed cropping systems seem to fit best in densely populated areas with a strong market for agricultural products. The kinds of crops planted depend closely on the local agro-ecosystem, farmers' preferences, and the market.

Stimulated by transmigrants from Java, farmers outside Java now practise mixed cropping systems. Such systems are even practised in problem areas, such as in tidal swamp and acid sulphate areas. This is possible through using a raised- and sunken-bed system, the so-called «*surjan*» system. On the raised bed farmers plant dryland crops, while the sunken bed is devoted to wetland rice or fish. Fertilizers, including potassium, are an important component in mixed cropping systems *(Nuryadi et al. [1983]).*

The Indonesian government promotes the intensification of mixed cropping practices in order to modify existing systems so as to achieve higher yields and farmer incomes. The «farming systems» approach to agricultural research has recently attracted much attention. The aim of such research is to find proper combinations of agricultural crops, animal husbandry and fish culture for a given agro-ecosystem. In Indonesia, crops form the basis for farming systems; mixed cropping systems can be described as rice-based, food-

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crops-based, or perennial-crops-based. Over the last 15 years, cropping systems research in Indonesia has developed several alternative cropping patterns for different agroclimatic and edaphological conditions. Despite the success of this research, there will always be a need for improvements in technology *(Syarifuddin et al. [1984])*.

This paper presents the results of tests on potassium in mixed cropping involving corn and soybean. The aims of this experiment were to determine the optimum plant spacing and population densities for corn and soybean in mixed cropping, and to investigate the nutrient uptake by each crop type.

2. Materials and methods

The experiment was conducted in Kuningan Experiment Farm, West Java, during the 1982 dry season. A randomized block design with 4 replications was used. The plot size was 8.4 × 4 m. Two popular Indonesian crop varieties, Harapan (corn) and Orba (soybean) were planted at different plant spacings and densities (Table 2). The corn population was the same for all treatments, namely 20 000 plants/ha, with different plant spacing and numbers of plants per hill. The soybean was planted between the corn rows at a spacing of 20 × 25 cm, with 4 population densities: 300 000; 350 000; 370 000 and 400 000 plants/ha. The corn and soybean were planted on the same day.

Both crops (corn and soybean received 60 kg/ha P_2O_5 and 60 kg/ha K_2O whether planted as sole or mixed crops. Corn received a total of 120 kg/ha N and soybean 60 kg/ha. Except for the nitrogen application for corn, all the fertilizers were applied as basal dressing in rows, 7 cm from the plant hills, in the form of urea, triple superphosphate and muriate of potash. For the corn, one-third of the nitrogen was applied as basal dressing, and the rest was given one month after planting.

Topsoil samples were collected for chemical analysis. For both crops, the plant height and grain yield were recorded, and the plants were analyzed at harvest for nitrogen, phosphorus and potassium contents to enable nutrient uptake to be calculated. Four representative plant hills from each replicate were collected for this purpose. Plant samples from the four replicates were combined for chemical analysis.

3. Results and discussion

The physical and chemical analysis of the topsoil is presented in Table 1. The soil is low in nitrogen, very critical in phosphate, and potassium seems to be in sufficient supply.

Table 1. Physical and chemical properties of Kuningan topsoil

Characteristics		Value	Characteristics		Value
Texture					
Sand (%)		14.8	Exch. K	(me/100 g)	0.37
Silt (%)		65.1	Exch. Ca	(me/100 g)	7.42
Clay (%)		20.1	Exch. Mg	(me/100 g)	2.11
pH (H_2O) 1 : 2.5		6.06	Exch. Na	(me/100 g)	0.22
Total N	(%)	0.18	Exch. Al	(me/100 g)	0.18
Total C	(%)	1.90	Exch. H	(me/100 g)	0.12
Avail. P	(mg/100 g)	0.31	CEC	(me/100 g)	26.6
Avail. S	(mg/100 g)	6.97			

3.1 Grain yields

3.1.1 Corn

All the corn populations were the same (20000 plants/ha), but the different plant spacings affected the corn grain yield: the denser the plants within the row, the lower the yield. The yield reduction is more serious with a single plant per hill than with two plants per hill. This negative effect can also be observed in the lower plant height with closer spacings (Table 2). A high population within the row causes mutual shading and therefore lowers yield. Competition for nutrients in the close spacing may result in lower uptake rates. The monocropped corn had the lowest plant height compared to the mixed-crop plants, indicating that etiolation occurs in mixed cropping. The yield from the monocropped corn was lower than from the mixed crops, indicating that in mixed cropping the corn plants may also have utilized the NPK fertilizer applied for the soybean. Corn plants can do this because they have a strong and extensive root system: the root density of corn is approximately five times that of soybean *(Barber [1978])*. It can be concluded that mixed cropping is more beneficial for corn than monocropping, provided that nutrients (including potassium) are in sufficient supply.

Table 2. Effect of plant densities on plant height and yield (kg/ha) of corn and soybean in mixed cropping systems. Kuningan, 1982 dry season

Plant population						
Corn	Soybean	Grain yields (kg/ha)			Plant height (cm)	
(variable spacing)	(20 cm × 25 cm)	Corn	Soybean	Total	Corn	Soybean
20000[1] (1×1 m)	300000[1]	1785	1218	3003	249	51.3
20000[1] (2×0.5 m)	350000[1]	1698	1908	3606	246	51.1
20000[1] (4×0.25 m)	370000[1]	1598	2474	4072	229	58.4
20000[2] (1×0.5 m)	300000[1]	2286	1010	3296	249	50.9
20000[2] (2×0.25 m)	350000[1]	1811	2056	3867	231	53.4
20000[2] (4×0.125 m)	370000[1]	1330	2596	3926	219	49.4
—	400000[1]	—	1602	1602	—	47.9
20000[1] (1×1 m)	—	1212	—	1212	210	—

[1] 2 plants per hill

[2] 1 plant per hill

3.1.2 Soybean

The soybean yield increased with higher populations grown in more widely spaced corn rows (Table 2). The yield of the highest population was more than twice that of the lowest population, although the former contained only 23% more plants/ha. The wider spaces between the corn rows meant more space for the soybean to grow and produce. Wider corn spacings also allowed the soybean to use NPK fertilizer, solar energy, moisture, and other environmental factors such as carbon dioxide, oxygen, and soil nutrients better. The soybean monocropping (400 000 plants/ha) gave a slightly higher yield than the low-population mixed crop (300 000 plants/ha), but lower than the 350 000 and 370 000 plants/ha soybean populations. It seems that besides soybean population, the fertilizer input (including potassium) also plays an important role here.

3.1.3 Corn and soybean total yield

It is clear that the total yield of corn-soybean mixed cropping is higher than the monocrops of either species individually. Total yields varied 2.5 to 3.4 times compared to corn monocropping, and 1.9 to 2.5 times compared to soybean alone. The beneficial effect of mixed cropping compared to monocropping is beyond doubt. By manipulating cultural practices and fertilizer inputs, it seems possible to utilize existing land more efficiently, thereby producing higher yields and diverse commodities, and providing farmers with greater incomes. Without fertilizer inputs, the yields of both corn and soybean will be low. Fertilizer use is becoming even more important as crops with higher yield potential are cultivated, such as hybrid corn, which was recently introduced into Indonesia.

4. Nutrient absorption

Table 3 shows the absorption of nutrients by the corn and soybean plants in the mono- and mixed crops. The N, P and K uptake follows the same trend as the yields. Corn at closer spacings within the row absorbed less nutrients, while higher populations of soybean absorbed more. The absorption of N and P by mixed-cropped corn was almost the same as in monocropping. For potassium, however, corn absorbed more in mixed- than in mono-cropping. This may be due to the use of muriate of potash applied to the soybean. This higher K absorption by mixed-crop corn produced higher yields (Table 3). This shows the significance of potassium supply for higher corn yield.

The nutrient absorption by soybean gives a different picture. The N, P and K absorption increased with more widely spaced corn rows (denser corn spacing within the row). Increasing nutrient absorption (Table 3) and higher soybean populations pushed up yields. When monocropped, soybean absorbed more nutrients than when mixed-cropped; this indicates that soybean grown alone does not suffer from nutrient competition with corn, as is the case in mixed cropping. This suggests that higher fertilizer inputs are a prerequisite for higher yields of soybean if it is to be mixed cropped with corn. However, the fertilizer requirements will depend on the soybean variety and the soil type: the efficiency of K uptake per unit root surface is dependent on the soybean variety and the K concentration in the rooting medium *(Raper and Barber [1970]).*

Table 3. Nutrient absorption of corn and soybean in mixed cropping systems with variable plant densities. Kuningan, 1982 dry season

Plant density		Nutrient absorption (kg/ha)								
Corn	Soybean	Corn			Soybean			Total		
		N	P	K	N	P	K	N	P	K
20000[1] (1×1m)	300000	66.0	10.5	40.8	57.8	9.40	10.2	124	19.9	51.0
20000[1] (2×0.5 m)	350000	52.6	7.80	30.1	82.8	13.0	14.7	135	20.8	44.8
20000[1] (4×0.5 m)	370000	38.5	6.00	32.2	108	19.2	20.6	146	25.2	52.8
20000[2] (1×0.5 m)	300000	52.1	11.5	36.4	79.2	9.74	10.4	131	21.2	46.8
20000[2] (2×0.25 m)	350000	38.6	7.47	27.1	82.3	14.9	14.0	121	22.4	41.1
20000[2] (4×0.125 m)	370000	52.0	5.87	31.3	108	21.8	20.4	160	27.7	51.7
—	400000	—	—	—	138	25.8	25.5	138	25.8	25.5
20000[1]	—	51.3	7.02	27.5	—	—	—	51.3	7.02	27.5
Average of mixed cropping		50.0	8.19	33.0	86.4	14.7	15.0	136	22.9	48.0

[1] 2 plants per hill

[2] 1 plant per hill

Table 4. Effect of potassium on yields (kg/ha) of corn and legumes in mixed cropping system, 1982-83 wet season *(Anon. [1985])*

Treatments, kg/ha			Site: Tambun, Bekasi[1]			Site: Tarunajaya, Bekasi[1]		
N	P_2O_5	K_2O	Corn	Peanut	Total	Corn	Mungbean	Total
0	0	0	2539	480	3019	2409	432	2841
45	60	0	3117	623	3740	2904	574	3478
45	60	40	3324	651	3975	3184	595	3779
45	60	80	3381	654	4035	3139	669	3808

[1] Corn : Kodok variety, spacing 40×200 cm
Peanut : Gajah variety, spacing 25×25 cm
Mungbean : No. 129 variety, spacing 20×40 cm
Soil type : Alluvial

The average total of N, P and K uptakes of corn and soybean in mixed cropping are higher than in corn monoculture. The uptake of N and P are about the same as in soybean monocropping, but K uptake is about twice as high in mixed cropping. This is further evidence of the importance of potassium supply in mixed cropping.

The relationship between nutrient absorption and crop yield is shown in Figure 1. There is a clear link between K absorption and corn and soybean yields when grown in mixed cropping.

Table 4 shows the significant role of potassium in mixed croppings of corn with other legumes, namely peanut and mungbean *(Anon. [1985])*. This table gives the results of two trials conducted by the *Directorate of Food Crops Production* at two locations in West Java. These trials demonstrated that K applications increased the grain yields of both corn and the legumes.

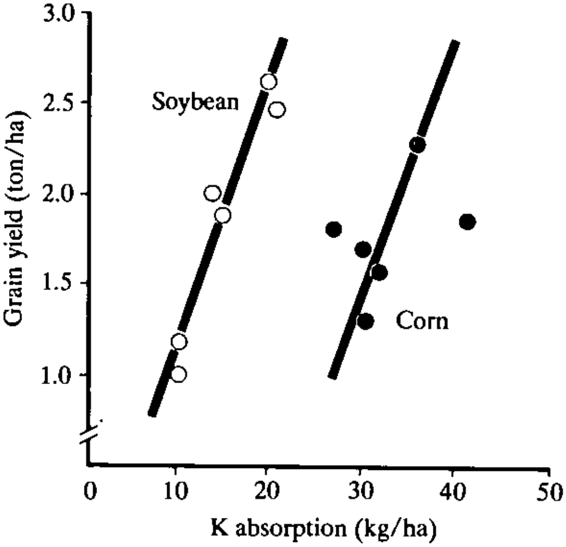

Fig. 1 Relationship between K absorption and yields of corn and soybean in mixed cropping system

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Potassium in Multiple Cropping System of Paddy Fields

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Summary

Soil characteristics affecting the supply of potassium to crops in multiple cropping systems are discussed.

Good responses to K fertilizer have been recorded on soils developed from red earths where the predominant clay mineral is kaolinite. Cereal crops are more responsive than oilseeds and fibre crops; winter crops more responsive than summer crops; wheat and barley are more responsive than rice. Responses to K may range from 12% to 23%. In areas where high rates of nitrogen have been used without P and K fertilizers there have been spectacular responses to potassium with marked NxK interaction.

Introduction

Multiple cropping (two or three crops planted successively in a year) has been introduced on more than two thirds of the total area of paddy in Southern China and has proved to be very effective in increasing crop yield and developing diversified production in agriculture *(Li [1982]).* It is now the principal cropping system of Chinese agriculture.

Generally, the multiple cropping system is based on single or double cropped rice combined with various winter crops such as barley, wheat, rapeseed and milk vetch *(Astragulus sinica).* There are also other multiple cropping patterns combining wetland crops (rice) and upland crops (cotton, jute, soybean, peanut etc.) rotated every year in the paddy fields. The multiple cropping system increases the demand for nutrients due to the higher cropping index and multiple harvests. The chemical industry has developed rapidly in China in recent years and this has greatly improved the supply of nitrogen fertilizer, but the same does not apply to phosphorus and potassium *(Zaas [1979]).*

Because cereal crops usually take up more potassium than nitrogen, special attention should be paid to satisfying the demand for potassium by cereal crops in multiple cropping systems. This paper considers a number of problems relating to the management of potassium fertilizer usage in multiple cropping systems and it is hoped that it will serve as a reference for the development of future multiple cropping production.

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1. The potassium status of paddy soils

The potassium content of the various paddy soils varies according to topography, climate and soil parent material *(Xie [1981])*. In Zhejiang, the gleyed type of paddy soil developed from lacustrine deposits is distributed over an alluvial plain. The dominant clay minerals in this soil are mica and montmorrillonite and the soils have a moderate potassium content (Table 1). Further, the relatively high ground water level and low soil permeability result in little leaching of potassium from the soil. Hence, crop response to potassium has not been recorded in such paddy soils. The water-logged paddy soils developed on the alluvial deposits of the valley plains have lower contents of potassium since they contain a much smaller amount of micas. On these soils, with the exception of high K demanding crops, crop response to potassium is not very marked. The submergic type paddy soils developed from Quaternary red earth in low hilly regions have kaolinite as the major clay mineral and are generally low in potassium. On these soils, almost all crops show a good response to potassium fertilizer.

Results from a series of trials in Southern China indicated that good responses to potassium fertilizer were obtained only on paddy soils with under 80 ppm available K and less than 250 ppm slowly available K. Consequently, the paddy soils located in the low hill and valley regions are short of potassium and should have priority for supplies of potassium fertilizer.

Table 1. Soil K contents in different paddy soils

Paddy soils	Samples	Soil K_2O		
		Available (mg/100 gm)	Slowly available (mg/100 gm)	Total %
Gleyed type in river-net plain	60	17.9	65.0	2.65
Waterlogged type in valley plain	46	8.0	36.9	2.34
Submergic type in low hill region	16	6.0	20.5	1.94

(1980, Zhejiang, China)

1.1 Effect of multiple cropping system on soil potassium

It is necessary to carry out long term experiments in order to evaluate the effects of the multiple cropping system on soil potassium and the resulting maintenance or depletion of soil K reserves in order to plan the rational application of potassium fertilizer.

Analysis of annual soil samples from a long term experiment showed that under a triple cropping system available K decreased if no potassium was applied, apparently due to the continuous removal of K in harvested crops (Figure 1). If either potassium fertilizer or manure were applied there was some fluctuation in available K level though it remained more or less adequate. K-fertilizer seemed somewhat more effective than organic manure. However, it should be emphasised that the proper way to ensure adequate potassium nutrition of all the crops in a multiple cropping system is by a combination of both organic manure and potassium fertilizer.

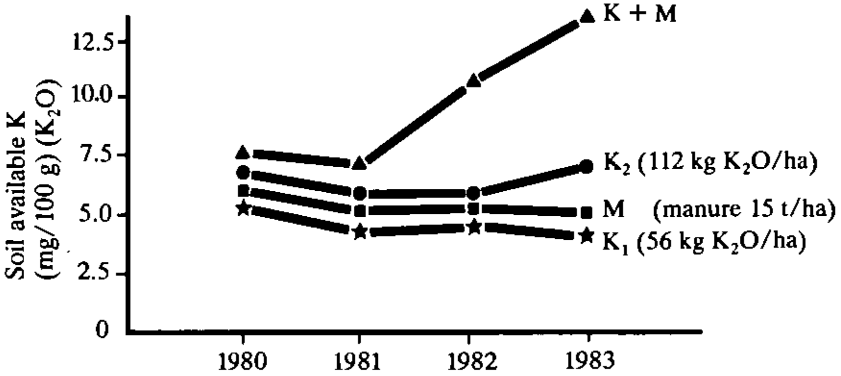

Fig. 1 Change in available soil K in a triple cropping system.

Another long term experiment compared the effects of applying 412.5 kg/ha N as various combinations of organic manure and N fertilizer (Table 2). 21 crops were taken over a period of 7 years. Under the Mh treatment (60 % N as organic manure) both available and slowly available soil K increased as compared with the original soil. When the proportion of organic manure was reduced, though available K remained satisfactory, there was a gradual decrease in slowly available K. Similar results were obtained in other studies *(Ma [1982])*.

Table 2. Effect of varying the proportion of organic manure and N fertilizer on soil K in a triple cropping system*

Treatments symbol	N ratio	Soil K mg/100 mg	
	Organic:Chemical	Available	Slowly available
Mh	6 : 4	12.6	47.5
Mm	4 : 6	11.9	45.5
Ml	2 : 8	10.6	43.8
–	Original soil	9.8	46.7

* Data from a long-term experiment (1974-1980) after 21 crops in a triple cropping system in Zhejiang, China. Annual N applied 412.5 kg/ha.

1.2 Sources of potassium supply in multiple cropped paddy fields

In any cropping system there are 3 sources from which the growing crops can obtain their potassium requirements: the soil, organic manures and fertilizer.

1.2.1 Soil

Readily available K as determined with conventional reagents comprises only 0.5 to 1% of total soil potassium *(Munson [1982])*. However, data from long term experiments show that, with 3 crops per year, the soil on control (no fertilizer) plots can supply as much as 270 kg/ha K_2O/year which is approximately one half of the total potassium requirement of 3 full crops *(Li [1983])*. This is well above the amount of readily available K, so much of this must originate from less readily available sources. While the soil is an important source of K, soil sources alone cannot supply sufficient to satisfy the needs of 3 full crops.

1.2.2 Organic manure

The main source of K in intensive cropping systems in China is organic manure *(Van [1984])*. Statistics for 1980-1982 for Zhejiang show that organic manure contributed 96.9% of the K input to multiple cropped paddy fields (Table 3), animal manures supplying 83.2%. Clearly, the conservation and recycling of nutrients within the system is of the utmost importance.

Table 3. K-fertilizer sources in multiple cropped fields*

K sources	Chemical fertilizer	Green manure	Animal manure	Others
Composition %	3.1	9.9	83.2	3.8

* Average data for K-fertilizer applied to the multiple cropped paddy fields in Zhejiang, China (1980-1982)

1.2.3 Fertilizer

An important aspect of the use of K fertilizer is the opportunity it offers to adjust the K supply to satisfy the K demand of crops at critical periods in their development, *i.e.* at periods of maximum K uptake during which soil K + organic manure K may not be available at a sufficiently high rate.

2. Response to potassium by individual crops in multiple cropping systems

In low hill and valley regions good responses to potassium fertilizer have been recorded for all the many crops grown. Table 4 lists the data from a large number of trials. Fibre crops like cotton and jute gave moderate responses and potassium fertilizer increased crop yield by as much as 12.1%-23.2% compared with the control plot. The magnitude of the response was in the order cereals > oilseeds > fibre crops. Among grain crops, winter crops like wheat or barley usually showed a better potassium response than rice of any season in a triple cropping system. A three year experiment (1980-1982) located in a paddy field developed from red earth, showed that potassium fertilizer gave an average increase of 23.5% in wheat, but only 5.4%-12.5% in rice yield (Table 5). The reason for variation in response between crops may be that wheat takes up more potassium than rice. Further, the alternate flooding and drying of the paddy fields may affect fixation and release of soil potassium and so affect the efficiency of potassium fertilizer.

Table 4. K response by crops in multiple cropping systems (relative yields; control = 100)

Crops	Rice	Wheat	Barley	Corn	Rapeseed	Cotton	Jute	Soybean
Trials No.	1361	50	25	16	18	33	21	8
+%	12.1	23.2	17.6	20.0	13.5	10.6	11.2	13.5

(1980, Zhejiang, Honan, Guang dong, China)

Table 5. K response by crops in a triple cropping system* (relative yield – control = 100)

Crops	1980	1981	1982	1983
Early rice	2.57	7.06	6.70	5.40
Late rice	15.73	10.80	11.01	12.50
Wheat	18.25	33.09	20.18	23.50

* Data from a long-term experiment with 112.5 K_2O kg/ha for each crop.

3. Management of K-fertilizer in multiple cropping system

3.1 Soil K level

Soil analysis is valuable in deciding on the rate of K-fertilizer to be applied. Table 6 gives the standards which have been adopted in Zhejiang and comparison with Table 1 shows that the paddy soils of the low hill and valley regions are generally of low or medium K status. Clearly K fertilizer is a key factor in the maintenance of soil fertility and crop yield in these regions *(Zhan [1980])*.

Table 6. Grades of soil K supplying capability in paddy fields

Grade	Soil K mg K_2O / 100 gm Available	 Slowly available	Response
Low	8	35	Good response by many crops
Medium	8-12	35-80	Good response by winter crops, but not stable in rice
High	12	80	No response except by K demanding crops

Investigation has shown that the so-called rice straw index is useful in predicting K fertilizer requirement *(Zhan [1984])*: good K response by rice can be expected if the index is below 1.2.

$$\text{K index} = \frac{\%\ \text{K in straw on control plot}}{\%\ \text{K in straw on N or NP plot}}$$

3.2 Crop requirement

K fertilizer should be applied in accordance with the needs of the different crops *(Zhu [1981])*. Field experiments have shown K response to be in the order: winter crops (wheat, barley or rapeseed) > late cropped rice > early cropped rice. Clearly, in this respect, in a triple cropping system the winter crops should have priority for K supplies. Results from experiments have also shown that on some depleted soils, good responses to potassium will be recorded when K fertilizer is applied to all 3 crops (Table 7).

Table 7. Effects of timing of K-application on the grain yield in a triple cropping system

Symbol	Barley	Early rice	Late rice	Annual yield t/ha
K_0	–	–	–	10.4
K	K	–	–	11.6
K	–	K	–	11.4
K	–	–	K	11.4
K	K	K	–	12.1
K	K	K	K	13.1

K – 112.5 K_2O kg/ha for each crop.

3.3 Combined effect of N + K

The ready availability of N fertilizer and inadequate supplies of P and K has given rise to serious problems through excessive use of N and inadequate potassium and phosphorus fertilizers. The result of such unbalanced fertilization has been low and decreasing efficiency of nitrogen fertilizer with serious loss of crop yield. In contrast to N fertilizer alone, combined N and K fertilizer had beneficial effects on both crop yield and quality. An experiment on a red earth paddy field (Table 8) showed that increasing the N dressing from 60 to 120 kg/ha N in the absence of K fertilizer reduced yield by 277 kg/ha: it increased yield by 330 and 413 kg/ha in the presence of 56 and 112 kg/ha K_2O, respectively, while there was a very large response in K fertilizer at either level of N. Similar results have been reported by *(Kemmler [1980]*.

Table 8. Effect of K combined with N fertilizer on rice yield in a red earth paddy field

Treatments		K_0	K_1	K_2
N_1	yield kg/ha	3960	5483	5970
	%	100	138.4	150.7
N_2	yield kg/ha	3683	5813	6383
	%	100	158.0	169.4

$N_{1,2}$ = 60-120 kg N/ha, $K_{1,2}$ = 56-112 kg K_2O/ha

3.4 Timing of K application

Generally, for all the crops in a multiple cropping system, potassium fertilizer is effective when applied as a basal-dressing. A large number of trials in Zhejiang, Honan and Guang dong indicated the efficiencies of timing potassium fertilizer application to the rice crop to be in the order basal dressing > top-dressing at tillering > top-dressing at the panicle stage. Potassium fertilizer applied to rice seedbed improved the health of rice seedlings and resulted in prompt greening and recovery from transplanting to the field. A very good and economical return from K fertilizer on rice is obtained from spraying 1.5% potash solution at tillering and *Lou [1983]* has reported grain yield increases of 4.7 to 17.9%.

Potassium fertilizer applied to rape seed as a basal dressing improved both the yield of soil seeds and the rate of oil extraction *(Cheng [1982])*.

Both KCl and K_2SO_4 are effective fertilizers but the former is cheaper and more readily available in the market.

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Nutrient Requirements of High Yielding Maize

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Summary

This review provides ample evidence that high maize yields may be achieved in the tropics, under a wide range of environnements. There is also evidence that fertilizer requirements may be significantly higher than under temperate conditions, because of high nutrient losses, and often also because of the need to build soil fertility. Experience also shows that high yields may be difficult to maintain over several years.

Insufficient fertilization, often due to an understimation of the fertilizer requirements, is in itself a cause of possibly rapid soil degradation, resulting in acidification, increased mineralization of organic matter, and lowered CEC.

Fertilization alone is not sufficient to sustain high yields. A positive K-balance, for example, may be hard to maintain if crop residues are not returned to the soil. Maintaining soil physical properties is also essential; this requires a close adjustement of cultural practices to the local environment. When high yields cannot be economically maintained, production systems aiming at greater stability are needed, even if yields may be reduced. The implication is that different R&D strategies are necessary for different environnments. A general trend in Asia as well as in Africa has been to aim at semi-intensive systems using open-pollinated varieties. Realizing that intensive cultivation may be quite successful, there is now a renewed interest for hybrids in many Asian countries.

Most of our present knowledge on soil fertility management in Asia is based on work dealing with semi-intensive systems. There would appear to be a pressing need to update this knowledge, so as to be able to: (i) select areas where intensive cultivation systems are justified, and (ii) develop intensive systems that are reasonably sustainable.

Finally, maize appears as a demanding crop (compared with cassava, millet, sorghum and some others) highly sensitive to adequate fertilization.

Introduction

While maize productivity has more than doubled in temperate countries over the past thirty years, farmers in the tropics have hardly benefitted from the new technology. Mean yields are still low: 1.2 t/ha in Africa, and around 2 t/ha in South America and Asia, as against 5 in Europe and 7 in the United States.

However, experiments long ago showed that high yields were attainable in the tropics with, in particular, fertilizer-responsive varieties and improved plant nutrition. On the basis of such results, a take-off in maize productivity could be expected during the seventies *(Arnon [1975])*.

This paper, which briefly reviews the work done by *IRAT* in Africa and Madagascar on maize nutrition, is also an attempt to understand why such hopes have not yet materialized.

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1. Nutrient requirements

Nutrient uptake is an indicator of net requirements. A review of results obtained in different countries shows that uptake values are highly variable *(Piéri [1983])* (see Table 1). Such variability may be related to water availability, as well as to nutrient availability. K fertilizer affects composition of straw more than it does that for grain.
P-content in the grain is known to be relatively stable. This was verified in western Ivory Coast, where *Pichot [1978]* also obtained very strong correlations between maize yields and P-content in the leaves at flowering (Figure 1). When such is the case, it is possible to use leaf analyses to monitor the mineral nutrition of the plant and to adjust fertilization to crop needs precisely.

Table 1. Yields and nutrient uptake per ton of grain.

Country (author)	Variety	Yield (t/ha)		total uptake (kg/tgrain)				
		straw	grain	N	P_2O_5	K_2O	CaO	MgO
Mali *(Traoré [74])*	Local	4.9	3.5	28	6.6	26	8.4	7.5
Ivory Coast *(Chabalier [82])*	Hybrid	4	3	34	11	42	6.2	5.8
Senegal *(Cissé [80]*	Local	4.1	2.4	26	6.5	30	11.2	10
Madagascar *(Arrivets [78])*	Line	4	3	23	7.3	14	6.7	6.8

Table 2. Leaching losses (kg/ha) as influenced by straw management Ampangabé, Madagascar *(Arrivets [1978])*

	Straw *	N	P	K	Ca	Mg
Fertilization		160	26	50	65	36
Whole plant removal	−	92	13	47	19	16
Removal / grain	+	56	9	17	1	5
Leaching	−	55	0	19	32	17
Leaching	+	66	0	23	41	26
Balance	−	10	13	-17	14	3
Balance	+	40	17	10	23	5

*/+: incorporated, −:removed.

Table 3. Leaching losses (kg/ha) in relation to N-fertilization, Ampangabé, Madagascar *(Arrivets [1978])*

N fertil. kg/ha	N	K	Ca	Mg	grain yield (t/ha)
0	40	37	35	17	3.5
80	75	26	59	20	4.7
160	108	26	103	22	6.7

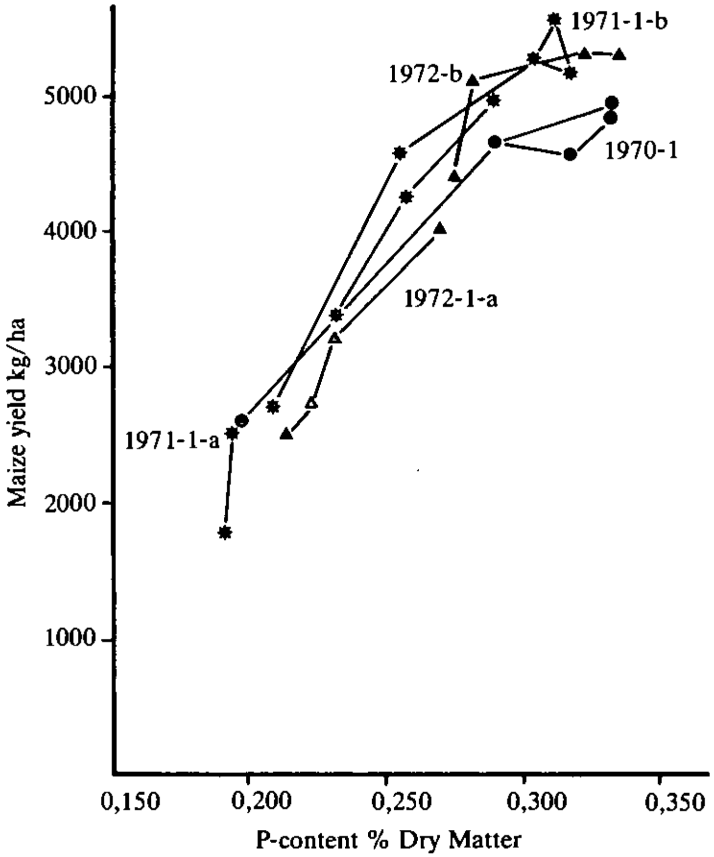

Fig. 1 Yield and P-content in leaves (Zouzousso, Ivory Coast [Pichot and al, 1978])

Nutrient losses occur through different ways: leaching, erosion and run-off, and N-denitrification/volatilization.

Leaching losses are influenced by fertilization, even when in the form of straw, as was shown by *Arrivets [1978]* (see Tables 2 and 3) Leaching losses, except for P, were particularly high that year because of high rainfall (1415 mm during the cropping season), and were all increased by straw incorporation, although the net nutrient balance was improved.

In another trial it was shown that K losses decrease when N-fertilization is increased, while the reverse was true for Ca and Mg. This may be explained by a preferential absorption of K, which increases when the vegetative development of the plant is enhanced by N (Table 3).

When compared with traditional African cereals, maize has similar requirements, but it must be remembered that the uptake rate is much higher in the case of maize *(Siband [1981])*.

2. Fertilizer requirements.

Response curves from field experiments are usually used to assess fertilizer needs. In a fertile soil, only losses and removals need to be replaced. In exhausted soils, the needs are much greater. In the highly degraded soils that cover extensive areas in Africa, considerable amounts of fertilizers may be needed to produce high yields. It is then useful to distinguish soil improvement fertilization from maintenance fertilization.

These concepts are well illustrated by the work done on the High Plateaux of Madagascar, on deeply desaturated ferrallitic soils. Such soils, which are totally unproductive without fertilizers, have been shown able to support high yields of 6 to 7 tons of maize grain after they received 3.5 tons of dolomite, 1 ton of P_2O_5 and 360 kg of K_2O per hectare (Table 4).

Table 4. Yield response of maize grain (t/ha) to increasing fertilizer rates (kg/ha), Ambohimandroso, Madagascar, (Velly, 1967).

Uniform dressing							
N	Yield	P_2O_5	Yield	K_2O	Yield	Dolomite	Yield
P_2O_5	= 1000	N	= 200	N	= 200	N	= 200
K_2O	= 360	K_2O	= 360	P_2O_5	= 1000	P_2O_5	= 1000
Dol.	= 3500	Dol.	= 3500	Dol.	= 3500	K_2O	= 360
0	3.3	0	1.9	0	0.4	0	1.0
80	5.0	100	2.8	90	2.4	0.5	2.4
120	5.6	200	3.5	180	3.4	1.1	3.5
200	6.6	400	4.7	360	4.7	2.2	5.2
300	7.4	1000	6.8	600	5.9	4.2	6.0
CV:	6.7%		9.6%		9.1%		11%

Such high fertilizer inputs are obviously out of reach for most farmers in developing countries. Unless they could be heavily subsidized by governments, they can only be brought gradually over a number of years. Another experiment conducted in Madagascar on desaturated ferrallitic soils with a view to compare different strategies relating to P fertilization showed however that, over a 5-year period, the maximum total output was obtained with the «one-shot» application (*Arrivets* quoted in *Piéri* [1985]) (Table 5). Similar experiments conducted on a less desaturated ferrallitic soil in Ivory Coast (*Pichot [1978]*) showed that a relatively small initial supply of 75 kg/ha of P_2O_5 could give a long-lasting advantage over annual maintenance rates.

Such long-term effects may not be observed with N or K. Leaching losses are often high and split-applications at selected growth periods are a current practice for N. Another experiment in Ampangabé, Madagascar, showed that yields were highest when N was applied at the period of rapid stem elongation, or half at that time and half at silking (*Arrivets [1980]*) (Table 6).

Application at sowing time promotes straw development. N-productivity is higher when applied at elongation stage, and further increased by split-application.

Table 5. Effect of P application on the yields of maize in Madagascar (Ampangabé 1973/74 to 1977/78) from *Arrivets.*

	Treatment	1	2	3	4	5
Annual quantity of P_2O_5 (TSP) applied kg/ha^{-1}	Year 1	90	45	180	180	360
	Year 2	0	45	0	45	0
	Year 3	0	45	0	45	0
	Year 4	0	45	0	45	0
	Year 5	–	–	–	45	0
Total quantity P_2O_5 kg ha^{-1}		90	180	180	360	360
Cumulative yields kg ha^{-1}		7750	9250	11450	16000	18400
Average yield kg ha^{-1} year^{-1}		1938	2313 2338**	2863	3200	3680
%			(81%)	(100%)	(87%)	(100%)

** P_2O_5 applied as rock phosphate form (Hyper Reno 30% P_2O_5, solubility in citric acid: 44%)

Table 6. Effect of rate and time of N-application on maize, Ampangabé, Madagascar (average of 2 years, 1979/80-81) *(Arrivets [80])*

N application (kg/ha)	Yield (t/ha)	grain/straw ratio
0	4.4	0.7
60 (sowing)	5.4	0.6
135 (elongation)	7.0	0.8
135 (65 at elongation 65 at silking)	7.8	0.9

Table 7. Effect on maize yield (t/ha) of various combinations of K_2O applications (kg/ha), Ampangabé, Madagascar, 1976-77 *(Arrivets [1978])*

	30 kg K_2O at sowing (S), at elongation (X)			
30 kg K_2O at silking (T)	–	S	X	SX
–	1.8	4.0	4.0	4.2
T	3.3	4.6	4.8	5.3

Table 8. Response of a maize crop to K with or without N, Ampangabé, Madagascar, 1976-77 *(Arrivets [1978])*

K_2O (kg/ha)	N (kg/ha)	N° of ears	Grain (t/ha)	K%	
				GRAIN	STRAW
0	0	13800	0.5	0.35	0.18
	160	0	0	–	–
60	0	36900	2.8	0.35	0.65
	160	54900	4.2		

On the same ferrallitic, sandy-clay soils with gibbsite, a split application of K was also shown to be beneficial, the best combination being 50% at sowing or elongation and 50% at silking stage *(Arrivets [1978])* (Table 7).
It may be noted that this soil, with very low CEC and exchangeable K (5.4 and 0.08 me/100 g respectively), is unable to support a crop of maize without fertilization, and absolutely unproductive with N-fertilization only (Table 8).
The above examples show that fertilizer requirements are related both to soil fertility and to the selected target yield. They also show that the potential yield may be much higher than could be predicted from the chemical characteristics of the soil. This does not mean however that the target yield may be chosen on purely economic grounds.

3. Yield sustainability

There are many examples which show that in the tropics it may be difficult to maintain high maize yields for any length of time even when adequate fertilizers are applied. This may be for a variety of reasons, including soil acidification, deterioration in soil structure and erosion, and increased incidence of pests and weeds.
Soil acidification is a major obstacle to sustained high yields, especially in semi-arid zones, where erosion, run-off, and nutrient leaching are particularly active. In the process of mineralisation, the organic matter releases NO_3^- and Cl^- ions which carry away alkaline cations in the drainage water. This was also found to be an important cause of acidification *(Piéri [1979]; Chabalier [1984])*.
As a result, soil acidification, which was first observed on research stations, is now more and more commonly found in farmers fields *(Ange [1984])*. In fact, the decrease in pH is only the expression of a more generalized degradation process which affects in particular the organic matter, and the effective exchange capacity *(Piéri [1982] and Siband [1972])*.
Acid soils can be improved by moderate liming and P-fertilization. Ground rock phosphate or partially acidified rock phosphates have been shown to give satisfactory results *(Truong [1984])*. This however is not sufficient to reach and maintain high fertility. With fragile soils, whether already acid or not, maintenance of proper conditions is usually sought through three major cultural techniques:

- application of fertilizers and organic manure to avoid soil depletion and erosion, and to maintain a favourable structure;
- soil preparation techniques to minimize structure deterioration or alleviate its effects, and control weed infestation;
- rotations to decrease weed, pest and disease problems, and to improve structure and organic matter content.

The benefit of suitable *rotations,* especially with a legume crop has rarely been challenged.
Organic matter is often used only to reduce the need for cash fertilizer inputs, by using locally available alternative *(Arrivets [1978])*. Experiments in Ivory Coast have shown that at the relatively modest rates of fertilizers tested (80-80-120 kg/ha of N, P_2O_5, K_2O), organic matter was essential to avoid rapid depletion in some elements *(Bigot [1977],* see Table 9).

Table 9. Changes in soil nutrients (OM: %; cations: me/100 g) after 4 years continous cropping. F_0: no fertilizer; F_2: 80-80-120 without manure, 40-80-60 with (30 t/ha) Ivory Coast *(Bigot [1977])*

		Without organic matter		With organic matter			
				Plant residues		Manure	
		1970	1974	1970	1974	1970	1974
O.M.	F_0	2.2	1.7	2.7	2.5	2.6	2.0
	F_2	2.2	2.4	2.8	2.4	2.2	2.4
Ca	F_0	0.5	0.4	0.74	0.52	0.86	0.44
	F_2	1.7	0.9	3.2	3.1	3.3	4.3
K	F_0	0.3	0.07	0.27	0.13	0.27	0.09
	F_2	0.36	0.16	0.33	0.24	0.43	0.40
Mg	F_0	0.24	0.08	0.28	0.12	0.36	0.12
	F_2	0.52	0.08	0.94	0.60	0.92	0.63

Without mineral fertilization all characteristics shown in Table 9 deteriorated over the years. With both organic and mineral fertilization, organic matter and calcium were maintained but K and Mg levels decreased.

The effects of *soil preparation* are much dependant on edaphic factors. A review of results available at *IRAT* from experiments in Africa *(Nicou [1979])* (Tables 10-12) concluded that:

- On sandy or sandy-clay soils, deep tillage with mould-board type plough was essential to obtain high maize yields. Special care should however be taken to minimize soil compaction during secondary tillage.
- With better structured soils in which root penetration is easy, deep tillage is not needed. Minimum tillage can be practiced if the rotation includes a crop which requires ploughing (upland rice, yam, ...), but regular ploughings should be done in the case of maize mono-cropping.

Table 10. Effect of different tillage practices on maize yields (t/ha) on a ferrallitic soil of northern Ivory Coast (average of trials with a drought during maize growth *(Nicou [1979])*

	Hoe	12" Plough	Diff. (%)
Ploughing done in too wet or too dry conditions	3.55	2.91	− 18
Ploughing in good conditions	2.62	3.57	+ 36

Table 11. Effect of tillage and organic matter on maize yields (t/ha) Senegal *(Nicou [1979])*

	N° of trials	Shallow tillage	plough 15-20 cm	diff. (%)
without organic matter (OM)	20	2.4	3.7	+ 50
OM ploughed-in	27	1.9	3.3	+ 73

Table 12. Effect of tillage on maize yields (t/ha) on ferrallitic soils more or less degraded. Togo *(Loynet 1982])*

Sites→	Davie (non degraded)	Glope (semi degraded)	Agbomedji (degraded)
Minimum tillage	2.1	0.5	0.9
Shallow tillage (traditional)	2.7	1.5	1.6
Ploughing + Crop residues	3.3	1.8	2.2

Since ploughing may not always be necessary, or even desirable, alternative ways to apply organic matter may be needed. An experiment in Ampangabe *(Arrivets [1978]),* would indicate that burning crop residues could be almost as efficient as incorporating them. When the straw is burnt, most of C and N are lost, but other nutrients are little affected. In conclusion to this part, the need to finely adjust cultural practices to the type of soil cannot be overemphasized, and interactions between mineral fertilization, organic matter, and soil tillage need to be considered (Table 13).

4. Conditions for intensive maize culture.

Even if there are technical solutions to the problem of maintaining high yields their practical application may not be feasible. Creating erosion control structures, keeping high levels of nutrients and organic matter, and maintaining at low levels weeds, pests and diseases, all entail costs, which may be out of reach of many farming communities, or simply make maize cultivation unprofitable. In other words, intensification can be justified only under favourable environment conditions.

Table 13. Nutrient restitution and effect on yield of incorporated or burnt crop residues (CR), Ampangabé, 1974-1977 *(Arrivets [1978])*

				Year (t/ha)			
N	P	K	Year	C.R.: exported	burnt	ploughed	cow manure
0	0	0	year 1	0.8	1	0.8	0.8
135	45	60	year 1	4.0	4.7	4.9	5.3
80	30	45	year 2-3				

		Nutrient restitution (kg/ha)					
C.R.	total DM kg/ha	C	N	P_2O_5	K_2O	CaO	MgO
raw	6.8	3600	27	7	14	17	17
burnt	0.5	100	3	7	20	11	7

In conditions of uncertain rainfall, response to fertilizers is low and unpredictable. Although improved soil tillage techniques will usually increase the crop tolerance to short drought spells, regular and sufficient rainfall may be a major requisite for high yields. Soil fertility is another important point. Obviously, chemical, and sometimes physical limitations may often be overcome or alleviated to some extent by proper fertilization, tillage and other cultural practices, as discussed above. But experience shows that their adoption in areas often sparsely populated, because of the low initial fertility, was often made difficult by serious supply and marketing constraints.

In such situations, less intensive systems will be preferred, by which the utilization of *e.g.* sturdy varieties and/or crop associations will increase stability, usually at some cost to the yield.

A study on the response to fertilizers of maize-soybean associations made in Cameroon *(Salez [1984])*, showed that maize in association with soybean responds less to fertilizer than maize alone (Table 14). The advantage of the association, in terms of total production value, over monocropped maize, was clear only under low fertility conditions.

Table 14. Yield response (t/ha) to NP fertilizer (kg/ha) of maize monocropped or intercropped with soybean (sb) on two soil types, Cameroon *(Salez [1984])*

		Latosol			Andosol		
N	P	maize	maize + sb		maize	maize + sb	
0	0	5.1	5.1	0.8	7.9	5.6	1.2
30	50	5.9	5.2	1.0	8.9	5.7	1.3
60	100	6.5	6.1	1.0	8.9	5.1	1.1

Several authors have noted that the most favourable conditions in the tropics would often be found in high elevations *(e.g.* above 1000 meters).

A review of potential maize yields in Africa *(Harrison [1973])* concluded that potential yields were 30% to 50% higher in such conditions, as compared to savanna and forest zones, respectively.

Favourable factors include longer growing periods, lower maximum temperatures, higher soil fertility sometimes (volcanic soils). Pests and, probably more important, diseases, also differ in altitude, as was shown in Cameroon *(Rouanet [1973])*.

There are also indications of different nitrogen dynamics, with a frequently extensive reorganization phase following the early rainy season mineralization. This leads to higher requirements for N later in the season, especially if organic matter was incorporated *(Rouanet [1975])*. On the other hand, response to N-fertilizers were often shown to be linear up to very high levels: 200 kg/ha or above *(Roche [1974])*.

In such favourable environments, it may be well justified to go for intensive cultivation. This is being realized in many countries in Africa or in Asia where maize hybrids are now being developped by public and/or private institutions. In Asia, hybrid seeds are now reaching a still small, but increasing number of farmers in countries such as India, Indonesia, Pakistan, the Philippines and Thailand.

This is a very recent development. Former efforts to introduce hybrids in the fifties or early sixties, for example in Pakistan or Sri Lanka, had to be discontinued, and open-

pollinated varieties were instead locally developped. Thus, most of our knowledge on soil fertility management is based on work dealing with semi-intensive systems. There would appear to be a pressing need to update this knowledge, particularly as regards fertilizer requirements for sustained intensive culture.
Since however intensive cultivation is often not possible or feasible, it would seem much advisable to characterize and identify areas with potential for intensive maize farming, so as to best allocate research and development efforts.

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Potassium Response in Root and Tuber Crops.

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Summary

Recent publications on response of cassava *(Manihot esculenta),* sweet potato *(Ipomoea batatus)* and yams *(Dioscorea* spp.) to potassium application are reviewed. Potassium reserves in major cassava-growing soils (kaolinitic Ultisols, Oxisols and Alfisols) are generally low. Cassava grown in soils containing 0.15 me/100 g or less of exchangeable K generally give large yield response to K. Maximum tuber yield can be achieved through optimum balance of N and K applications. Much research on soil and crop management for cassava is needed in order to narrow the yield gap between researchers (30 to 60 t/ha) and the small holding farmers (5 to 15 t/ha).

Sweet potato grown in highly weathered lateritic soils (Ultisols and Oxisols) responded to both N and K applications. The crop generally shows more response to N than K when it is cultivated on raised beds or ridges in paddy fields after rice. The high yielding potential of some sweet potato cultivars (50 to 70 t/ha fresh tuber) was demonstrated in China when the crop received large doses of N, P and K in the form of farmyard manure or compost.

Reports on fertilizer response in yams are scarce and often inconsistent. The crop is generally grown with staking on large mounds on more fertile soils. Major production constraints are high costs of planting material, land preparation and staking.

1. Introduction

Published work on potassium responses in root and tuber crops including potato, sugar beet, cassava, sweet potato, yams and cocoyams were reviewed by *Jansson [1978], Obigbesan [1980]* and *Howeler [1981].* Their common conclusion is that unlike potato and sugar beet, little is known of the mineral nutrition of important tropical root and tuber crops. *Howeler [1981]* further pointed out that even many published data on fertilization are of limited usefulness because of incomplete information on soil characteristics and history of soil management of the experimental sites.

This paper reviews current progress on potassium response in three important tropical root and tuber crops: cassava, sweet potato and yam.

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2. Cassava *(Manihot esculenta)*

Cassava is a major staple throughout the humid tropical regions of Africa. But in Asia and Latin America, the crop is mainly produced for starch and livestock feed.

Cassava is well known for its ability to survive and produce under a wide range of adverse soil and climatic conditions such as acidic and infertile soils, high soil temperature and drought stress. Thus, under traditional systems of cultivation, cassava is grown either as a «security crop» in mixture with maize or upland rice, or as the last crop in a rotation before returning the land to bush fallow. The use of chemical fertilizers in such systems is rare. Tuber yields from farmer's fields are generally low, ranging from 5 to 10 t/ha of fresh tuber *(Ofori [1973])*.

Substantial progress in varietal improvement in recent years has called for more research in nutrient requirement and fertilization of cassava. For example, cassava cultivars resistant to mosaic virus and bacterial blight developed at IITA can yield 20 to 40 t/ha of fresh tuber on relatively infertile soils *(Hahn et al. [1979])*. Improved Asian and Latin American cultivars have yield potentials of 40 to 60 t/ha when growing in favourable climate and soil environments *(Holmes and Wilson [1976]; CIAT [1974])*. However, unlike the elite food crops, such as rice, maize and wheat, the yield potential of cassava in farmer fields has been little explored. Considering it is the highest known yielder of starch among all cultivated crops, there is ample room for research on yield maximization through genetic improvement, fertilization and cultural practices.

Inspite of the high yielding potential of improved cassava, recent statistics indicate that the average yield in the world's five important cassava producing countries, namely, Nigeria, Zaïre, Brazil, Thailand and Indonesia, ranges from 5 to 15 t/ha. *(FAO [1984])*. In Indonesia, substantial yield increases in farmer's fields in recent years was attributed mainly to the use of chemical fertilizers on continuously cropped land *(Falcon et al. [1984])*.

2.1 Soil K reserve.

Major soils now under cassava are highly weathered Ultisols, Oxisols *(USDA [1975])*. These soils have low cation exchange capacity and low reserves of K and other mineral nutrients. They contain predominathly kaolinite in the clay fraction and little or no weatherable minerals in the silt and sand. *Juo and Grimme [1980]* reported that the K reserve in major soils of tropical Africa is low. This is particularly so in major cassava growing areas in the high rainfall coastal regions of West and Central Africa. Potassium status of some cassava growing soils in Nigeria are given in Table 1. Judging from the relatively low levels of exchangeable and non-exchangeable K in these soils, it is evident that the K requirement of cassava in traditional systems is primarily supplied through burning of fallow vegetation. Thus, once the stable cycle is broken because of more intensive land use, K deficiency will become more widespread.

In West and Central Africa, there are two major groups of cassava growing soils, namely, the strongly acidic Ultisols derived from sandstones and coastal sediments and the non-acidic Alfisol derived from basement complex rocks, mainly granitic gneisses. The former have very low levels of non-exchangeable K; whereas in the latter group of soils, the non-exchangeable K level varies with parent material and the amount of mica and illite present in the clay fraction *(Juo and Grimme [1980])*. Similar trends were reported for cassava growing soils in Latin America and Asia *(Cox [1972]; Ritchey [1979] and Kaddar et al. [1984])*.

Published data indicate that exchangeable K may adequately predict response to K application. This is because neither K fixation nor non-exchangeable K reserve is an important factor controlling K supply in major cassava growing soils in the humid tropical regions *(Juo and Grimme [1980])*. Critical values of 0.15 to 0.20 me/100 g of exchangeable K in surface soils with sandy to loamy texture are reported by several workers *(Silva and Freire [1968]; Obigbesan [1977]; Kang [1984])*.

Table 1. Potassium status in some cassava growing soils in Nigeria.

Depth cm	pH H_2O	Clay %	Organic C. %	Effective CEC meq/100g	Exch. K me/100g	Non-Exch. K ppm
			Alfisol from banded gneiss, Ibadan, secondary forest			
0- 5	6.5	21	1.54	5.45	0.39	77
5-15	6.4	25	1.50	6.99	0.15	220
15-45	6.8	37	0.75	5.26	0.12	98
45-65	6.4	56	0.28	4.33	0.10	83
			Alfisol from coastal sediments, Ikenne, secondary forest			
0-13	6.2	17	1.41	5.68	0.08	17
13-36	6.5	22	0.43	3.15	0.04	15
36-68	6.2	38	0.32	3.42	0.02	17
			Ultisol from sandstone, Nsukka, grass fallow after cassava			
0- 6	4.8	26	1.23	1.99	0.05	25
6-43	4.9	25	0.94	1.83	0.04	20
43-70	5.0	29	0.61	1.87	0.04	8
			Ultisol from coastal sediments, Onne, bush regrowth			
0-15	4.2	18	1.04	2.86	0.07	18
15-30	4.3	20	0.64	2.67	0.02	16
30-45	4.3	28	0.48	2.54	0.02	8
45-60	4.5	34	0.64	2.73	0.02	10

(Source: *A.S.R. Juo*, unpuplished).

2.2 K response in different production systems

In South-East Asia, cassava is generally grown on small farms either in monoculture or intercropped with maize on land under continuous cultivation. Fertilizers are applied to the maize crop. Tuber yields generally, ranges from 10 to 20 t/ha *(FAO [1984]; Falcon et al. [1984])*. In Indonesia, commercial production of the crop using fertilizer on the fine-textured, well-drained basaltic soils, commonly gives yields of 40 to 50 t/ha of fresh tuber *(Kang,* personal communication). The use of K fertilizer on continuously cropped land becomes essential when exchangeable K drops below the critical level *(i.e.* 0.15 me/100 g).

As cassava is not a major staple in tropical Asia and Latin America, the realization of the high yielding potential of the crop through K fertilization and other inputs will ultimately be determined by the demand from the starch industry and livestock sector.

The situation, is quite different however, in Sub-Saharan Africa where cassava is a major food staple and the crop is primarily cultivated on small farms in rotation with natural bush fallow. In such systems, little or no fertilizer or other purchased inputs is used on cassava. The crop is either grown in mixture with maize and yam on land newly cleared and burnt from bush fallow *(i.e.* at intervals of 7 years), or planted as a sole crop at the end of the cropping cycle (*i.e.* the 3rd year cropping) before the land is returned to bush fallow. Yields under such systems of production are generally low, ranging from 5 to 10 t/ha *(Ofori [1973]; Ezumah and Okigbo 1980]).*

Cassava growing on high base status Alfisols newly cleared from bush fallow gave no response to K application during the first 2 to 3 years of cropping. But the crop showed significant response to K application when exchangeable K dropped below 0.15 me/ 100 g due to continuous cropping *(Obigbesan [1977], Kang and Okeke [1984]).*

In the strongly acidic Ultisols in the high rainfall region, exchangeable K level is generally below 0.10 me/100 g. Cassava grown on such soils without K application often shows reduced growth and small leaves – typical symptoms of K deficiency *(Kang [1984]).* Thus, to increase production on Ultisols and Oxisols, an important step would be to ensure optimum supply of K fertilizer to the crop.

In monoculture experiments, an application of 30 kg K/ha to a sandy Ultisol in Nigeria containing 0.13 me/100 g exchangeable K raised fresh tuber yield from 15 t/ha (control) to 20 t/ha *(Kang [1984]; Juo* [unpublished data]). However, in a clayey lateritic soil from Malaysia, application of 150 kg K_2O/ha during the fourth crop increased fresh tuber yield from 30 t/ha (control) to 40 t/ha, mainly due to significant increase in tuber size *(Inst. Penyelidikan [1974]).*

Published data indicate that the method of K application generally has no significant effect on growth and yield. But the time of application may be a more important factor for efficient use of K by the plant. Reports from Thailand, India and Brazil, indicate optimum times of K application for maximum tuber and starch yields varying from one to three months after planting depending upon soil type *(Kumar et al. [1971]; Sitiboot, et al. [1977]*and *Gomez and Ezeta [1982]).*

2.3 N:K balance

Potassium is well-known for its important role in root and tuber crops because it is an element essential for carbohydrate translocation from the top to the roots. Under conditions where other nutrient elements such as N, in particular, are in sufficient supply in the soil, insufficient K supply often causes cassava to produce excessive amounts of leaves and stems but little tuber *(Silva and Freire [1968]; Obigbesan [1977]; Howeler [1981]).* It is for this reason that K and N responses in cassava should best be studied in conjunction.

A field trial using different N and K rates in an acid lateritic soil (Ultisol) in Kerala, India showed that applications of N and K_2O at 50 and 100 kg/ha, respectively, were optimum. Fresh tuber yield was raised from 16 t/ha (control) to 31 t/ha (Figure 1). Further application of K resulted in luxury consumption. The uptake of both N and K by the tubers was positively and significantly correlated with tuber yield. The positive effect of N on K uptake was attributed to the influence of N on the efficiency of the root system *(Rajendran et al. [1976])*.

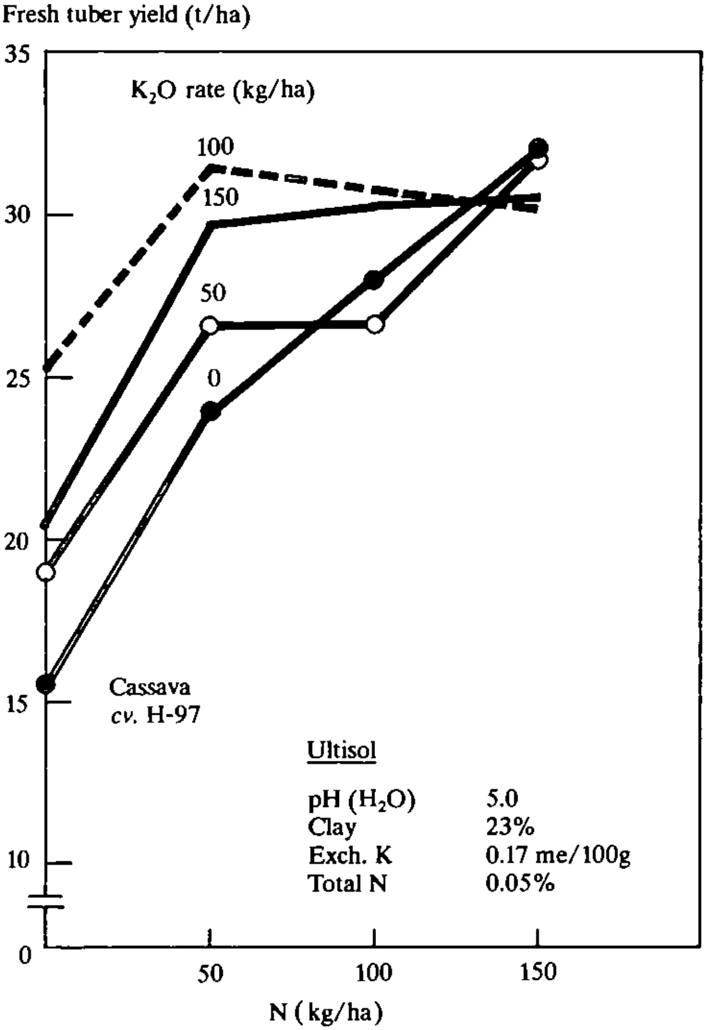

Fig. 1. Effects of N and K on tuber yield of cassava grown on a lateritic soil (Ultisol) in Kerala, India (After *Rajendran, et al.:* J. Root Crops, *2,* 35-38 [1976])

A similar experiment was conducted on an acidic Ultisol (Typic Paleudult) in Onne, Nigeria. Fresh tuber yield from the third cropping at different N and K levels are given in Figure 2. The results showed that there was a large response to K application in this K-deficient soil. Maximum yield can be achieved either by applying 100 kg K_2O/ha alone, or by applying N and K at the rates of 100 and 50 kg/ha, respectively (Figure 2).
It is important to point out that the Kerala soil contains moderate amounts of exchangeable K but a very low level of total N, whereas the reverse was true for the Onne soil. Such differences in initial soil N and K status may help explain the large response to N in the Kerala soil and the large response to K in the Onne soil (Figures 1 and 2).

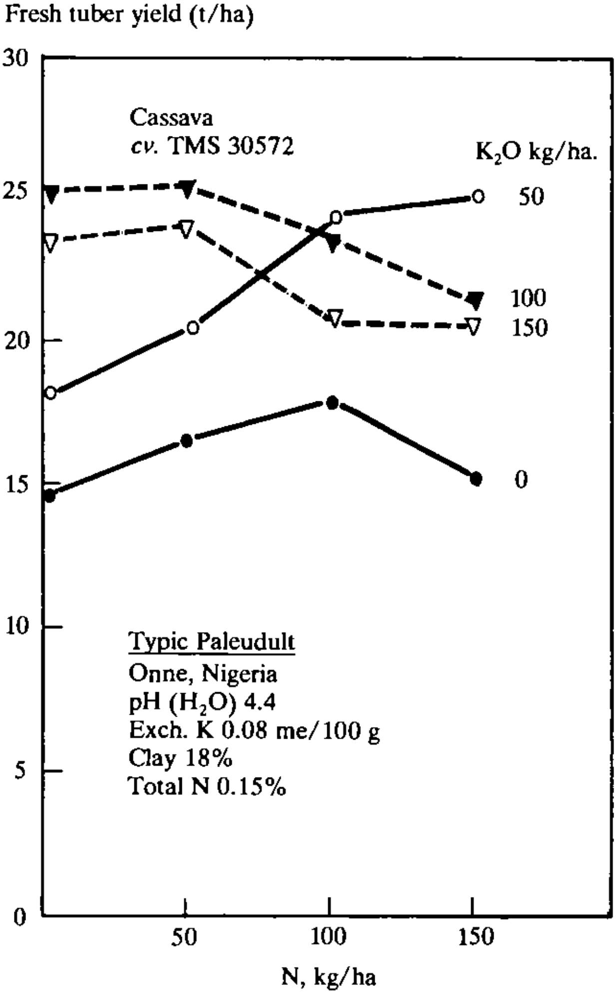

Fig. 2. Effects of N and K on tuber yield of cassava grown in an Ultisol (Typic Paleudult) in Onne, Nigeria *Kang, B. T., Juo, A. S. R. and Heys, G.*, unpuplished).

3. Sweet Potato *(Ipomoea batatus)*

Although Asia produces about two-thirds of the World's sweet potato, the crop is mainly used for starch production. In many countries in Africa and the Caribbean, however, it is an important food and vegetable crop. Sweet potato is grown over a wide range of environments between 40°N and 40°S of the Equator, and between sea level to 2300 m altitude. Much like cassava, sweet potato can produce a reasonable yield in marginal soils. Under favourable conditions, average fresh tuber yields of 20 t/ha (approximately 6 tons dry matter) in 4 to 5 months has been recorded in many countries *(Hahn [1977]; Hahn and Hozyo [1984])*.

There are two international research institutions where sweet potato improvement is a major part of their research programs. The *Asian Vegetable Research and Development Center (AVRDC)* in Taiwan focuses on improving the crop as a leafy vegetable as well as an industrial crop. The *International Institute of Tropical Agriculture (IITA)* in Nigeria, on the other hand gives major emphasis to improving the crop as a staple food.

Sweet potato is generally grown either on well-drained upland soils in the humid tropical and sub-tropical regions, or as a minor season crop in rice paddies. Upland soils commonly used for sweet potato cultivation are mostly lateritic soils (Ultisols, Oxisols) with relatively low K reserves. Whereas the K status in the paddy soils is generally higher, particularly in those derived from recent alluvium.

3.1 Lateritic soils.

Sweet potato grown on strongly weathered lateritic soils (*e.g.* Ultisols, Oxisols) often give large responses to both K and N applications. Results from field trials on lateritic soils with low exchangeable K (mostly below 0.20 me/100g) indicated that the application of 60 to 90 kg K_2O/ha gave a yield increase in the order of 10 t/ha of fresh tuber with moderate applications of N and P (*i.e.* 45 and 25 kg/ha of N and P_2O_5), respectively *(Uriyo [1973]; Wargiono [1981]; JAAS and SAAS [1982]; Purcell et. al. [1982]; Nwale and Salvi [1984])*.

The relative yield of tuber and vine depends upon a balanced supply of N and K. In an intensively cropped Ultisol in Sierra Leone, application of 200 kg K/ha at a N/K ratio of 3 gave maximum tuber yield but low vine yield. High vine yield was obtained at a low rate of K (50 kg K/ha) and a N/K ratio of 3 to 1 *(Godfrey-Sam-Aggrey [1976])*.

Field experiments on N/K responses were conducted in Indonesia on three soil types, namely an Ultisol, an Andisol (or Andept) and an Entisol *(Wargiono [1982])*. Results from these trials showed that N at rates of 45 to 90 kg/ha increased tuber and vine yield by 20 to 50% in all three soils. Application of 90 kg K_2O/ha increased tuber yield significantly in the Ultisol (latosol) but not in the Andept and the Entisol. Initial soil K data were not given by the author.

Sweet potato is important in the Red Soil (mainly Ultisols) regions of southern and south-eastern China. The crop ordinarily receives 15 to 23 t/ha (or 2000 to 3000 jin/mu) of organic manure, followed by a top dressing of ammonium sulfate in order to achieve high yield and high starch content. Because of shortage of K fertilizer in China, the element is supplied almost entirely by organic manuring. A potassium fertilizer trial on a K-deficient red latosol (Ultisol) in Hunan Province showed that application of 56 kg K_2O/ha increased fresh tuber yield from 23 t/ha (control) to 33 t/ha *(JAAS and SAAS [1982])*.

A summary of selected data on yield responses to K application is given in Table 2. These data indicate that K supply is a critical yield-limiting factor for sweet potato growing in the strongly weathered lateritic soils.

Table 2. Effect of K application on yield of sweet potato in K-deficient lateritic soils (Ultisols and Oxisols).

Location	K Rate (kg/ha)	Fresh Tuber (t/ha)	Reference
Maura, Indonesia	0	14	*Wargiono [1981]*
	90	22	
Maharastra, India	0	12	*Nwale and Salvi [1984]*
	90	23	
Hunan, China	0	23	*JAAS/SAAS [1982]*
	76	33	
Morogoro, Tanzania	0	28	*Uriyo [1973]*
	60	37	
Clayton, Nort Carolina USA	0	19	*Purcell and Walter [1982]*
	76	30	

3.2. Paddy soils and less weathered upland soils.

Sweet potato grown in paddy soils (*e.g.* Entisols) and other moderately fertile upland soils (*e.g.* Alfisols and Inceptisols) generally give larger responses to N than to K application. The crop is widely grown as a minor season crop after paddy rice on raised beds or ridges in Japan, Korea. Taiwan, and southern China. It is also widely grown as a summer crop after wheat in eastern China.

Results from a series of field trials attempting to correlate soil fertility status with sweet potato yield in eastern China showed that high yield of 69 t/ha of fresh tuber (or 26 t/ha of dry tuber) was recorded in soils containing 30 to 60 ppm of water soluble N, 23 ppm of available P and 115 ppm of available K. A high level of water soluble N (*i.e.* greater than 70 ppm) in soil caused excessive growth of vine. The amounts of nutrients removed by the crop (tuber plus vine) were 334, 91 and 790 kg/ha (or 44, 12 and 104 jin/mu) of N, P_2O_5 and K_2O, respectively. Maximum yields of over 7000 jin/mu of fresh tuber (53 t/ha) were obtained by the application of large doses of farmyard manure or compost at N/K ratio of 1 to 2 with supplemental use of mineral fertilizer. It was estimated that at the yield level of 53 t/ha for every 500 kg of fresh tuber, equivalent amounts of 2.5 kg of N, 2.5 kg of P_2O_5 and 5 kg of K_2O are required. Maximum yields of fresh tuber and rates of N, P, K used at different experimental stations in China are given in Table 3 *(JAAS and SAAS [1982])*. These data depict the high yielding potential of sweet potato under favourable soil and climatic conditions as well as high levels of management and inputs.

Numerous reports have dealt with the effect of fertilization, time and methods of application on the tuber and vine yields of sweet potato grown in lowland fields in rotation with paddy rice. In the Philippines, *Pardales Jr. et al. [1978]* reported that application of N, P_2O_5 and K_2O at rates of 60-30-60 doubled both total and marketable tuber yields. In Bangladesh, application of 39 kg/ha of N and 84 kg/ha of K increased tuber yield from 22 t/ha (control) to 39 t/ha *(Hafizuddin and Haque [1979])*. In Taiwan, split applications of N and K to sweet potato growing in lowland fields after rice resulted in relatively small increases in vine and tuber yields of 5 and 15 percent respectively *(Kuo [1972])*. In China, banded application of farmyard manure resulted in 10 percent higher tuber yield than broadcasting *(JAAS and SAAS [1982])*. Published fresh tuber yields of sweet potato grown in rice paddies range from 15 to 40 t/ha.

Table 3. Rates of nutrient applied mainly in the forms of farm yard manure or compost to achieve high yield of sweet potato (Summer crop) at different experimental stations in China *(JAAS and SAAS [1982])*.

Location (Province)	Fresh Tuber t/ha	Yield jin/mu	Nutrient element applied (kg/ha) N	P_2O5	K_2O
Hepei (Bejing)	70	9211	479	281	1117
Hunan	71	9384	448	433	1003
Shandong 1	60	7883	258	91	555
Shandong 2	57	7480	251	334	494
Shandong 3	61	8059	258	342	532

4. Yams *(Dioscorea* spp).

Yams are highly priced food crops in West Africa, South-East Asia and the Carbbean. The commonly cultivated species are white yam *(Dioscorea rotundata)*, water yam *(Dioscorea alata)* and Chinese yam *(Dioscorea esculenta)*. Very little information is available on the physiology and yield potential of yams. Moreover, genetic diversity is narrow and inadequate for plant improvement *(Coursey [1967]; Sadik [1976]; Hahn and Hozyo [1980]; Miege and Lyonga [1982])*.

Published data on nutrient requirement and response in yams are scarce. Early work on the response of yams to N, P, K and organic fertilizers was reviewed by *Ferguson and Hynes [1970]*. In an Ultisol in Nigeria, *Enyi [1972]* reported that N application increased tuber number per plant and K application increased dry matter accumulation in the tubers of Chinese yam *(Dioscorea esculenta)*. Both N and K applications increased the rate of tuber development.

On the other hand, *Lyonga [1976]* reported that yams grown in an Ultisol containing 0.37 me/100g of exchangeable K in the western highlands of Cameroon gave no significant response to K application. Similar results were obtained by *Koli [1973]* on white yam in soils with exchangeable K levels between 0.3 to 0.4 me/100g.

Obigbesan et al. [1976] reported a positive but inconsistent response to K application of four yam cultivars grown in an intensively cropped Alfisol in Nigeria containing 0.15 me/100g of exchangeable K. However, in a lateritic soil (Ultisol) containing 0.02 me/

100g of exchangeable K in Kerala, India, application of 120 kg K_2O/ha gave maximum fresh tuber yield of 24 t/ha of *D. esculenta* in comparison to 16 t/ha by the control treatment *(Singh, et al. [1973])*.

In West Africa, white and yellow yams are commonly grown with staking on large mounds in wetland areas with more fertile soils. Chemical fertilizers are not used. Staking was found to increase tuber size and yield because it improves the exposure of leaves to sunlight *(Irvine [1940]; Enyi [1973]; Okigbo [1973])*. It was also shown that white yams grown on large mounds gave significantly larger tuber number and size than those grown on the flat *(Okigbo [1973])*.

Thus, tuber yield of yams per unit area depends not only upon soil fertility but also upon plant density and cultural practices. For example, in Taiwan, yam *(D. alata)* grown on ridges in a fine-textured alluvial soil (Entisol) gave significant response to K application. But tuber yield per plant increased with increasing distance between rows and dry tuber yield was highest at 6600 kg/ha with 60 cm row spacing *(Shyu and Cheng [1978])*.

Among the three major root crops commonly grown in the tropics, yam is a less productive crop than cassava and sweet potato. Major constraints limiting further expansion of yam production are the high cost of planting material, land preparation and staking.

Acknowledgement

The author wishes to thank Mrs. *A. Dabiri* and Mr. *F.O. Ochiobi* for their assistance in the preparation of this review paper.

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Co-ordinator's Report on Session No. 3

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Improvement and Maintenance of Soil Fertility in Tropical Farming

Von Uexküll put forward the following fact: «Rain forest, in the tropics, is higly productive (25-35 tons of DM [dry matter] annually) in nature. When the forest is removed the same soil produces initially only 5-7 tons/ha DM»

The question to be asked is – Why?

The natural growth factors, radiation, rainfall, air temperatures, did not change upon forest clearing, nor did some of the soil characteristics known as potential constraints in acid soils: low pH, low base saturation, high Al and Mn, high phosphate fixation-type of soil minerals and low water retention. The factors that does change with mechanical forest clearing are: Removal of the dense organic matter that cover the forest soil, soil compaction, soil erosion and top soil temperatures.

No one growing factor is working alone. In each soil type the yield decline is a result of several constraints operating in sequence or in parallel.

Soil compaction lead to shallow root penetration which result with water and nutrients stress. Removing the physical leaf or litter coverage of the soil leads to severe soil erosion due to rain impact. Soil erosion should be blamed for removing the phosphate and potassium rich top soil leaving behind a nutritional desert. To prevent such a disaster it was suggested by *von Uexküll* that any forest clearing should be carefully carried out, leaving the top organic cover untouched and leaving some of the trees in place.

Corley's work (paper presented in 1st session) demonstrated that this conclusion, when skillfully applied, conserves the soil and allow productive perennial crops. However, the general experience is that «Permanent use of acid soils for arable crops leads to soil degradation».

It was stated also by *Dauhphin* that «On sandy or sandy clay soils *deep tillage* was *essential* to obtain (relatively) high maize yields».

It is obvious that maintenance of acid soils productivity should take care of the physical and chemical properties that affect root penetration.

The major physical constraints are: 1) *Compaction,* that leads to shallow root activity that leads to water stress. 2) High soil temperatures fluctuations that leads to delay in plant's development, and quick dessication of the shallow root zone.

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The chemical constraints affecting root penetration are: *low pH* that leads to Al and Mn toxicities and to Ca and P deficiencies. The last two are aggravated by soil erosion.

Dauphin stressed the fact that even with ample supply of nutrients in the soil the yields of maize decline with time. It is, therefore, possible that the most problematic constraint in growing arable crops on acid soils is the gradual increase in soil compaction.

The major efforts of the research, therefore, should be aimed to 1) develop practical methods to clear the forest for agricultural use while maintaining thick organic mulch on the soil. 2) Find agrotechnical methods to plant annual crops into the organic mulch. These are needed since perennial plantation, like oil palm, cannot occupy the whole extra area needed to feed the increasing population in countries where the rain forest is the main soil reserve. The subsistence farmer must learn to clear the forest while retaining its productive soil.

For the subsistance farmer:

Mixed cropping is one avenue suggested by *Ismunadji* to increase yields as compared to mono-cropping in the tropics. The reasons for the benefit are not yet clear, but one can't deny the facts. It was stressed, in the discussion, that mixed cropping is a viable strategy for zero-to-minimum input farming, especially when rainfall distribution and other non-preditcable risk factors besides nutrient levels in the soil, control the final yields. Soil analysis was shown as a practical tool to predict the response to additional amount of potassium fertilizer. The methods used in China to estimate available and slowly available soil K are the ammonium acetate extraction and 10 min. extraction in nitric acid, respectively.

When climatic conditions do not restrict plant growth, it is possible to produce 3 crops a year. This put a heavy load on the K supplying potential and additions of K in fertilizer or organic matter are needed.

As has been shown before, increasing N level increased the efficient use of K by the plant.

Chairman of the 4th Session

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4th Session

Research and Extension in South East Asia and their Implications for the Use of Potassium

Experimental Approaches in Defining the Needs for Potassium

(with special reference to rice in Asia)

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Summary

The experimental approaches used to define the needs for potassium involve plant and soil analyses and field experimentation. None of these alone is likely to be adequate as a basis for assessing potassium requirements of crops. Potassium is unlikely to be used economically for rice-based cropping systems unless those soils where it is needed are adequately defined, and the requirements of the cropping system determined. Little information of this type is at present available for rice-based cropping systems in South East Asia. Hence it is probable that much potassium is used wastefully at the present time, and that there are many instances where potassium could produce an economic response but it is not used. It is unlikely, that soil characterisation at the family level, or adequate soil testing services, will become available in many developing countries in the near future. Thus recommendations may need to be based on soil and land classification at a higher level, and use of a simplified system of fertility assessment such as the «FCC» method of *Sanchez and Buol [1985].* To verify the validity of recommendations many more long term field experiments covering a range of farming systems and ecological conditions are needed. These experiments will need to be supplemented by simple *JEEP (Joint Experiment and Extension Plot)* trials, on at least some of which soil analyses are conducted. Progress may be accelerated if work in different countries is coordinated. This may be done by existing collaborative networks such as the *International Network on Soil Fertility and Fertiliser Evaluation for Rice (INSFFER),* the *Asian Farming System Network, (AFSN)* supported by the *International Board for Soil Research and Management (IBSRAM)* and *Soil Management Support Services (SMSS).*

1. Introduction

There is a great need in Asia today to be able to relate fertilizer use to crop requirement. Fertilizer use is often based on a «blanket» recommendation, sometimes for nitrogen only, sometimes for a compound fertilizer which happens to be available. This occurs in spite of the fact that it is known that for many soils a nitrogen response is dependent on removal of another limiting factor, and for others there is only a response to nitrogen. If potassium is to be used effectively and economically, it is essential that its use is properly tailored to the soil and crop requirement. How is this best done in those countries with a limited, and sometimes non-existent, soil testing and advisory service? Although most of the necessary basic knowledge is available as far as upland soils and crops are con-

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*Prof. *D. J. Greenland,* Deputy Director General, The International Rice Research Institute, P.O.Box 933, Manila/Philippines cerned, does the necessary knowledge exist for rice and wetland soils, the major crop production system of Asia? And is sufficient known of either upland or lowland soil characteristics in Asia? This paper attempts to assess the present state of knowledge regarding the requirements of rice and other crops for potassium, the ability of the soils of Asia to meet that need, and the ways in which such knowledge can be most effectively applied to ensure that the experimental definition of the needs for potassium can be used to improve economic efficiency of crop production.

2. Potassium requirements of crops

At the 11th Congress of the *International Potash Institute* held on the occasion of its 25th Anniversary, a special session was devoted to the potassium requirements of crops, and the papers presented give a thorough summary of the needs of tree crops, forages, root crops, cereals, and grain legumes. *Kanwar [1974]* has also made a thorough assessment of potassium requirements of the major crops produced in Asia, and it is unnecessary to review this information again here. Those papers gave relatively little information on rice, but because of its dominant importance in Asian cropping systems the needs of rice were reviewed in an early symposium at *IRRI [1965]*, and are again reviewed in a paper to the present meeting *(De Datta [1984])*. A detailed discussion of the potassium nutrition of the rice plant has also been presented *(De Datta and Mikkelsen [1985])* at a recent symposium held in the United States. These authors find that

- rice has a moderately high potassium requirement, potassium tends to be concentrated in the leaf and culm
- the greatest demand occurs in the late tillering to booting stage, and the total requirement per ton of grain produced is about 25-50 kg, of which about 3-5 kg is in the grain.

Mikkelsen [1983] has suggested that leaf analysis can be used to determine potassium status. He suggests a critical level of 12 g/kg in the Y-leaf at mid-tillering and 8 g/kg at panicle initiation, in agreement with *Tanaka and Yoshida [1970]* who give 10 g/kg at tillering. The validity of leaf analysis may be limited to dry climates, as under monsoonal conditions much potassium may be recycled through the leaves to the soil, so that the leaf concentration may be dependent on antecedent weather conditions.

Other problems in determining the potassium requirements of rice from tissue analysis have been discussed by *Yoshida [1981]*. They include particularly the status of other nutrients and toxic substances in the plant. The critical level is also dependent on the crop variety, and of course specific to the growth stage and plant part analyzed. Much information about potassium nutrition in relation to nitrogen *(Jones et al. [1982])* and iron toxicity is available *(IRRI [1985]; Yoshida [1981])* and some in relation to sodium and sodium chloride *(Yoshida and Castañeda [1969])* but compared to that available for other species *(cf. Bergmann [1983])* the information for rice is very limited. Rice normally grows in reduced soil conditions, so that the cation ratios in the soil solution are rather different to those in oxidized soils. Nitrogen is primarily present as ammonium ions, and unusually high levels of several heavy metals may be present, for example, of ferrous iron and manganous manganese. Thus the use of tissue analyses in defining the needs of the rice plant for potassium is still limited by inadequate information on how the behavior of potassium in the plant is influenced by other ions. This is an area where much further research could usefully be undertaken.

3. Soil characteristics and potassium supply

3.1 Chemical analysis

Potassium enters the plant through mass flow in the transpiration stream, and by diffusion into the soil solution adjacent to the plant root, as the region near the root is depleted by uptake *(Nye and Tinker [1977])*. The concentration in the soil solution is maintained by exchange of other ions with potassium on the surfaces of soil colloids. This potassium is itself slowly replaced by diffusion of ions from other less accessible sites on and in the soil colloids. The easily accessible, and therefore easily exchangeable, surface potassium determines both the equilibrium level of potassium in the soil solution, and the extent to which that level can be maintained. Thus it is not surprising that the exchangeable potassium content correlates moderately well with potassium supply to crops, and that a level of 0.2 me/100 g (2 m mole/kg) can be used for many soils and many crops as the level below which it is expected that a crop will show a positive response to applied potassium. Nevertheless it is also well known that crop requirements considerably exceed the exchangeable potassium contents of soils. *Arnold and Close [1961]* long ago showed with a pot experiment that ryegrass extracted far more potassium than corresponded to the depletion in the exchangeable amount. The long term fertility experiments conducted at *IRRI* and the *Maligaya* and *Visayas Research Stations* in the Philippines *(De Datta and Gomez [1975, 1982])* lead to a similar conclusion. The amounts of potassium removed in 16 years much exceed the decrease in exchangeable potassium. There has in fact been little change in exchangeable potassium levels since 1977. Thus the exchangeable potassium must be largely replaced by non-exchangeable reserves. *Kemmler [1981]* has calculated for a similar experiment at *IRRI* that potassium supply from the soil will be adequate for the next 60 years, on the assumption that replenishment of the exchangeable potassium remains about constant. Clearly it is not only the exchangeable potassium which is important, but potassium additions in irrigation water, and the rate at which non-exchangeable reserves become available.

There have been many attempts to produce satisfactory simple methods to determine the latter. Theoretical considerations of the thermodynamics of cationic free energies in the soil *(Woodruff [1955]; Beckett [1964]; Laudelout [1978])* lead to the «Quantity/Intensity» or Q/I approach but relatively few investigators have found the experimental methods associated with such measurements convenient to use as a routine soil test. Empirical extraction methods which dissolve some of the non-exchangeable potassium have been quite widely used, particularly those involving successive treatments with 0.1 M nitric acid *(Haylock [1956])*. Electrodialysis, more recently in the form of electro-ultrafiltration (EUF) methods *(Németh [1975, 1979]; Wanasuria, De Datta and Mengel, [1981]; Wanasuria, Mengel and De Datta [1981])* have been widely studied. Application of an electric current to the soil suspension essentially induces an acid attack on the soil particles, but the intensity of the attack can be controlled, and successive attacks conducted rather easily once the appropriate equipment is available.

These methods certainly assist in the understanding of the ability of the soil to supply potassium to plants. Thus they are a valuable supplement to field experiments which reveal on any one occasion the specific needs of a specific crop in a specific season, grown in a specific cropping system. But the methods are not particularly convenient to use, and do not necessarily provide a simple guide to fertilizer use on a specific soil. It might be expected that they would have become widely used by soil survey organizations, in characterizing specific soils in terms of potential potassium requirements. With a few exceptions *(e. g.* in New Zealand, as discussed by *Lee and Metson [1981],* this does not seem to have happened. Most soil surveys provide advice on the potassium status and requirements of soils based on soil families, sub-groups or groups, for which the potassium status has been derived from measurements of total and exchangeable potassium, the sand and clay mineralogy, and other soil properties.

3.2 Mineralogical analyses

How useful are mineralogical characterizations in agronomic terms? Undoubtedly there are major differences between the soils in which the clay fraction is dominated by low activity clays (1:1 minerals and hydrous oxides) and those where the clay fraction consists predominantly of 2:1 type clay minerals. The quantity factor as far as potassium is concerned is almost always low in soils with low activity clays, although the proportion of exchange sites occupied by potassium, the intensity factor, may be, and often is, high. The reserve of potassium in mineral forms in such soils is also normally low, so that there is little buffering capacity *(Acquaye [1973]; Juo [1981 a & b]).* Even very small amounts of 2:1 clays in such soils may be of importance to potassium nutrition.

Soils with low activity clays are typical of the older, weathered uplands of the tropics. Wherever sustained cropping is practiced on such soils, it is to be expected that potassium fertilization will be needed to replace the potassium removed by crops.

Where soils are dominated by 2:1 minerals, much more varied potassium characteristics occur. Such soils dominate the lowlands of Asia. Often they are enriched with relatively young alluvium derived from mountainous areas, containing potassium bearing minerals. The lowlands are not leached of potassium, and so, except where the soils are derived from already depleted materials, the high potassium reserves are reflected in both total and exchangeable potassium contents as illustrated by data for the wetland soils of the Philippines (Table 1). Quantity and buffering capacity tend to be high in lowland soils, but the intensity factor determined by other exchangeable ions, may be high or low.

More specific factors influencing potassium dynamics in the soil are determined by differences between the 2:1 minerals. They are usually related to the presence of vermiculite or interstratified hydrous mica.

In contrast to most upland soils in the tropics, vermiculite occurs relatively frequently in the clays of the lowlands. It was a dominant clay mineral in two of the four Bangladesh profiles studied in detail by *Habibullah, Greenland and Brammer [1971]. Kawaguchi and Kyuma [1977]* and *Kyuma [1978]* found that smectite and vermiculite dominated the clay fraction of 40 per cent of the 410 samples of paddy soils they collected in Asia, and vermiculite was present in smaller quantity in many more. Vermiculite was more dominant in soils containing medium to low proportions of the smectite-vermiculite minerals. Of the 160 surface soils studied by *Bajwa and Ponnamperuma [1980]* it was dominant in 61 (Table 2), and is present as a major component of the clay fraction in 9 of the 22 benchmark soils of the wetlands in the Philippines.

Not only has vermiculite been observed in the paddy soils of the Asian region. It is also found in the wetland soils of Nigeria *(Greenland [1981])* in West Africa, and the Amazonian area of Peru *(Sanchez and Buol [1974]).* Its occurrence is important in relation to potassium nutrition, as vermiculite has a high bonding energy for potassium, and in most soils where it is dominant, exchangeable potassium is low (Table 3). *Wanasuria, Mengel and De Datta [1981]* found that much potassium was removed from solution

Table 1. Exchangeable and total potassium contents of the Benchmark wetland soils of the Philippines. (From «Benchmark soils of the Philippines», Philippine Bureau of Soils, Soil Management Support Services, and International Rice Research Institute. In press.)

			Classification		Potassium content	
	Profile No.	Series	Soil Taxonomy	Fertility capability	Exchangeable me/100 g.	Total, g/100g
VERTISOLS	8	Binangonan	Pellustert	Cgvd	0.6	0.2
	10	Bantog	Entic Pellustert	Cgvd	0.1	0.4
	13	Bigaa	Chromustert	Cgvd	0.1	0.7
	20	Pili	Pelludert	Cgvd	0.2	0.0
	21	Santa Rita	Pelludert	Cgvd	0.2	0.7
MOLLISOLS	4	Maahas	Andaqueptic Haplaquoll	Cgχv	0.6	0.3
	6	Maahas	Vertic Haplaquoll	Cgχv	0.1	0.2
	12	San Manuel	Fluvaquentic Haplaquoll	Lgdb	0.1	0.3
	14	San Manuel	Typic Haplaquoll	Lg'db	Tr	0.0
	15	San Manuel	Aquic Haplustoll	Lg'db	0.1	0.0
	19	Libon	Fluvaquentic Hapludoll	Lg'χ	0.4	0.6
	24	San Manuel	Cumulic Haplustoll	Lg'd	0.2	1.0
INCEPTISOLS	5	Calumpong	Aeric Tropaquept	Cg'χ	0.3	0.3
	7	Maligaya	Vertic Tropaquept	Cgvh	0.5	0.0
	9	Tagulod	Aeric Tropaquept	Cgd	0.3	0.5
	11	San Manuel	Aeric Tropaquept	LCgd	0.4	0.8
	16	San Manuel	Vertic Tropaquept	LCgvd	0.1	0.0
	17	Luisita	Typic Tropaquept	Lgd	0.4	0.2
	27	Maligaya	Vertic Tropaquept	Cgvd	0.2	0.1
ENTISOLS	18	Casiguran	Vertic Fluvaquent	Cgv	0.3	0.4
	26	Luisiana	Aquic Troporthent	Cgh	0.3	0.2
	29	Langa	Aquic Tropfluvent	Lg'	0.3	0.5

Table 2. Dominant clay minerals in surface soils samples from different provinces of the Philippines *(Bajwa and Ponnamperuma [1980]).*

Province	No. of samples analyzed	Dominant clay mineral						
		hydrous mica	vermiculite	beidellite	montmorillonite	X-ray amorphous material	halloysite	kaolinite
Bataan	8		1		3	2	2	
Batangas	4				2	2		
Bulacan	4				4			
Iloilo	3				3			
Laguna	14				11	1	2	
Pampanga	9		5	4				
Pangasinan	22		6	4	8		2	2
Nueva Ecija	38	2	20	16				
Quezon	10		6	2	2			
Rizal	8				5		3	
Tarlac	20		11	8	1			
Zambales	20		12	8				
Total	160	2	61	42	39	5	9	2

Table 3. Clay mineralogy in relation to exchangeable K in 160 Philippine soils *(Bajwa and Ponnamperuma [1980]).*

Exchangeable K (meq/100 g.)	Dominant minerals[1]	Major minerals	Minor minerals
< 0.1	Vermiculite/ beidellite	—	Occasional halloysite
0.1-0.2	Vermiculite/ beidellite	—	Montmorillonite
0.2-0.5	Montmorillonite/ halloysite/x-ray amorphous material	Montmorillonite/ halloysite/x-ray amorphous material	—
> 0.5	Montmorillonite	Hydrous mica	Feldspars

[1] Dominant = > 50%; Major = 20-50%; Minor = < 20%; — = not observed.

(«fixed») when it was added to the Maligaya clay with a high vermiculite content. Thus rather larger additions of potassium may be needed by soils rich in vermiculite to obtain a response to potassium *(Wanasuria, De Datta and Mengel [1981]).* The need to saturate sites where potassium is strongly and specifically sorbed may well account for the interesting trends in potassium response observed in the long-term trials at Maligaya and Bicol (Figure 1). The Maligaya soil contains vermiculite, and the potassium response (above the NP treatment) increased steadily over 10 crop years, and has subsequently declined. The decline in response is presumably due to establishment of a sufficient potassium intensity once the most strongly absorbing sites are potassium saturated. The clay fraction of the Bicol soil (Pili clay) is dominated by montmorillonite, where the strongly sorbing sites are fewer and no vermiculite is detectable. Thus the initial additions of potassium give a high response, because the potassium intensity is low, but subsequently there is a higher intensity of potassium in the soil, and so a lower response to the added potassium. The yield levels do not decline in the later crops (Figure 2) even though the potassium response is much lower.

Bajwa and Ponnamperuma [1980] found that in the 160 Philippine soils they studied there were 81 clays with dominant 2:1 expanding lattice minerals. They suggested that of these, 42 were beidellite, and 39 montmorillonite. But beidellite and vermiculite were often found together, and are difficult to distinguish (Table 2). These soils had very low levels of exchangeable potassium (Table 3).

Hydrous mica was not found as the dominant clay mineral in any of the soils studied by *Bajwa and Ponnamperuma*, and was only observed in 70 of the 410 soils included in the *Kawaguchi and Kyuma* study.

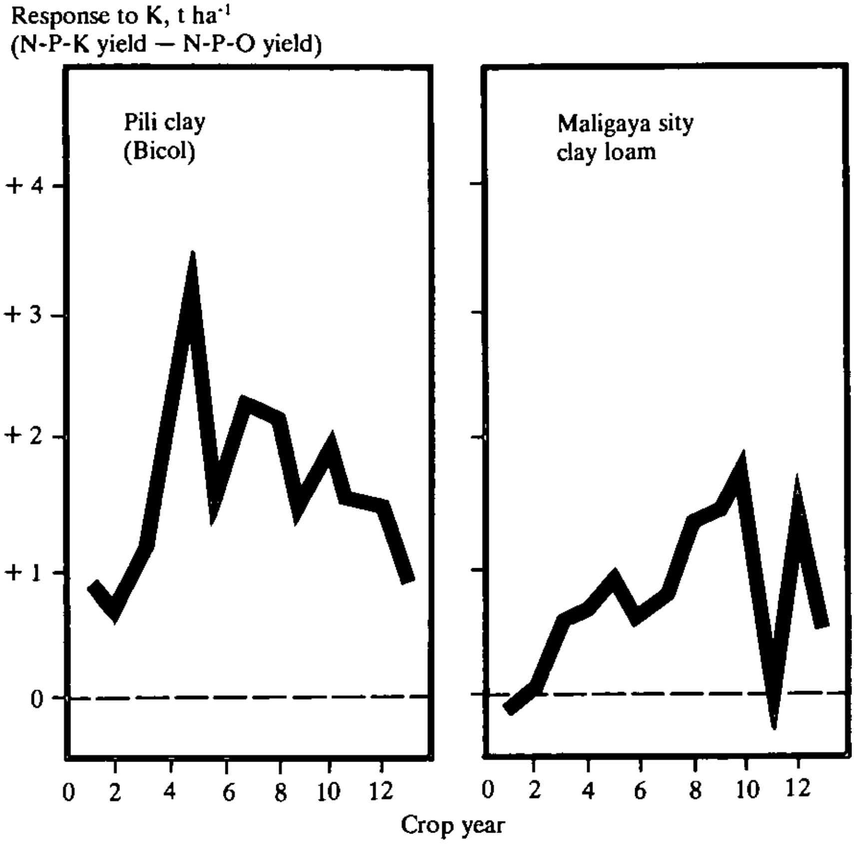

Fig. 1 Response to K (N-P-K yield less N-P-O yield) at Bicol on a montmorillonitic soil, and at Maligaya on a soil with vermiculite, 1968-1980. Dry season data only *(De Datta and Gomez [1981])*.

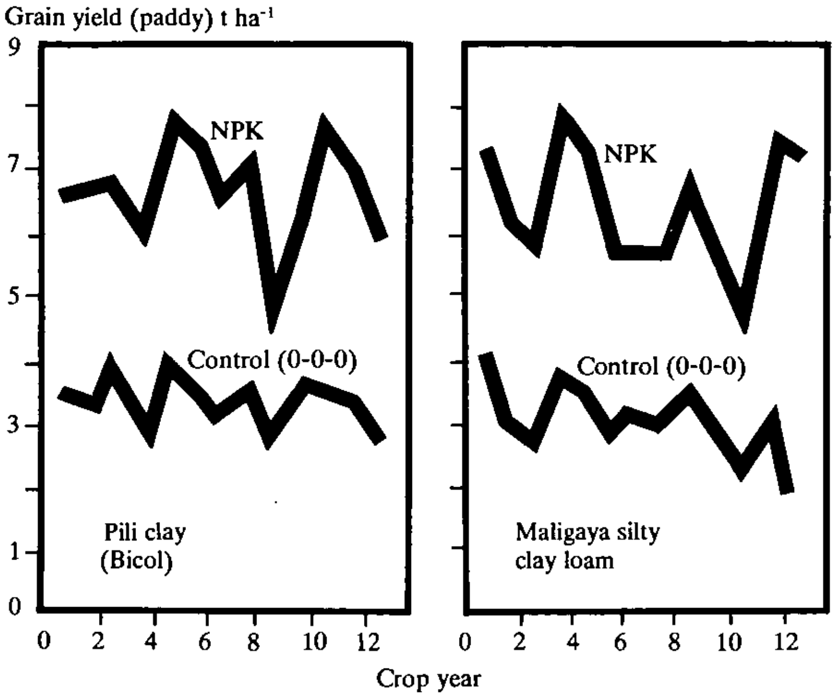

Fig. 2 Yields of paddy rice at Bicol and Maligaya experiment stations for NPK and control treatments. Dry season data only. (Data kindly supplied by Dr. *S. K. De Datta).*

There are of course many factors besides the presence or absence of vermiculite which determine the intensity of potassium in the soil solution. Nevertheless the potential importance of vermiculite in wetland soils of the tropics may well have been underestimated in earlier evaluations.

Few studies of the coarse fraction mineralogy of lowland soils in Asia seem to have been reported. The total potassium contents of the soils studied by *Kawaguchi and Kyuma,* and the Benchmark lowland soils of the Philippines all indicate substantial reserves of weatherable minerals.

3.3 Other factors

Other soil factors which might be expected to influence the availability of potassium to rice include pH, organic matter, other cation species, and the texture and structure of the soil. In flooded soils the pH always tends to neutral, so that there is no likelihood of a major effect. Organic matter may have some importance in promoting the breakdown of potassium bearing minerals, but does not appear to be generally significant. The rather high levels of ferrous iron present in some paddy soils may be important in competing with potassium for exchange sites. Little detailed information is available regarding ferrous iron/potassium exchange relationships with smectites and vermiculites, although the possible significance has been recognized for some time *(Ponnamperuma [1984])*. The importance of aluminium in the soil solution of acid upland soils in determining the intensity factor for potassium has been well established *(Tinker [1964])* but flooded soils do not normally remain sufficiently acid for the aluminium concentration to be significant. Texture is of course almost always important in determining the quantity of exchangeable potassium, and also usually the intensity. For rice it has a particular importance in determining the ease of puddling, the retention of water, and the ease with which a puddled soil may bc reconverted to a seedbed suitable for the establishment of upland crops. There has been far too little work conducted to determine the factors controlling the rather special physical properties of soils to be used for rice and upland crops *(Greenland and De Datta [1985])*. Structural factors related to flow and diffusion of ions to roots are likely to be less important in flooded soils than in others subjected to drying, when the pathways to the root may be finer and more tortuous, and ionic concentrations higher. Nevertheless flow and diffusion of ions in paddy soils is a neglected subject which merits greater attention.

4. Field and greenhouse experiments

It is difficult to overemphasize the importance of field experiments to define the needs for potassium. Only the field experiment integrates all the crop and soil factors which determine potassium requirements. This is well known and innumerable field experiments have been reported which describe potassium responses of crops. Most valuable of these are long term trials on well characterized soils, which allow the results to be extrapolated with confidence, in both time and space. In general, in the tropics particularly, there are too few such experiments, although there are examples in India *(Nambiar and Ghosh [1984])* and in the Philippines on irrigated rice *(De Datta and Gomez [1975, 1981])*. Unfortunately there appear to be very few long term trials on rice-based cropping systems, in which fertilizer use is managed in relation to the needs of the system rather than the individual crop.

Long term experiments require careful initial site selection, a continuing commitment for initially small returns, and accurate recording of crop performance and soil characteristics over several years. Expenditure on such experiments is likely to be of low priority for many developing countries, in spite of the fact that such experiments are critically important to any successful program of soil fertility maintenance. Higher yields and more intensive cropping systems inevitably mean that more nutrients are extracted from the soil. Yields fall rapidly on upland soils when the nutrients are not replaced *(Sanchez [1976])* and rather more slowly for lowland rice production systems *(De Datta and Flinn [1984])*. Philippine and Indian experience shows clearly that high yields can be maintained, provided that correct fertilizer management is practiced.

In upland soil management maintenance of the organic matter is usually a critical part of fertility management. In wetland soil management the specific requirements for organic matter maintenance are less clear. Much more information is needed about the optimum levels of organic matter in wetland soils, to make puddling easy and minimize water loss, yet allow the soil to be easily restructured when an upland crop is grown after rice. Long term experiments in Japan *(Kumazawa [1984])* have shown that correct management of fertilizers and compost can lead to high yield levels sustained over a long period (Figure

3). In the Philippines, inorganic NPK alone over 12 years at the *Maligaya Rice Research and Training Center* maintained yields at 8 t/ha in the dry season and 6 t/ha in the wet season. At *IRRI* and two other sites there has been a very slight downward trend in maximum yield levels *(De Datta and Flinn [1984])*, although the yield levels at *IRRI* are still at the high level of 6 to 8 t/ha for wet and dry season crops, respectively. In Indonesia, *Fagi and Partohardjono [1982]* have found that inorganic NPK maintained yields at 5-6 t/ha on a Vertisol, but failed to do so on an Inceptisol, or an Oxisol (Figure 4).

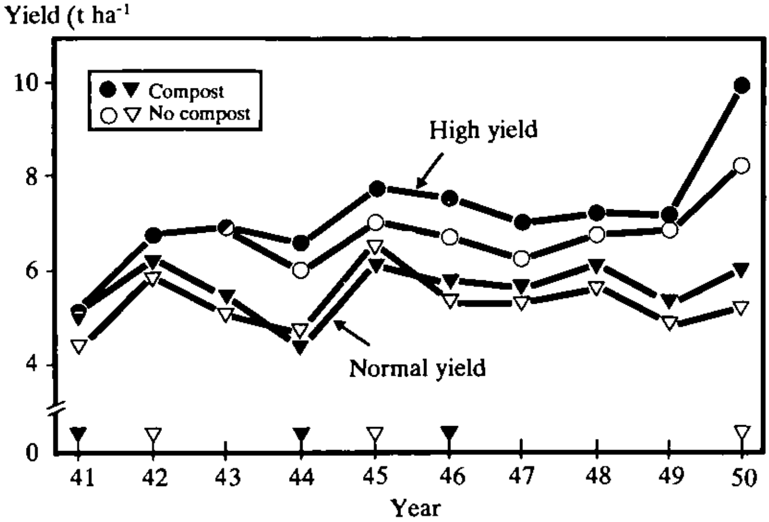

Fig. 3 Long-term effects of compost on rice yields at high and low fertility sites. Experiments conducted in Japan, 1941-1950. (Data of *Kamata et al.* reported by *Kumazawa [1984]*).

5. Extrapolating the results of field experiments

The results of field experiments can only be extrapolated with confidence to other soils and environments of similar characteristics. Obviously basic soil characteristics need to be recognized for this, but in addition those factors which change with time must be taken into account. A well developed background of soil information and soil surveys, supported with sufficient analytical information can be a great help *(Sudjadi et al. [1985])* but will normally need to be supported by soil test information. If the soil classification and soil survey information is not available in sufficient detail, what are the alternatives? One possibility is to apply the *«Fertility Capability Classification»* system, adapted to wetland soils *(Sanchez and Buol [1985])*. This emphasizes the surface soil characteristics, and while best supported by proper taxonomic classification, is very much simpler and convenient for field use *(Lin [1984])*.

A further option is to use small plot experiments at many locations, which are *«Joint Experiment and Extension Plots (JEEPS)»* distributed over an area of similar environmental characteristics *(Denning [1985])*. Such plots are used in multilocation testing of farming systems technology.

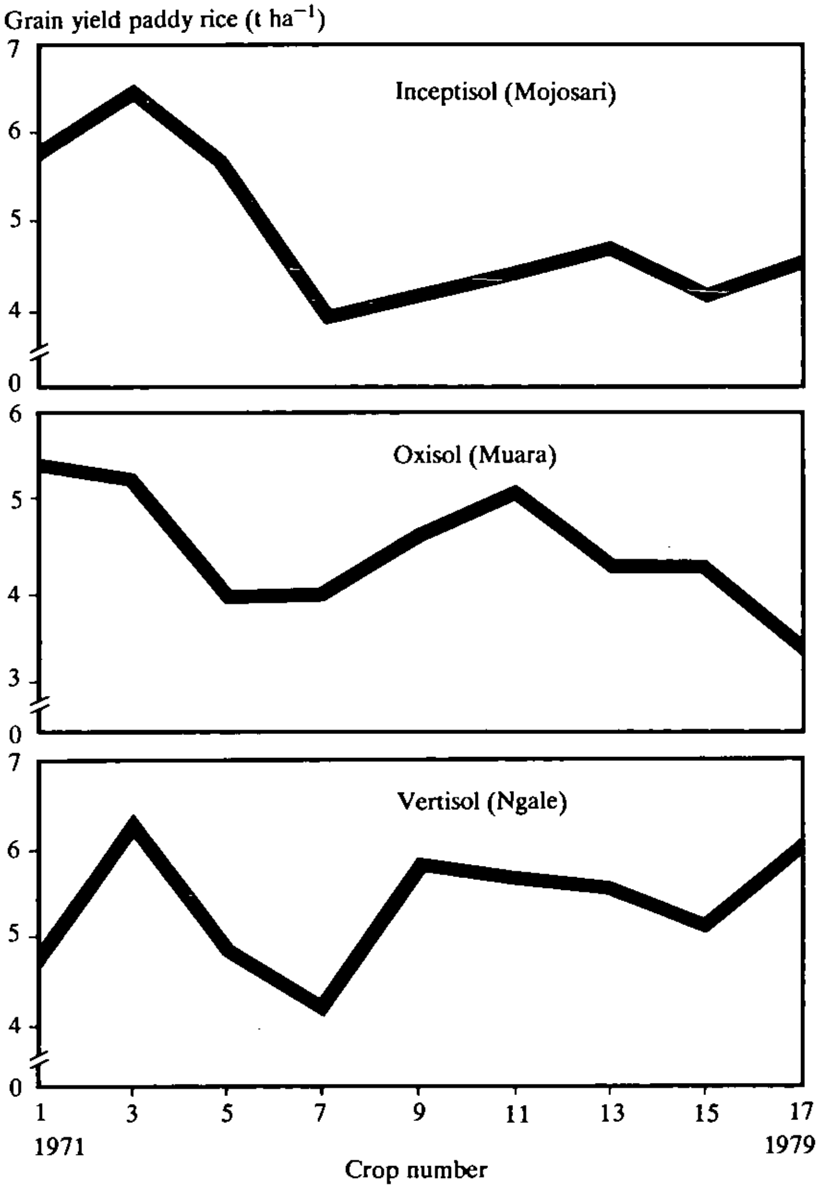

Fig. 4 Grain yields (paddy) of the NPK treatments in the long-term fertility trials, Indonesia. NPK rate 120-60-60. *(Fagi and Partohardjono [1982]).*

The inherent variability of soils, and the large amount of field and laboratory work required make it desirable that international collaboration be developed so that work on similar soils is shared. Several organizations already exist to help in this sharing of experience, such as the *International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER),* the *Asian Farming Systems Network (AFSN),* the *International Board for Soil Research and Management (IBSRAM),* and the *Soil Management Support Services (SMSS).*

6. Experimental studies of potassium use in different farming systems

Nutrient use and efficiency should always be studied in the context of the farming system within which crops are grown. For many tropical farming systems, it remains true that the number of experiments on fertilizer efficiency in intercropping and relay cropping experiments is inadequate to make useful generalizations. *Pendleton, Hoopper and Pandey [1982]* concluded from a review of fertilizer management in wetland cropping systems that management recommendations have been difficult to obtain on a single crop basis, and that the difficulties increase many fold when more intensive systems are studied. Nevertheless it is essential to have information about how best to use fertilizers to optimize economic returns from the system. This is only possible if experiments are conducted on the system.

Unfortunately there appear to be very few long term trials on rice-based cropping systems, in which fertilizer use is managed in relation to the needs of the system rather than the individual crop. Experiments conducted over a long period on one farming system are invaluable as a guide to the major problems that may arise. For instance differences which arise in potassium nutrition of rice depend on the method of straw disposal. *Morris and Meelu [1985]* indicate that there may be little difference between burning or incorporating straw, and that if potassium is used, it is better used on the crop following rice. However more frequently differences between methods of fertilizer use and crop management are less easily demonstrated in relation to the farming system. Although experiment stations provide an invaluable guide, on-farm studies are also needed. An experimental methodology for conducting such trials has been developed and with various modifications has been widely used in south and south east Asia. *Morris [1985]* has discussed the complementarity of experiment station and on-farm research, and emphasized the need for both types of research. He also discusses the important link between on-farm research and extension, and the difference between them. On-farm research tests established methods and new innovations within the context of the actual farm system. It does not necessarily lead immediately to extension, although if the innovations are successful, it will facilitate rapid adoption and extension.

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FAO Experience with Responses to Potash Fertilizers

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Summary

Results from more than 12000 simple trials and demonstrations (7700 rice, 1900 other cereals, the rest other crops including grain legumes, roots, fibres, sugar and vegetables) in Bangladesh, Indonesia, Philippines, Sri Lanka and Thailand are discussed. Response to K fertilizer (kg crop/kg K_2O) averaged 4 to 24 for rice, 5 to 78 for wheat, 6 to 14 for maize, 4 to 8 for sorghum, 2 to 6 for groundnut, 2 to 5 for soya and 40 to 50 for cassava. K response was correlated with exchangeable soil K in Thailand and the influence of soil type on K response is discussed. Positive interaction between K and Zn is reported from the Philippines. Limited work on timing of K application to rice indicates that split application is to be recommended. Grounds for concentration by *FAO* on large numbers of simple trials in widely spread cultivators' fields are the possibilities of locating areas of K deficiency and of formulating location-specific recommendations.

1. Introduction

The purpose of the *FAO Fertilizer Programme,* started in 1961, is to assist in increasing crop production, particularly of food crops grown by small farmers, using fertilizers as a spearhead for their sustained adoption of improved cultural practices. Field projects are located in regions of developing countries where fertilizer use is minimal or non-existent. A main activity is to carry out large numbers of simple fertilizer trials and demonstrations on farmers' fields in order to assess soil fertility, to identify nutrient disorders and to educate the farmers in the economical use of fertilizers. We discuss here recent experience in Bangladesh, Indonesia, the Philippines, Sri Lanka and Thailand.

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2. Review of results obtained in some countries of South and East Asia

2.1 Soil potassium in general

Except for soils of recent volcanic or alluvial origin, most tropical soils are highly weathered, and many are acid and low in bases. They have a low cation exchange capacity (CEC) and are unable to absorb on the exchange complex large quantities of K from fertilizers.

Kawaguchi and Kyuma (1977) report on the K status of soils of the region as in Table 1. This indicates exchangeable K to be highest in the Philippines and lowest in Sri Lanka.

Table 1. Exchangeable K in paddy soils of some Asian countries *(Kawaguchi and Kyuma [1977])*

Country	No. of samples	Mean	Minimum	Maximum
		me/100 g		
Bangladesh	53	0.3	tr.	0.8
Indonesia (Java)	44	0.4	0.1	1.2
Philippines	54	0.5	0.1	1.7
Sri Lanka	33	0.2	tr.	0.7
Thailand	80	0.3	tr.	2.6

Bangladesh

46% of 200 soil samples taken from *FAO Fertilizer Programme* trials and demonstrations conducted in Bangladesh in 1983 contain less than 0.15 me/100 g of exchangeable K and only 5% contain more than 0.30 me/100 g indicating that most of the Bangladesh soils are low in exchangeable K. The few samples with high K content were from parts of Barisal and Khulna Districts in the South West of the country where soils are of gangetic alluvium with high clay (mainly vermiculite with some illite) and silt content.

Thailand

Percentage distribution of exchangeable K in 1892 surface soil samples from fertilizer trial and demonstration sites in 1981-84 are listed in Table 2. In summary:

1. Paddy soils in the regions of Northeast and East tend to be lower in exchangeable potassium than in the regions of North, Center, West and South. 55% of the soils in Northeast and East contain less than 41 ppm of exchangeable potassium as compared with only 22% of the soils in North, Center, West and South.

2. Among upland crop soils those carrying kenaf tend to be lower in K, those with sugarcane and soya higher, those with groundnut or cassava intermediate. Maize soils are the highest (51% over 100 ppm K).

Table 2. Percentage distribution of exchangeable K in soil samples from Thailand

Crop	Exchangeable K (ppm)	% Distribution
Rice (NE, E)	< 41	55
(n = 348)	41 – 80	24
	81 – 120	10
	> 120	11
Rice (N, C, W, S)	< 41	22
(n = 251)	41 – 80	35
	81 – 120	22
	> 120	21
Maize	< 51	20
(n = 447)	51 – 100	29
	101 – 150	19
	> 150	32
Soybean	< 36	13
(n = 122)	36 – 55	22
	56 – 100	33
	> 100	32
Groundnut	< 36	31
(n = 117)	36 – 55	21
	> 55	49
Cassava	< 31	39
(n = 319)	31 – 50	29
	> 50	32
Sugarcane	< 36	19
(n = 58)	36 – 70	29
	> 70	52
Kenaf	< 21	25
(n = 263)	21 – 30	21
	31 – 45	28
	> 45	25

2.2 Crop response to K fertilizer

Tables 3 to 7 show responses by the various crops in the different countries in terms of unit crop produce per unit K_2O applied in the columns headed «FPI» (fertilizer productivity index).

2.2.1 Cereals

The unit responses were between 4.4-10.8 kg rough rice per kg K_2O at the low level of 30-40 kg K_2O/ha (exceptional high response of 24.1 kg grain/kg K_2O at the level of 20 kg K_2O/ha in one series of trials obtained from Bangladesh in 1981-83). The application of an additional 30-40 kg K_2O/ha depressed the yield except in one series of trials obtained in Sri Lanka where response was linear up to 80 kg K_2O/ha. In the Philippines, the response of rice yield to potash is higher in the second crop than in the first crop (Table 3).

Table 3. Responses of cereals to potash

Country*/period	No. of sites	Yield of K_0 plot (kg/ha)	K_2O used (kg/ha)	FPI**	VCR
T3.1 Rice					
BGD 1978-80	411	3601	0-34	4.9	4.4
			34-67	-2.8	-2.5
BGD 1981-83	105	3476	0-20	24.1	21.4
			20-40	8.1	7.2
			40-60	-8.0	-7.1
BGD 1981-83	3368	3748	0-45	8.8	7.8
INS 79/80-81/82	113	1942	0-30	6.4	6.8
			30-60	-1.8	-2.0
PHI 1st crop 1978-79	1378	4702	0-30	4.4	2.0
PHI 2nd crop 1978-79	930	4714	0-30	5.9	2.7
SRL 1980-84	689	4032	0-40	7.6	5.8
			40-80	9.0	6.9
THA NE & E 83/84-84/85	428	3446	0-25	10.8	3.6
THA N, C, W & S 83/84-84/85	287	4604	0-25	7.1	2.4
T3.2 Wheat					
BGD 1978-80	108	2353	0-34	5.1	4.0
			34-67	-2.2	-1.8
BGD 1981-83	567	1947	0-45	7.8	6.2
T3.3 Maize					
INS 77/78-81/82	645	2059	0-30	11.4	7.0
			30-60	-0.8	-0.7
SRL 1980-84	147	3030	0-40	14.0	9.2
			40-80	7.0	4.6
THA 1981-84	53	4408	0-31	6.3	1.7
			31-63	2.1	0.6
THA 1983-84	344	3639	0-31	7.5	2.0
T3.4 Sorghum					
INS 77/78-81/82	6	2180	0-30	7.8	5.2
			30-60	7.1	4.8
THA 1982-84	31	3341	0-31	4.1	1.1
			31-63	-0.8	-0.2

* BGD = Bangladesh INS = Indonesia PHI = Philippines SRL = Sri Lanka THA = Thailand

**FPI = Fertilizer Productivity Index (the number of kilograms of crop, *e.g.*, grains, tubers etc. produced per kilogram of nutrient [K_2O]

Wheat

At the level of 34-45 kg K_2O/ha, the mean responses per kg K_2O were 5.1-7.8 kg grain in Bangladesh. Additional 33 kg K_2O/ha depressed the yield (Table 3.2).

Maize

At the lower level of potash (30- 40 kg K_2O/ha), unit potash response was highest in Sri Lanka (14.0 kg grain/kg K_2O) and lowest in Thailand (6.3-7.5 kg grain/kg K_2O) (Table 3.3).

Sorghum

A limited number of trials in Indonesia show a linear response to potash application up to the rate of 60 kg K_2O/ha, while in Thailand, no yield increase is observed beyond 31 kg K_2O/ha (Table 3.4).

2.2.2 Grain legumes

The results of 1997 trials and demonstrations in 1977-84 are summarized in Table 4. The unit responses were between 2.1 and 6.6 kg grain/kg K_2O at the lower level of potash (30-40 kg K_2O/ha). Applying more potash gave a good potash response only in Sri Lanka.

2.2.3 Root crops

For cassava, 94 trials showed the unit responses of 41.5 and 49.4 kg tuber/kg K_2O for Indonesia and Thailand at the level of 60 and 50 kg K_2O/ha, respectively. Beyond this level, the unit responses fell to 19.3 and 4.3 kg tuber/kg K_2O (Table 5.1).
For potato, the unit response was higher over the range 80-160 kg K_2O/ha than over the range 0 – 80 kg K_2O/ha (Table 5.2).

2.2.4 Sugarcane

A good potash response was observed from 23 trials and demonstrations in Thailand. Unit response was 152.2 kg cane/kg K_2O at the level of 38 kg K_2O/ha (Table 6).

2.2.5 Fiber crops

There was a good response in a series of 52 kenaf trials with high management practice while a relatively poor potash response was obtained from another series of 156 kenaf demonstrations with low management practice (Table 7).

2.2.6 Vegetables

Results of 187 trials conducted in Sri Lanka show that potash requirements of tomato, onions, beans and chillies are high (Table 8).

Table 4. Responses of grain legumes to potash

Country/period	No. of sites	Yield of K_0 plot (kg/ha)	K_2O used (kg/ha)	FPI*	VCR
T4.1 Groundnut					
INS 77/78-81/82	620	875	0-30	2.4	11.2
			30-60	-0.8	-3.6
SRL 1980-84	123	1639	0-40	4.9	6.4
			40-80	3.4	4.5
THA 1982-84	43	1687	0-38	6.6	5.5
			38-75	1.0	0.8
THA 1983-84	93	1694	0-38	3.8	3.2
T4.2 Soybean					
INS 77/78-81/82	506	1076	0-30	3.0	8.4
			30-60	0.5	1.4
SRL 1980-84	47	1364	0-40	2.7	3.5
			40-80	4.0	5.2
THA 1980-84	61	1768	0-38	4.8	3.4
			38-75	-3.4	-2.4
THA 1983-84	105	1375	0-38	2.2	1.6
T4.3 Mungbean					
INS 77/78-81/82	235	763	0-30	3.6	10.0
			30-60	-1.2	-3.5
THA 1982-84	38	977	0-38	3.8	3.1
			38-75	1.2	1.0
T4.4 Cowpea					
SRL 1980-84	126	885	0-40	2.1	2.5
			40-80	3.1	3.7

*see explanation page 310

Table 5. Responses of root crops to potash

Country/period	No. of sites	Yield of K_0 plot (kg/ha)	K_2O used (kg/ha)	FPI*	VCR
T5.1 Cassava					
INS 78/79-81/82	64	20535	0- 60	41.5	7.1
			60-120	19.3	3.3
THA 81/82-83/84	30	24284	0- 50	49.4	3.3
			50-100	4.3	0.3
T5.2 Potato					
SRL 1980-84	29	14074	0- 80	6.1	9.9
			80-160	11.3	18.6

*see explanation page 310

Table 6. Responses of sugarcane to potash in Thailand 83/84-85/85

No. of sites	Yield of K_0 plot (kg/ha)	K_2O used (kg/ha)	FPI*	VCR
23	47949	0-38	152.2	7.6

*see explanation page 310

Table 7. Responses of fiber crops to potash in Thailand 1981-84

Crop	No. of sites	Yield of K_0 plot (kg/ha)	K_2O used (kg/ha)	FPI*	VCR
Cotton	38	1473	0-38	5.0	7.2
			38-75	0.4	0.5
Kenaf	52	2157	0-50	14.2	15.8
			50-100	2.5	2.7
Kenaf	156	1233	0- 75	1.9	2.1

*see explanation page 310

Table 8. Responses of vegetables to potash in Sri Lanka 1980-84

Crop	No. of sites	Yield of K_0 plot (kg/ha)	K_2O used (kg/ha)	FPI*	VCR
Tomato	43	11051	0-40	54.5	47.6
			40-80	20.8	18.2
Onions	60	10506	0-40	19.1	16.6
			40-80	28.6	24.9
Beans	48	4446	0-40	18.3	18.0
			40-80	7.6	7.4
Chillies	36	1848	0-40	6.9	31.5
			40-80	3.5	15.8

*see explanation page 310

2.2.7 Maize/legume intercropping

300 trials with maize intercropped with legumes in Indonesia gave good responses to potash. The higher rates (60-80 kg/ha K_2O) gave the best results except in two series (maize/soya and maize/mungbean) (Table 9).

Table 9. Responses of maize/legume intercropping to potash in Indonesia 77/78-81/82

Maize/Legumes (region)	No. of sites	Yield of K_0 maize/legumes (kg/ha)	K_2O used (kg/ha)	Yield increase maize/legumes (kg/ha)	VCR
Maize/Groundnut	104	715/ 610	0-30	79/ 34	9.1
(West Java)			30-60	34/ 30	6.8
Maize/Groundnut	100	857/1042	0-40	60/ 13	3.0
			40-80	25/ 26	3.8
Maize/Soybean	68	886/ 869	0-30	62/ 33	5.4
			30-60	-19/ 5	-0.2
Maize/Soybean	12	485/ 711	0-40	158/125	11.6
			40-80	50/ 31	3.1
Maize/Mungbean	3	1260/ 540	0-30	283/ 53	13.8
			30-60	127/ 4	4.2
Maize/Mungbean	13	972/ 813	0-40	73/ 40	4.8
			40-80	56/-37	-1.3

2.3 Soil tests.

The relationship between K response and exchangeable K level was investigated in Thailand where soil samples were taken from a large number of trial sites with various crops (Table 10).

Similar studies in Indonesia were inconclusive though the following tentative ratings have been adopted for upland soils using Olsen method:

Rating	*Available K (ppm)*
Low	< 150
Medium	150 - 300
High	> 300

Figure 1 relates exchangeable K status of rice soils in different *upazilas* in Bangladesh with expected response to K fertilizer.

Table 10. Correlation of soil exchangeable K with percentage crop responses in Thailand

Crop	Soil group	Correlation coefficient	Critical concentration (ppm)
Cassava	Duptric Regosols	0.605**	50
Sugarcane	Chromic Luvisols & Orthic Acrisols	0.639**	70
Cotton	Orthic Acrisols, Calcic Camisols & Duptric Regosols	0.701**	120
Kenaf	Orthic Acrisols	0.613**	45

2.4 Influence of soil type

Indications that soil type is an important factor affecting crop response to potassium is contained in Figures 2-5 showing response to increasing rates of potash fertilizer by rice, soybeans and cotton on trial sites grouped according to soil type in Bangladesh, Sri Lanka and Thailand. The figures in parentheses indicate the number of trial results averaged in each case. There are some interesting contrasts in behaviour both as regards yield of the control (no potash treatment) and as regards response to applied potash. It is interesting that there is no correlation between control yield and response; for instance compare the steep linear response curve for rice on Vertisols in Sri Lanka which shows the highest control yield with the much less marked response on the lower yielding Ferralsols in Sri Lanka or with the two groups of Gleysols in Bangladesh where there is negative response when more than 40 kg/ha K_2O is applied. Similarly with soya, the Gleyic and Orthic Acrisols (control 2.0 t/ha) are more responsive than the other two groups (no response on Luvisols – control yield 1.6 t/ha). In cotton, the pattern differs, the group with the highest control yield showing no response.

The indications are that knowledge of soil classification could be of help in formulating advice on potash fertilization.

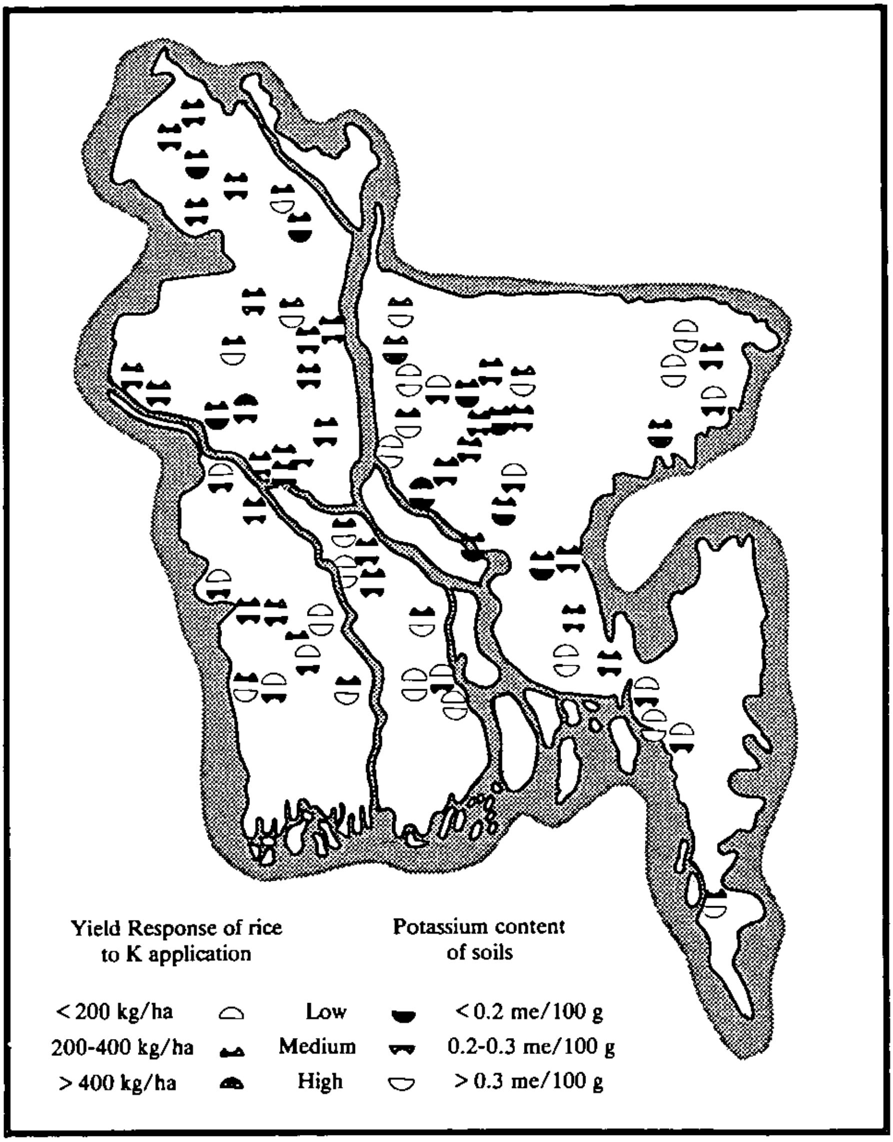

Fig. 1 Potassium status in soils of Bangladesh (based on the results of fertilizer trials and demonstrations on farmers'field, 1980-1983)

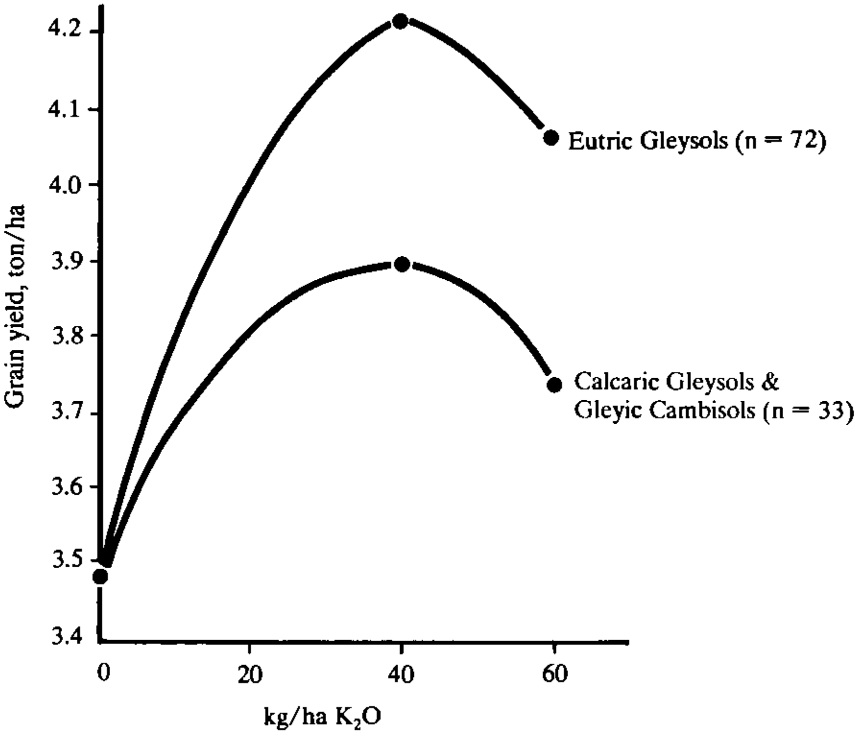

Fig. 2 Yield response of paddy rice to potash on two soil groups of Bangladesh

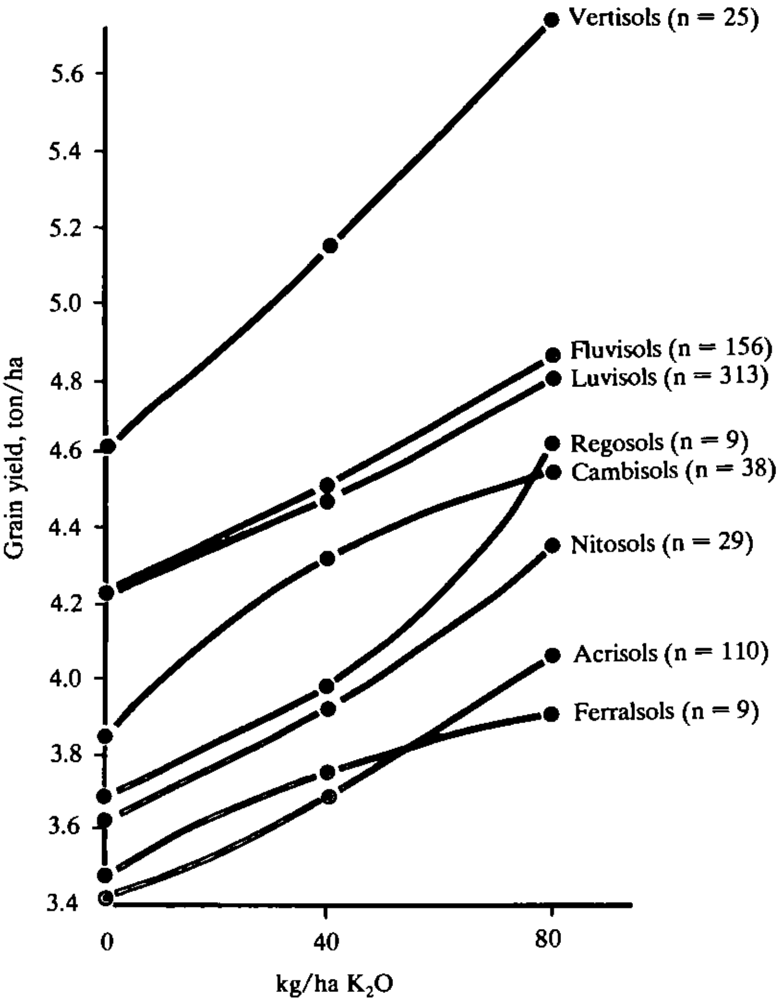

Fig. 3 Yield response of paddy rice to potash on various soil groups of Sri Lanka

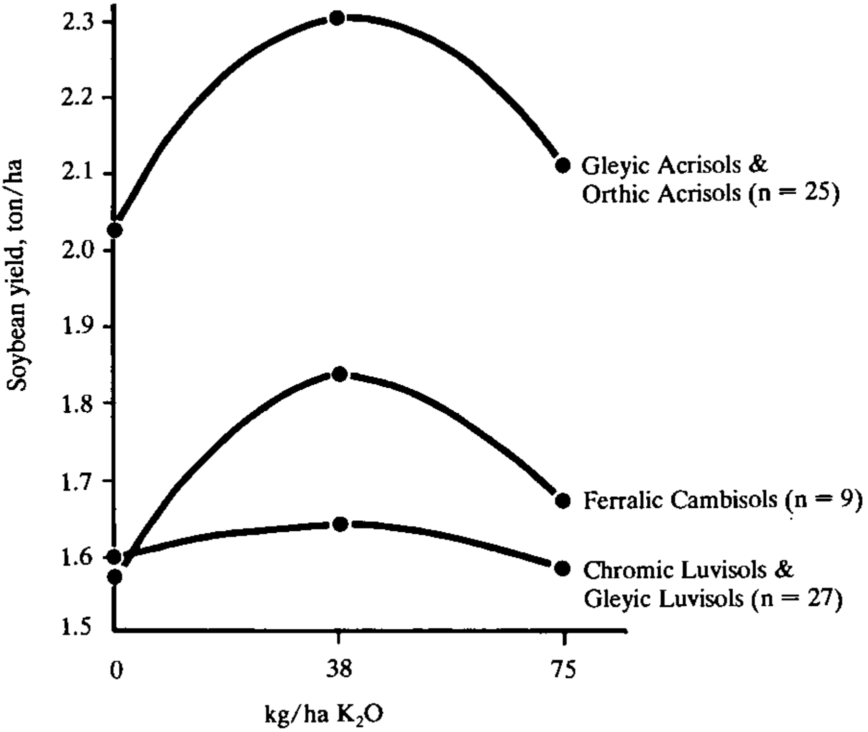

Fig. 4 Yield response of soybean to potash on various soil groups of Thailand

2.5 Interactions with other nutrients

2.5.1 Major nutrients

Fertilizer nutrients are utilised efficiently only when supplies (from soil and fertilizer) to the plant are well balanced. The continued use of unbalanced fertilizer results in depletion of soil supplies of nutrients supplied in the fertilizer and consequent decline in fertilizer response. Many cases have been reported of declining crop yields resulting from application over a period of nitrogen only, which may give spectacular results the first time it is used, but, by increasing yield, increases withdrawal of nutrients from the soil. An extreme example of this effect with cassava as test crop is shown in Table 11. NP fertilizer seriously reduced yield as compared with no fertilizer; applying a light dressing of potash along with NP restored yield to about the same level as control while doubling the rate of potash further increased yield by 5t/ha.

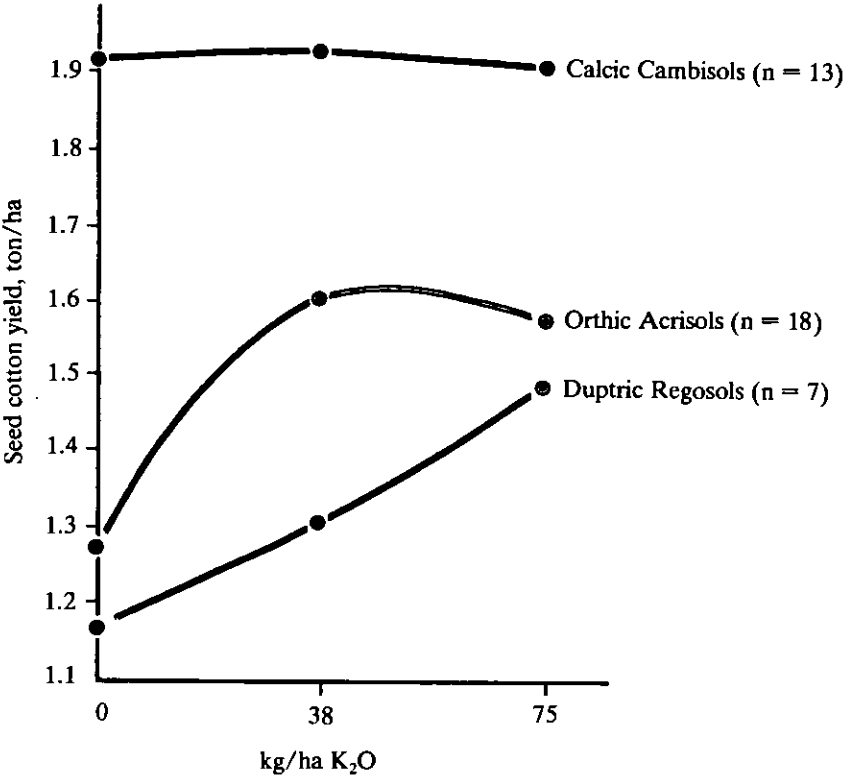

Fig. 5 Yield response of cotton to potash on three soil groups of Thailand

Table 11. Response of cassava to K application

N-P_2O_5-K_2O (kg/ha)	Stem & leaf (ton/ha)	Root yield (ton/ha)	Starch content (%)
0- 0- 0	12.39	21.88	19.3
75-38- 0	11.98	9.16	6.0
75-38- 50	16.14	22.29	17.0
75-38-100	31.23	27.13	19.3

Soil Group: Orthic Acrisols	Organic matter: 0.37%
Texture: Sandy loam	Available P (Bray's No. 2): 4 ppm
pH: 5.2	Exchangeable K: 17 ppm

2.5.2 Minor nutrients

Spectacular interactions between potassium and various micronutrients have been reported in various countries (sulphur and zinc in Bangladesh, zinc in the Philippines).

In such cases application of the relevant micronutrients along with balanced NPK fertilizer has resulted in phenomenal increase in fertilizer use efficiency. An example of potassium – zinc interaction in the Philippines is given in Table 12. Response to K without Zn 452 kg/ha; with Zn 740 kg/ha padi.

Table 12. Response of paddy rice to N, P and K with and without Zn; dry season 1976/77 (kg/ha)*

	Grain yield		
N-P_2O_5-K_2O	A (without Zn)	B (with Zn**)	B-A
0- 0- 0	2110	2806	696
69- 0- 0	2590	3686	1096
69-30- 0	2643	3575	932
69-30-30	3095	4315	1220

* Averages from 15 trials carried out in Pangasinan, Mindoro Oriental and Iloilo
**Method of zinc application:
Pangasinan: Applying 5 g/m^2 of $ZnSO_4$ to the seed bed
Mindoro Oriental: Applying 20 kg/ha of $ZnSO_4$
Iloilo: Dipping seedling in 2% ZnO in water

2.6 Effect of timing of potash application to rice

Nine experiments, 3 in each dry season 1976/77 and 1977/78 and three in the wet season 1977/78 were carried out in Mindoro Oriental, Philippines, an area where large K responses had been recorded, to test the effect of splitting the potash dressing as compared with applying all either as a basal dressing or 20 days after transplanting. The rate of potash used was 60 kg/ha K_2O in both wet and dry seasons. For the dry season crop, 80 kg/ha N with 30 kg/ha P_2O_5 were applied and for the wet season, 69 and 27 kg/ha respectively. As can be seen from Table 13, the best results were obtained by splitting the potash dressing into three equal parts (basal, 20 days after transplanting and panicle initiation).

Table 13. Effect of timing of potash application on paddy yield in the Philippines (kg/ha)

	% of K_2O distribution			76/77-77/78	1977/78
	Basal	20 DAT	Panicle	Dry season*	Wet season**
1)	–	–	–	4335 (100)	4228 (100)
2)	100	–	–	5344 (123)	5134 (121)
3)	–	100	–	5075 (117)	5121 (121)
4)	–	67	33	5323 (123)	5071 (120)
5)	50	–	50	5483 (126)	5220 (123)
6)	33	33	33	5725 (132)	5278 (125)

* Averages from 6 locations
**Averages from 3 locations

2.7 Economics of potash usage

To be persuaded to spend money on fertilizer, a farmer needs to know how much he stands to gain. Commonly used indicators of profitability are net return and value cost ratio (VCR). The latter is preferred for small farmers who are generally more impressed by treatments giving a high VCR than in obtaining the maximum net return. Experience shows that the VCR should be at least 2 if a new technology is to be adopted by farmers in a developing country. Even in Thailand where the crop-fertilizer price ratio is one of the least favourable in the region, it will be seen from Tables 2-8 that use of 30-40 kg/ha K_2O gave a VCR exceeding 2. K applied to vegetables in Sri Lanka showed very high VCRs.

3. Present practice in the use of K fertilizer

As in other parts of the world, farmers in S.E. Asia are more ready to adopt nitrogen fertilizer than other nutrients. This is because the visual effects of N are obvious and because initially yield response to N is spectacular. The effects of P and K are less obvious and, indeed may be small in the early stages. However, the introduction of high yielding varieties, increases in cropping intensity and growing evidence of response to potash will gradually persuade the farmer to accept and use potash.

There are a number of constraints which militate against the wider and more rapid adoption of potash. Among the more important are: 1) lack of credit, 2) inadequate use of other inputs, 3) lack of information, 4) uncertainty about produce and fertilizer prices, 5) inadequate irrigation, 6) availability of K fertilizer in the remoter areas.

4. The need for future work

4.1 Strengthening of extension effort

The *FAO Fertilizer Programme* plays an important role on improving the link between research and extension by assisting in the promotion of effective communication and feedback between research institutions dealing with soil fertility problems and agricultural advisory services and hence the farming communities. More specifically, it can:

- identify and suggest problems for inclusion in national research programmes especially in soil fertility/fertilizer matters;
- pass on to the extension services practical results from the Programme's work which it is considered will, if adopted by farmers, increase crop production.

In such ways it is expected that the Programme will have effects on the adoption and use of potash.

4.2 Locating potash deficient soils

Many research workers prefer to use complex replicated designs for the investigation of soil fertility problems. While such detailed work is indeed necessary, it is somewhat limited by the necessity, for adequate control, to site experiments on research stations and easily accessible sites on the more advanced farms. The complexity of the design also places a limit on the number of experiments that can be done. Such experiments cannot be truly representative of conditions over wide areas.

FAO approaches the problem in a contrasting way. By carrying out large numbers of simple, unreplicated 8 plot trials, it is possible to cover a wider range of conditions in an area and under practical, small farmer, conditions. What the method lacks in precision and detail is made up for by the much wider coverage and the possibility of locating areas with specific fertilizer problems. In the context of this paper, the location of potash deficient soils is of high importance.

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Response to Potash Fertilizers of Main Crops in China

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Summary

Results from numerous recent experiments on major crops carried out by the *Fertilizer Institute of the Chinese Academy of Agricultural Sciences* in various parts of China are discussed. The modernisation and intensification of Chinese agriculture with increasing use of N and P fertilizers resulting in higher yields has led to a greatly increased offtake of potassium and the need for K fertilizer has become evident for a wide range of crops and soil types. The effects of potassium on yield, quality characteristics and plant health are discussed for the following crops: rice, wheat, potato, sweet potato, cotton, jute, peanut, rape, soybean, sugarcane and orange.

Traditional Chinese farmers always realised that potassium was an important crop nutrient and applied K-containing materials (ash and organic manures) to maintain soil fertility. Indeed «Never sow wheat without ashes» is a widely known proverb. Home-made potassium fertilizers are still important.

To answer the question «Is chemical potassium fertilizer needed for crop production ?» many and widespread field experiments have been done over the past 30 years. Up to the early sixties, there was little response to K fertilizer, because at that time most soils were well supplied with K and yields were limited chiefly by lack of N and P. Yields with the low rates of N and P fertilizers then used were relatively low, consequently K removals were only moderate and soil K could be maintained at a sufficiently high level simply by returning crop residues to the field.

Starting from the late sixties, agriculture has been progressively intensified. High yield varieties (HYV) were introduced, and spread rapidly, more N and P fertilizers were used and multiple cropping was increasingly practised. The K supplied by returning crop residues was insufficient to maintain soil K status and soils became depleted of K. Potassium deficiency in crops, evidenced by weaker growth especially in the seedling stage, low yields and inferior crop quality, has become a frequent occurence. Field experiments in various regions have shown good and paying responses to potassium fertilizer.

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1. Food Crops

Rice

Rice is the principal grain crop of S. China. Growing use of hybrid rice, supported by N and P fertilizer has increased yields and thus increased K removal so that many rice fields are now deficient in K, especially those with low K buffering capacity. K deficient rice shows stunted growth in the seedling stage, yellowing of the lower leaves and then yellow-brown spotting of the leaves. Such K deficient rice is prone to disease. Field experiments have shown grain yield responses to K fertilizer on the poorer soils. The main effects of K fertilizer can be summarised as follows:

Early growth and light utilisation.

– With K fertilizer, transplanted seedlings green up earlier and tillering is advanced by 2 to 4 days. It improves plant height, tiller number, leaf number, fresh and dry weights.

– *Yield components*

The effects on plant height, ear number, grain/ear, % fertile grain and 1000 grain weight are shown in Table 1. All were considerably increased.

– *Quality*

It was found in Hunan and Guangdong that applying 75 kg/ha K_2O improved hulling percentage (73.6 - 76.4% in control) by 3.7%. Grain protein content was increased by 1.2% as an average.

– *K content and K_2O ratio*

Table 2 shows that these values, related to resistance to stress (drought and disease) were increased by applied K.

Table 1. The effect of K application on yield components of rice and other properties

Treatment	Rice height (cm)	Productive heads (mio/ha)	Total grains per head	Kernel grains per head	Kernel grains (%)	Weight of 1000 grains (g)
Control	74.3	3.62	60.4	44.7	74.0	25.4
75 kg of K_2O/ha	85.9	3.95	72.7	60.1	82.6	25.8

Rice variety: Gui Chao

Table 2. The effect of K application on K_2O content and K_2O/N ratio of rice

Treatment	N %	K_2O %	K_2O/N
Control	0.98	1.35	1.38
75 kg K_2O/ha	1.18	2.36	2.00

Wheat

Generous use of N and P fertilizers in recent years has considerably improved yield but the effects of the resulting increased removal of K are becoming evident in yellow leaf margins, poorer seedling growth, weak stems and reduced ear number and 1000 grain weight. The effects of K application on such characteristics are shown in Table 3.

Table 4 shows the effect of applied K on K content of the stem. Note that the effect is larger in the lower nodes.

Table 3. The effect of K application on wheat

Treatment	Wheat height (cm)	Head length (cm)	Productive heads (mio/ha)	Grains per head	Weight of 1000 grains (g)	Grain yield (t/ha)
Control	79.7	6.4	2.28	36.8	34.1	2.70
65 kg of K_2O/ha	86.1	7.9	2.46	39.1	35.9	3.13

Table 4. The effect of K application on K content of wheat stalk

Treatment	First node	Second node	Third node	Fourth node	Fifth node
	K_2O%				
Control	1.21	1.61	2.25	2.63	2.50
K applied	1.65	2.20	2.60	2.83	2.58

•Nodes of wheat stalk counted from the first node near the roots of wheat
•Wheat variety: Taishan No. 1

Maize

Maize is a K-demanding crop and is sensitive to K shortage. As with rice and wheat, the unbalanced use of N and insufficient return of crop residues has resulted in K deficiency also in this crop. When maize is deficient in K, potassium will transport from the old leaves in lower parts of maize to upper parts, so that the K content is significantly decreased in lower leaves. K content of maize leaves has been employed to predict K deficiency or K adequacy in maize. In the light of experimental data, the symptoms of K deficiency on maize occur as soon as the K content in lower leaves is less than 1%, leaf margin become orange-yellow in colour. If there are 3-4 yellow leaves in the lower parts of maize during the tasselling period, it means that K content is very low and the soil on which maize is grown is seriously deficient in K. Moreover, the ability of maize for photosynthesis and respiration is decreased greatly; the synthesis of carbohydrates and the growth of maize roots and stems are influenced by lack of K. In general, K fertilizers are more efficient for maize than for rice and wheat. K application can protect maize from lodging, and can promote the development of maize ears. The results from 19 field experiments showed that 634 kg of maize grain have been produced in addition by adding 75 kg of K_2O/ha compared to the control. (Table 5). The trials conducted by the *Soil and Fertilizer Institute of the Chinese Academy of Agricultural Sciences* showed that protein content of maize grain was 10.8% with K application but only 9.17% without K.

Table 5. Corn development as influenced by K application

Treatment	Plant height (cm)	Ear length (cm)	Weight of 1000 grains (g)	Leaf area per plant (cm^2)	Grain yield (t/ha)
Control	233	19.8	393	4155	4.72
210 kg of K_2O/ha	263	21.5	399	4485	6.25

Potato

Potato responds well to K application. Results from Guangdong show that tuber yield was 1125 kg higher with 70 kg K_2O/ha applied compared with control (without K). The effect of K fertilization on tuber yields was closely related to tuber numbers and the ratio big tubers/small tubers.

Sweet Potato

392 experiments showed that K fertilizer was very effective on sweet potato; yield was always increased by applying K. On the average, applying 70 kg/ha K_2O increased yield by 3.7 t/ha. The increase in yield resulted from increases in both tuber number and the ratio large/small tubers. Starch, reducing sugar and total sugar content were enhanced by K (Table 6.).

Table 6. The effect of K application on starch and sugar content of sweet potato

Treatment	Starch (%)	Reducing sugar (%)	Soluble sugar (%)
Control	4.86	3.60	5.28
75 kg K_2O/ha	6.30	3.76	5.44

Cotton

It has for long been the practice to use N fertilizer for cotton and continued use of NP fertilizers with organic manures as the only source of K, insufficient to replace crop removals, has led to declining soil K contents in permanent cotton fields. K deficient plants shed their leaves earlier, have smaller and fewer bolls, lower yield and poorer lint quality, which defects can be corrected by applying K fertilizer (Table 7). In 26 field experiments, 75 kg/ha K_2O increased lint by 94,5 kg/ha.
In trials by the *Soil and Fertilizer Institute,* 150 kg/ha K_2O increased lint yield and improved gin turnout by 3.8%.

Table 7. The effect of K application on cotton

Treatment	Plant height (cm)	Bolls per plant	Shedding ratio of bolls (%)	Weight per boll (g)	Gin turnout (%)	Dead leaves (%)
Control	54.7	10.7	46.1	2.50	33.5	37.9
112.5 kg of K_2O/ha	60.0	12.4	36.7	3.47	34.2	14.9

Jute

K fertilizer improved root, stem and leaf growth and significantly increased fibre yield. In 22 experiments the average increase in fibre yield was 547 kg/ha from 120 kg/ha K_2O applied. The main effect of K was to increase stem height, bark thickness and tensile strenght of fibre. In Guangdong, 10 kg/ha K_2O by 0.64 to 4.16 kg/g with increased cell number and cell wall thickness.

Peanut

The average yield increase from 48 kg/ha K_2O in 171 experiments was 403 kg/ha unshelled nuts. Some details of the results are given in Table 8.
In Guangdong oil content was increased from 47.9 to 49.8%. K fertilizer has a beneficial effect on growth and benefits root nodule formation.

Table 8. Effect of K fertilizer on peanut yield (t/ha)

Location	No K	+ K
Hua xian, Guangdong	1.99	2.24
Sui xi, Guangdong	1.15	1.57
Dai shan, Zhejiang	1.81	2.33

Soybean

41 field trials showed an average yield increase of 283 kg/ha when 93 kg/ha K_2O was applied through generally improved growth and improvement in N fixation. Number of root nodules and N content of the roots were improved.

Sugarcane

The average increase in cane yield from 93 kg/ha K_2O in 146 experiments was 285 kg/ha Sucrose content was increased from 12.9 to 13.4% in early spring planted cane and from 10.8 to 11.9% in late spring planted cane.

Orange

In Guangdong and Hunan, applying K to fruiting trees increased fruit yield by 9.6% above control (74.6 kg/tree). In Guangdong, sweet orange yield was increased from 17.9 to 19.1 kg/tree with total sugar in fruit at 9.6 and 10.8% for control and K treated trees respectively. The rate applied was 1.5 kg/tree K_2O. The corresponding figures for vitamin C extent were 40.4 and 47.6 mg/100g. In Hunan, applied K increased total acid content from 0.78 to 0.94%.

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The Performance of Traditional and HYV Rice in Relation to their Response to Potash

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Summary

The introduction of high yielding varieties (HYV) has made an important contribution to increasing production of rice and other crops. Because of their high potential yield, lodging resistance and other desirable characteristics, the growing of HYVs and Hybrids has spread very quickly and for the past ten years improved varieties have occupied from 30 to 50% of the rice growing areas in some provinces. Their yields are 20-40 per cent higher than the local varieties but the new varieties are only able to show their full capabilities with good soil and water management and with adequate supplies of balanced NPK fertilizer. Over the past 15 years NP fertilizer has been increasingly used and has given yield increases but the higher yields taken off the field have resulted in a rundown of soil K reserves. Recent experiments show that response by rice to K fertilizer is now very much higher than it was ten years ago. The importance of balancing NP with adequate K for maintaining high yields cannot be overstated.

1. Potassium requirement of HYV rice.

An outstanding feature of the new HYV rice is its high potassium requirement. *Xiao [1982]* found that for the production of 1 t grain, K removal from the field was 25.8 and 33.2 kg K_2O respectively for local (Guang Xiang 3) and hybrid (Nan You 2) varieties. *Luo [1983]* obtained similar results in Hunan: 25-26.6 kg and 35-43.1 kg K_2O per ton grain for local (Dong Ting and Xiang Ai) and hybrid (Wei You 6 and Nan You 2) varieties. Hybrid rice took up 20-75% more potassium than local varieties. The K content of rice plants at various growth stages has been investigated by *Luo [1983]* in Hunan and *Zhu [1980]* in Guangdong and their results are given in Tables 1 and 2. K content of the straw, in particular, was much higher in HYVs.

The rate of K uptake and the percentage taken up during different growth stages differ greatly between HYV and local varieties (Table 3). In both cases maximum uptake was in the period from late tillering to full heading. At this stage the local variety ceased taking up K but the HYV continued to do so until ripening; 8.7% of total uptake was over this period. This behaviour seems typical of the HYV.

In the HYV, a high leaf K content is needed for maximum photosynthesis, spikelet, pollen and grain formation. Ear number and grain/ear were increased by K fertilizer.

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Table 1. NPK content of two rice varieties in different growing stages (% in DM)

Growth stage	N %		P_2O_5 %		K_2O %	
	Hybrid	Local	Hybrid	Local	Hybrid	Local
Transplanting	1.97	2.05	0.71	0.71	2.96	2.50
Tillering initiation	3.19	3.41	0.69	0.64	3.89	3.46
Maximum tillering	3.35	3.68	0.82	0.66	4.37	4.46
Panicle initiation	2.26	2.55	0.71	0.66	3.41	3.58
Heading	1.67	1.86	0.57	0.50	2.60	2.64
Ripening straw	1.30	0.90	0.66	0.32	2.17	2.32
grain	1.40	1.58	0.90	1.00	0.32	0.32

Hybrid late rice: Wei You 6, Local late rice: Dong Ting, Soil: Red earth paddy.

Table 2. K content of two rice varieties in different parts and growth stages

Parts of rice	Growth stages	HYV (Gui Zhao, 2)	Local (Ke Shi)
		K_2O % (in DM)	
Leaves	Tillering	3.66	3.43
	Panicle initiation	3.14	4.36
	Heading	2.80	2.34
Sheath	Tillering	6.56	5.28
	Panicle initiation	5.95	6.01
	Heading	2.72	2.20
Straw	Ripening	3.80	2.16

Soil: Alluvial paddy.

Table 3. Amount and percentage of K uptake during different growing stages of two rice varieties

Growth Stages	Amount of K_2O removed (kg/ha)		% of total K_2O uptake	
	Hybrid	Local	Hybrid	Local
Sowing – transplanting	23.92	8.0	8.10	4.50
Transplanting – tillering initiation	27.0	11.9	9.16	6.70
Tillering initiation – late tillering	80.9	37.7	27.4	21.2
Late tillering – heading	138.0	120.2	46.7	67.6
Heading – ripening	25.5	0.0	8.83	0.0

Hybrid rice: You Wei, 9. Yield: 8010 kg/ha
Local rice: Dong Ting. Yield: 6675 kg/ha

2. Yield response to potassium in HYV and local varieties.

HYVs are more K responsive than the traditional varieties and this is clearly seen in results from Guangdong Province (Table 4). Percentage response to K fertilizer by HYV is approximately double that of the traditional rice.

Applying K fertilizer increases plant K content and the K/N ratio. The latter is an indicator of N:K balance. A high ratio shows the crop is high in K and this is beneficial to N metabolism (Table 6). The effect of fertilizer on K/N ratio is much greater in the HYV than in traditional varieties (Table 5).

Table 4. Response to potash of different rice varieties

Location		Variety	Yield (kg/ha) NP	Yield (kg/ha) NPK	Yield increase kg/ha	Yield increase %
Guangdong	Hybrid	(Xian You, 2)	5107.5	6735.0	1627.5	31.9
		(Ai You, 2)	4878.0	6600.0	1722.0	35.3
	Local	(Zao Guang, 2)	3960.0	4725.0	765.0	19.3
		(Hu Qiu, 4)	4402.5	5212.5	810.0	18.4
Kaiping, Guangdong	HYV	(Ke Qing, 3)	3838.5	5273.3	1434.8	37.4
	Local	(Xi Nan Ai)	2805.0	3352.5	547.5	19.5
		(Ping Bai, 1)	2394.8	2883.8	489.0	20.4
Guangxi	Dwarf rice	(Guang Qiu)	2872.5	3397.5	525.0	18.2
	Tall rice	(Ma Ke Hong)	2550.0	2745.0	195.0	7.6
Guangdong	Hybrid	(Xian You, 6)	3090.0	3517.0	427.0	13.8
	HYV	(Gui Zhao, 2)	2047.5	2962.5	915.0	44.7
	Local	(Guang Ai, 2)	3345.0	3427.5	82.5	2.5

Table 5. Effect of potassium on the ratio of K_2O/N of rice tissues of different varieties

Variety	Treatment	Maximum tillering			Panicle initiation			Ripening		
		K_2O	N	K_2O/N	K_2O	N	K_2O/N	K_2O	N	K_2O/N
Hybrid	NP	1.45	3.48	0.42	0.84	1.98	0.42	1.75	1.09	1.61
(Xin You)	NPK	2.02	2.75	0.73	3.80	1.94	1.96	2.02	0.93	2.16
HYV	NP	1.28	2.85	0.43	0.82	2.13	0.38	1.20	1.05	1.14
(Gui Zhao)	NPK	2.38	2.70	0.88	1.95	1.75	1.11	2.08	0.98	2.12
Local	NP	1.08	2.80	0.39	0.70	1.91	0.35	1.02	1.08	0.94
(Guang Ai)	NPK	2.18	2.86	0.76	1.71	1.75	0.98	1.10	0.79	1.39

Table 6. Effect of K applied on the amino acid content of different rice varieties

	Hybrid (Xin Zhao) %			HYV (Gui Zhao, 2) %			Local (Guang Ai, 2) %		
Amino Acid	NP	NPK	increase or decrease by K	NP	NPK	increase or decrease by K	NP	NPK	increase or decrease by K
Lysine	0.44	0.44	0.00	0.49	0.50	0.01	0.55	0.53	−0.02
Histidine	0.33	0.35	0.02	0.36	0.35	−0.01	0.41	0.40	−0.01
Arginine	1.00	1.09	0.09	0.97	1.01	0.04	1.14	1.16	0.02
Aspartic acid	0.92	1.01	0.09	0.79	0.87	0.08	1.07	0.88	−0.19
Serine	0.44	0.48	0.04	0.51	0.53	0.02	0.39	0.38	−0.01
Glutamic acid	2.35	2.46	0.11	2.26	2.37	0.11	2.45	2.45	0.00
Proline	0.36	0.32	−0.04	0.42	0.41	−0.01	0.42	0.34	−0.08
Glycine	0.44	0.50	0.06	0.50	0.48	−0.02	0.52	0.51	−0.01
Alanine	0.61	0.62	0.01	0.59	0.61	0.02	0.61	0.60	−0.01
Valine	0.62	0.64	0.02	0.71	0.62	−0.09	0.72	0.71	−0.01
Methionine	0.27	0.26	−0.01	0.14	0.14	0.01	0.27	0.27	0.00
Isoleucine	0.39	0.40	0.01	0.42	0.39	−0.03	0.44	0.45	0.01
Leucine	0.87	0.94	0.07	0.87	0.86	−0.01	0.94	0.97	0.03
Tyrisine	0.49	0.49	0.00	0.36	0.38	0.02	0.43	0.48	0.05
Phenylalanine	0.55	0.57	0.02	0.54	0.55	0.01	0.58	0.67	0.09
Total	10.08	10.57	0.49	9.92	10.07	0.15	10.94	10.80	−0.14

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International and National Cooperation in Long-Term Coordinated Schemes of Experimentation on Fertilizers

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Summary

The substantial increase in food demand in the coming decades requires a concerted effort among agronomists and soil scientists to develop more effective and efficient means of utilizing resources. Because of limited funds and facilities in some developing countries critically in need of food, a coordinated effort among international and national organizations to improve food production is imperative.

The *International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER)* is described as an example of a network where several national programs cooperate to develop means of increasing fertilizer use efficiency by rice and improving and maintaining rice soil fertility.

1. Introduction

The urgent need to substantially increase food production during the next decades can not be over emphasized. Projections suggest that food supplies should be increased by 50% to feed the world's population by the year 2000 and by 100% 15 or 20 years later *(Winrock International, [1980])*. Yet land available for food production will not significantly increase. The few remaining locations in Asia, Africa, and Latin America where large agricultural land areas may be developed have specific soil-related problems that must be overcome before significant increases in food supply can be expected *(Dudal [1980])*. Furthemore, food produced from the increased arable land is enough to feed only one-third of the increased population *(Swindale [1980])*.

To keep up with the increasing food demand, existing arable land should be intensively cropped. However, land use intensification and expansion in crop yields require increased and efficient use of agricultural inputs such as fertilizers and pesticides, irrigation facilities, and high-yielding crop varieties. Inefficient nutrient and irrigation management may further lead to soil problems that would be difficult to alleviate at a reasonable cost. With intensified cropping and increased yields, soil productivity especially in the tropics and subtropics may rapidly decline unless proper soil management is adopted. A sustained and concerted effort among agronomists and soil scientists is therefore needed to develop methods and approaches of maintaining the productivity of existing arable land and improve the marginally fertile or less fertile soils.

Because of limited resources in many developing countries, the important research

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investigations on conservation of soil productivity are often neglected. The developed countries, International Agricultural Research Centers (IARC) and other international organizations should assist in the programs of developing countries concerned either bilaterally or multilaterally. However, since similar soil and environment conditions prevail in many developing countries, and to use resources of donor countries effectively as well as minimize duplication, a coordinated approach is advisable.

This paper briefly discusses the rationale of the need for a coordinated effort in approaching the problems related to soil productivity. Further, it describes an example of a coordinated network on soil fertility and fertilizer use in rice.

2. The need for long-term coordinated schemes on soil fertility and fertilizer experiments

There is a wide diversity in soil and environmental conditions among and within countries and yet there are also similarities. Thus, with coordinated efforts among scientists of different countries especially among developing countries, prevailing soil fertility and fertilizer problems can be solved at relatively lower costs. Moreover, developed knowledge or methodologies will have a wider application.

According to *Swindale [1980]* coordination is needed (1) because agricultural research is costly and the creation of a sufficiently large national effort is often beyond the resources of developing countries; (2) so that knowledge building can proceed at widely different locations; and (3) to help harness the substantial reservoir of talents and facilities for soil fertility and fertilizer research existing in developed countries or among the international agricultural research centers. An agreement to utilize common methodologies would provide the first basis for coordination. It would also lead to comparative studies of methods and eventually improve their accuracy. A valuable side benefit is the training in methodology provided to staff of cooperating centers and other researchers.

While there are advantages in coordination, there are also disadvantages. Coordinated international research may slow down the efforts of national scientists in developing their abilities to perceive the pressing need in their countries. Coordinated multilocation trials may divert scarce resources of time and funds of scientists and institutions away from more important national concerns. It is important for national scientists to participate in the formulation of coordinated trials and for the objectives of investigations to fit with those of their national programs.

A number of international networks involved in soil and soil management studies have been established such as the *International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT), International Board for Soil Research and Management (IBSRAM)* and the *International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER). Food and Agriculture Organization (FAO)* and *International Atomic Energy Agencies (IAEA)* of the *United Nations (UN)* also jointly coordinated studies in soil fertility and fertilizer management particularly using isotope techniques. A common objective of these networks is to improve soil productivity through alleviation of soil constraints and proper use of fertilizer and alternative sources.

Closer coordination among these international organizations is imperative to minimize the pressures on the limited resources of the national programs. It is very likely that the same national scientists are involved in other networks, therefore, diluting their meager resources to a point where results obtained may be of less value. Different networks should then clearly define their objectives and determine the areas of common interest where they can work together.

In the event that the international networks are operating in the same region, their activities should be coordinated to minimize duplication. Moreover, their activities should be complementary. Coordination according to regional or commodity coverage could be another approach in case these networks are working on similar problems. An open communication and exchange of information among international and national networks should be promoted.

The problem areas where cooperation among networks is needed include soil and fertilizer management techniques under different soil and environmental conditions in a rice based farming system. This requires a longer period to ensure proper interpretation and transferability of results to other locations. Further, management of different crops varies. An optimum management of a certain crop in the system may not be compatible within another. Thus, there is a need to carry out this type of work within the framework of a farming system. Site characterization should also be closely coordinated so that a common language is used in describing a site, otherwise, scientists outside the network would not be able to use the results wisely. This is also true in soil testing where the test values of a method will be correlated with another. A set of soil test methods common to the whole network is ideal.

3. The International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER)

INSFFER was formally organized in 1976 with 10 countries initially participating. It was in response to the declining fertilizer supply and increasing prices brought about by the energy crisis in 1973-1974. The initial objective was to increase fertilizer use efficiency then later included soil fertility improvement and maintenance in rice soils.

Participants in the network. Agronomists and soil scientists of participating national programs, the *International Rice Research Institute (IRRI)* and *International Fertilizer Development Center (IFDC)* collaborate in the network.

The number of participating countries grew from 10 in 1976 to 19 in 1985 (Table 1). Some do not participate regularly, thus the number fluctuates every year. The number of collaborating scientists from the national programs grew from 16 to 51 and the number of sites from 27 in 1976 to 94 in 1984 based on the number who have submitted experimental data.

Participation in the network is voluntary inasmuch as the collaborators are responsible for raising the logistics required to undertake the research trials.

3.1 Components of the network:

The main activities of the network are:

(a) the collaborative research trials, (b) training, and (c) site visit tour and workshop.

a) Collaborative research trials. There are 12 different trials being undertaken as of 1985 (Table 2). These include N fertilizer efficiency trials, P sources, integrated use of inorganic and organic fertilizers, biofertilizers like azolla, and long-term fertility trials. The N fertilizer efficiency trials covers all major types of rice culture, namely, irrigated, rainfed wetland, upland, and deepwater rice while the others are designed specifically for a certain type of rice culture.

Table 1. Countries and number of collaborating scientists participating in the INSFFER Program in 1985.

Country	Number of collaborators[a]
Bangladesh	1
Burma	3
Cameroon	1
China	3
Colombia	1
Cuba	1
Dominican Republic	1
India	21
Indonesia	6
Liberia	1
Malagasy	1
Malaysia	1
Nepal	1
Nigeria	2
Pakistan	4
Philippines	7
Sri Lanka	1
Thailand	2
Vietnam	5
Total	63

[a] Only senior investigators are included.

Table 2. Current collaborative research trials of *INSFFER*, 1985.

1. Sixth N fertilizer efficiency in irrigated lowland rice (1984)[a]
2. Third N fertilizer efficiency in rainfed lowland rice (1981)
3. Second N fertilizer efficiency in deepwater rice (1982)
4. First N fertilizer efficiency in rainfed upland rice (1984)
5. Long-term fertility trial in irrigated lowland rice (1976)
6. Phosphorus sources for irrigated lowland rice (1977)
7. Azolla use in rice (1979)
8. Acid lowland soil nursery (1981)
9. Comparison of hand and machine applied N fertilizer in irrigated lowland rice (1983)
10. Integrated use of inorganic and organic N sources in irrigated lowland rice (1983)
    Management of acid soils for upland rice (1984)
11. a. for soils with $pH > 5.0$[b]
    b. for soils with $pH < 5.0$[c]

[a] Years in parentheses indicate the year formulated and implemented.

[b] Essentially a long-term fertility trial using the minus one element design.

[c] The trial is a P x lime interaction.

b) Training. The training component was incorporated into the network when collaborators recognized the lack of adequately trained junior staff. In 1979, the *INSFFER* course was instituted with the objective of strengthening the capabilities of junior researchers and technicians in the theoretical and practical aspects of soil fertility, chemical fertilizer and biofertilizer use, experimental techniques, site characterization and classification, statistical and economic analysis and report writing. The training participants spend about 40% of their time in the classroom and the rest in carrying out *INSFFER* trials, visiting soil fertility and fertilizer trials in farmers' fields, and observing problem soils. The course is offered once a year and lasts for 4 months. Since 1979, 155 participants representing 78 organizations in 17 countries have been trained. Unfortunately, many of them are not involved in conducting *INSFFER* trials.

c) Site visit tour and workshop. Site visit tours were first conducted in 1980 and since 1983, a workshop has been held after each tour. Its objectives are as follows:

1. To observe and characterize *INSFFER* trial sites.
2. To observe soil problems and soil fertility management practices in the areas visited.
3. To exchange information among tour participants and local scientists.
4. To review *INSFFER* trial results in preceding years and formulate future trials.
5. To discuss future direction of research on soil fertility and fertilizer management in rice.

Soil scientists of varied disciplines including pedologists, soil chemists and specialists of soil fertility from 21 countries joined the *INSFFER* collaborators in the site visit tour and workshop held in the Philippines in 1984. This workshop aimed primarly to discuss the characterization, classification, and utilization of wetland soils with emphasis on rice soils. The site visit tour and workshop were jointly sponsored by *IRRI, Soil Management Support Services (SMSS)* and the *Bureau of Soils* of the *Ministry of Agriculture* of the Philippines.

The 1985 site visit tour and workshop was held in Griffith, Australia. It was jointly sponsored by the *Australian Centre for International Agricultral Research (ACIAR), Commonwealth Scientific and Industrial Research Organization (CSIRO),* and *IRRI.* Fifty eight participants joined the *INSFFER* site visit tour and workshop, 18 of which were collaborators from 11 countries. Resource persons are invited to the workshops to present recent developments in soil fertility and fertilizer management in rice. Information shared during the workshop is used in defining directions of the network's program.

3.2 Formulation of research trials

Every year, collaborators who are invited to either the *INSFFER* workshop or the *International Rice Research Conference* evaluate trial results to determine whether such trials should be continued or terminated. In case the group decides to formulate new trials, they discuss treatments to be included and the kind of information to be collected and reported. It is important that participating national programs are involved in formulating and planning the research trials. This ensures the relevance of the trials to their respective needs and problems. Local funding can only be secured by the collaborators if the objectives are compatible with those of the national program. This explains why collaborators do not carry out every trial of the *INSFFER* program.

An annual report for each trial is prepared and distributed to collaborators every year. It contains all collaborators' results and information on the different sites including analyses of soil properties. Collaborators are encouraged to publish their results and use the reports as references.

3.3 Role of collaborators

Collaborators from national programs, are primarily the implementors of the research trials besides being involved in their formulation. *IRRI* staff, however, also conduct trials within the host country.

Fieldbook preparation, packing and shipping of experimental materials, soil analyses from collaborating sites, data collation, statistical and economic analyses of experimental results, and preparation of reports are done at *IRRI*. *IFDC* supplies new materials for testing and together with *IRRI*, provides the technical coordination and assists in training.

3.4 Constraints in the network

An important constraint in the network is the lack of facilities. This has restricted some collaborators in providing the necessary information in interpreting their results and comparing them with the others. Attempts are now made to assist national program collaborators in collecting information. For example, soils of their sites are being analyzed at *IRRI*. This minimizes variation of analysis among sites caused by different analytical methods and techniques used. Assistance to characterize *INSFFER* sites is now offered to collaborators seeking such services. In doing so, we hope to attain uniform characterization and classification of all *INSFFER* sites. This should lessen the difficulty of interpreting results and facilitate transfer and adoption of the results to similar sites.

4. Brief highlights of *INSFFER* collaborative research trials

The N fertilizer efficiency trials compare different urea forms, application rate, time, and method. Prilled urea (PU) is split applied with ⅔ N broadcast and incorporated just before transplanting and ⅓ topdressed 5-7 days before panicle initiation. All of sulfur-coated urea (SCU), a slow release material, is broadcast and incorporated before transplanting. Urea supergranule (USG) is deep placed 10-12 cm between 4 hills. This set of treatments was tested in the irrigated, rainfed lowland, and deepwater rice cultures. In the upland rice trial, PU and ammonium sulfate were applied with or without a nitrification inhibitor, dicyandiamide (DCD). Based on the results accumulated so far, USG deep placement and SCU application resulted in higher yields than PU best split in about 45% of the irrigated wetland rice sites reporting *(IRRI [1985])*. On the average, it required 30-45% less N from USG or SCU than from PU to bring about a 1 t/ha increase.

Trials have also been conducted on deep placement of either PU or USG using simple machines developed at *IRRI* and compared with USG hand placement. Application by machines resulted in yields more variable than yields obtained with hand placement. This indicates the need to further improve the machine application method.

Azolla showed great potential as a supplementary N source especially in locations where it grows successfully without much care. The biomass produced during land preparation or within 2 weeks and when incorporated before transplanting produced yield equivalent to 30 kg N/ha from urea *(IRRI [1985])*. The combination of urea and a crop of Azolla, however, prduced consistently more yield than Azolla alone applied twice.

Phosphate rock produced grain yields comparable with more soluble superphosphate especially during the wet season. However, during the dry season, soluble phosphate source was slightly superior to phosphate rock apparently because of greater yield increases which require more readily available P during the latter season.

The long-term fertilizer trials suggest that in some sites, N alone remains limiting even for as long as 6-8 crop seasons *(IRRI) [1985])*. However, P response becomes evident only when N is added suggesting that P deficiency could occur sooner except that the effect of P if added alone is masked by N deficiency.

An experiment on P and lime interaction in acid upland rice soils was recently started. No significant results have been reported yet. Preliminary observations, however, suggest that in an Ultisol soil, P is more critical than lime. Lime alone does not improve crop growth while P alone substantially improves plant growth.

Tolerance to acid sulfate soil condition of certain rice cultivars is enhanced by applying 60 kg P_2O_5/ha. Of the 60 test cultivars, only CR 261-7039-236 and IR5741-73-2-3 were rated tolerant to acid lowland conditions under 2 P levels (O-P and 60-P). Eleven of the test cultivars received high rating for phenotypic acceptability at 0 kg P_2O_5 and 21 cultivars at 60 kg P_2O_5 *(IRRI [1985])*.

5. Future programs of the *INSFFER* Network

To maintain the network's relevance and efficiency, undertaking the following activities is considered. These are not necessarily arranged according to importance.

5.1 Uniform characterization and classification of experimental sites.

One difficulty encountered in interpreting the varying results among sites is the lack of information on the physical and biological factors prevailing during the experiment. As shown in Figure 1, there is so much variation in yield response to different urea forms and application methods in irrigated wetland rice. Unless sufficient information on prevailing soil and environmental parameters is availbale, it will be difficult to explain the variations observed. Application of the results to other location will likewise be difficult unless thorough characterization of the sites is obtained. It is essential that sites are categorized based on crop response and soil characteristics. Adoption of the *Fertility Capability Classification (FCC)* developed by *Sanchez et al. [1982]* would be useful since it emphasizes plow layer soil properties which mainly account for the varying crop yields among sites. *FCC* is a soil classification system which groups soils according to their fertility constraints quantitatively. Attemps should also be made, however, to classify the sites according to Soil Taxonomy and correlate it with their productivity.

5.2 Development of resource scarce technology.

Rice farmers of developing countries are increasingly concerned with the continuing price increases of farming inputs and the absence of corresponding price increase in their products. Therefore, it is imperative to continue seeking ways of improving the effi-

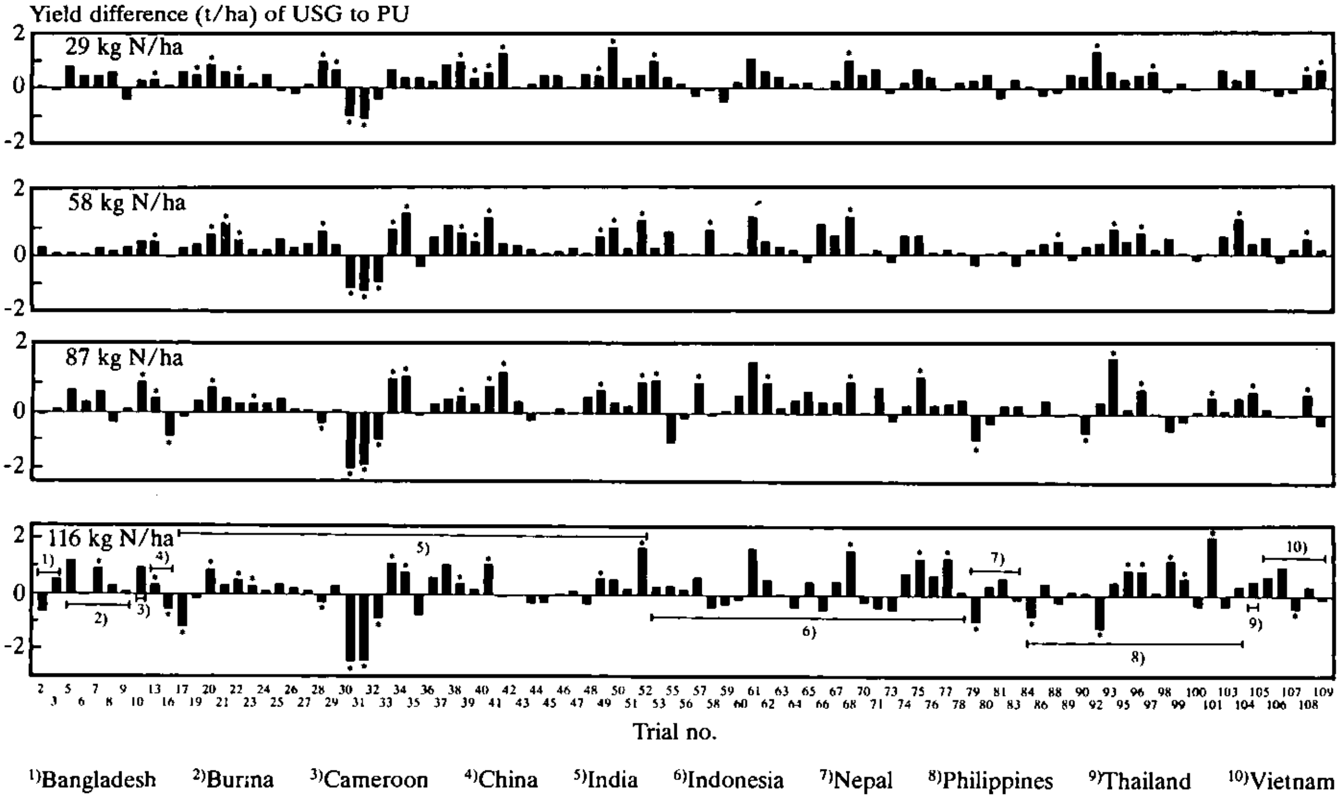

Fig. 1 Significant increase or decrease in grain yield of 93 trials with N as urea supergranules, point placed, compared with prilled urea, applied best split at 4 rates. The Fifth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Rice. 1981-83 (wet season)

ciency of applying inputs and to utilize whatever farm residue or waste is available to cut down production costs. Studies on integrated nutrient management will be intensified to sustain high yields.

5.3 Strengthening the cooperation among the 3 IRRI international networks

Results of the *INSFFER* program can be more relevant if cultivars tested and found by the *International Rice Testing Program (IRTP)* to be suitable under the various environmental conditions were used by *INSFFER* collaborators. Likewise the soil and fertilizer management technology generated by *INSFFER* should be tested by the *Asian Rice Farming System Network*. A move will also be made to coordinate *INSFFER's* activities with other international networks involved in soil and fertilizer management.

5.4 Formation of mini-networks

Because certain countries have specific needs or problem soils, it is advisable to form mini-networks involving only the countries confronted with a common problem. This will enable them to thoroughly deal with the problem. Problems of special environments such as deepwater rice areas, or nutrient deficiencies which are not found in all countries are examples of needs where the mini-network concept is advisable.

5.5 Formation of an Advisory Committee

The group will be made up of representatives from participating national programs preferably *INSFFER* collaborators and scientists from developed countries, international research centers or international organizations. The major role of the committee is to review regularly the network activities and formulate guidelines for future programs.

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Trends in the Use of Potassium Fertilisers in the Humid Tropics

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Summary

This paper reviews the trends in fertiliser consumption especially of K in the humid tropics. The data indicates that there is a relatively large increase in the use of fertilisers. Up to 1982, the increase in the use of N was more than that of K. Nevertheless, there are indications that this trend is likely to change and substantially more potassium is likely to be used in order to maintain and increase productivity.

1. Introduction

The humid tropics covers those areas of the world with high and constant temperature with a dry season of less than 3 and at the most, 4 consecutive months. Additionally, the natural vegetation is tropical forest. Under the hot and humid environment, weathering of soils is rapid and thus there are large areas of ultisols and oxisols in these regions. It is estimated that in S.E. Asia, ultisols covering about 197 million hectares, account for more than 50 % of the land area (FAO-Unesco, 1979), while oxisols with about 50 million hectares, account for 4 % of the land area in the region (*Dent [1980]).* On the other hand, in the humid tropical America, ultisols covering 213 million hectares account for 31.6 % of the area and oxisols with 332 million hectares account for 49.3 % of the total area *(Sanchez [1985]).* Generally, these soils are low in fertility. The poor fertility is brought about by the high aluminium content, low activity clay and also the low organic matter content. The limitations are often reflected in the following properties:—

- ○ low pH (< 5.9) and high exchangeable aluminium
- ○ low C.E.C. and low base saturation
- ● low organic matter content
- ● high phosphate fixing capacity

Generally, the soils are dominated by low activity kaolinite clay and have low organic matter content. Further, the CEC is normally low (< 10 me per 100 g soil). Due to severe leaching and high aluminium saturation, the base saturation hardly reaches 5 %. Hence the soils are especially of low fertility. This is further complicated by the zero or positive net charge of the soils brought about by the variable charge, iron and aluminium oxide/hydroxide colloids and also the broken edges of kaolinite which results in high leaching losses of applied nutrients.

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Thus with population pressure and the demand for more food or alternative income to obtain the food through other agricultural produce, there is a greater demand for land. At the same time, there is a need to increase production. Land is often a limited commodity. Nevertheless, as a result of the pressure for land, new areas being brought under cultivation are often the more marginal soil areas which results in the need for more fertilisers as they would be of lower fertility than soils which had already been brought into cultivation. Generally for food crops, such as rice in Asia, initial cultivations were on young alluvial soils which have a relatively high degree of base saturation. Thus on most of the wetland soils, nitrogen was the primary nutrient constraint. Phosphate and potassium were not considered deficient but they are likely to become constraints. This would be particularly evident with rice as has been demonstrated by *Kemmler [1980]*. Similar situation was also found applicable for growing of wheat, for example, in India (Table 1). It was shown that in these areas, response to potassium was already evident particularly in the first 3 mentioned sites. With continued cropping, soil K levels have declined. *Pushparajah and Bachik [1985]* in their review, showed that on these soils, particularly the ultisols and oxisols in the humid tropics in Asia, for arable cropping of both annuals and perennials, fertiliser was a pre-requisite for improved or reasonable productivity. Similarly, *Sanchez [1985]* has shown that the situation in humid tropical America is akin to that in the Asian region in as far as requirements for fertilisers are concerned.

Table 1. Changes to soil K status in long term experiments[a]

Parameters	Site & Country			
	Ludhiana (India)	New Delhi (India)	Maligaya (Philippines)	IRRI (Philippines)
Crop	Wheat	Wheat	Paddy	Paddy
Cropping period (years)	5	5	7	10
Initial Avail K[b] (mg/100 g)	4.0	7.1	17.8	60.2
Avail K after cropping period a) In NP plots	3.4	5.9	4.3	46.3

a) after *Kemmler [1980]*

b) N – Ammonium acetate extractable

2. Past trends in fertiliser use

The consumption of fertilisers in selected countries in Asia has been based on the *Tennessee Valley Authorities* Report on *«An Appraisal of the Fertiliser Market and Trends in Asia»*. The totals of the various nutrients, *viz.* nitrogen, phosphorus and potassium are given in Figure 1. For the countries under consideration (*viz.* Bangladesh, Burma, India, Indonesia, Malaysia, Philippines, Pakistan, Sri Lanka, Thailand and Vietnam), total nitrogen consumption increased from 1 352 300 tonnes of N in 1967 to 7 329 000 tonnes in 1982; a growth of 5 976 700 tonnes over the period of 15 years, giving an annual growth rate of about 398 500 tonnes, about 29 % per year.

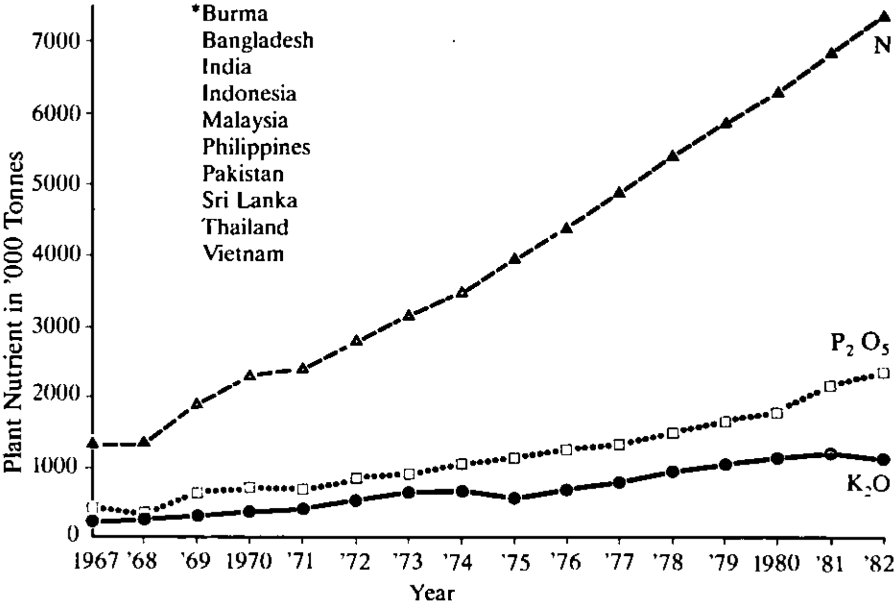


Fig. 1 Trends in fertiliser use in selected regions of Asia (in '000 tonnes)

In the case of phosphate, the increase was from 400 500 to 2 348 000 tonnes P_2O_5 during the same period or an increase of about 1.95 million tonnes or 129 000 tonnes P_2O_5 per year; a growth rate of about 32 % per year. For potassium, the increase was from 243 100 tonnes in 1967 to 1 117 000 tonnes K_2O in 1982. The annual increase was 62 260 tonnes or 25 %. Hence it is evident that the growth rate in the use of potassium fertilisers in this region is lower that of nitrogen and phosphorus.

Malavolta [1984] considered the trends in fertiliser consumption in Latin America for the period 1962-1982. He showed that during this period, the growth rate of nitrogen in Latin America was 659 % or 36.6 % per year. For phosphorus, the growth rate was 700 %, giving an annual rate of 38.9 %. Similar growth rate was also observed for potash, i.e the growth rate of phosphorus and potash were almost identical (Figure 2). In 1981, the consumption of nitrogen was about 3.15 million tonnes, P_2O_5, 2.86 million tonnes and K_2O, 1.86 million tonnes. Within the years 1980 to 1982, there was a decrease in the consumption. The decrease in nitrogen consumed was 4 %, phosphorus 21% and potash 32 %. Nevertheless, the total consumption of NPK nutrient in Latin America was 6.2 million tonnes.

As the main emphasis of this paper is on trends in potassium fertiliser use, the consumption of potassium fertiliser from 1967 to 1982 in selected countries in tropical Asia was considered in detail (Table 2). In 1982, India consumed the largest amount of potassium at 622 000 tonnes K_2O. Malaysia was second, with 194 000 tonnes and Indonesia 133 000 tonnes of K_2O. Most of the other countries, excepting Indonesia and Philippines consumed less than 50 000 tonnes of K_2O.

Table 2. Consumption of K_2O ('000 tonnes) in selected countries

Country	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
Bangladesh	4.1	4.9	7.5	8.5	8.4	11.3	11.2	10.7	14.5	14.5	25.1	27.4	29.3	28.7	28.1	28.0
India	133.7	129.8	154.2	299.4	256.3	312.1	381.0	317.5	227.0	377.3	482.7	560.1	545.5	617.6	670.4	622.0
Pakistan	–	0.2	2.2	1.3	0.7	1.3	2.7	2.1	1.9	2.4	5.8	7.6	9.6	9.2	21.8	26.0
Sri Lanka	38.4	33.4	43.6	25.0	30.4	20.1	31.6	35.8	15.9	29.7	25.4	30.3	34.3	46.0	47.0	45.0
Sub-total	176.2	168.3	208.5	244.2	296.2	344.8	426.5	366.1	299.3	423.9	539.0	625.4	618.7	701.5	767.3	721.0
Burma	3.0	3.5	4.0	5.0	1.4	1.5	0.7	2.3	1.5	1.5	1.9	3.2	2.2	3.1	11.0	11.0
Vietnam	10.5	19.1	8.1	17.3	26.3	24.7	40.4	34.1	35.8	34.2	26.6	27.3	36.4	39.3	22.1	22.0
Sub-total	13.5	22.6	12.1	22.3	27.7	26.2	41.1	36.4	37.3	35.7	28.5	30.5	38.6	42.4	33.1	33.0
Indonesia	4.0	5.5	7.0	8.2	4.7	30.0	40.3	33.0	25.0	30.0	38.4	76.5	84.2	91.0	136.0	133.0
Malaysia	29.0	32.5	29.5	47.5	59.6	80.8	89.3	102.9	133.7	141.0	147.1	168.6	195.8	194.9	173.6	194.0
Philippines	12.5	30.0	40.0	37.7	36.9	38.8	55.6	60.1	48.8	51.5	45.9	56.6	63.7	55.8	60.7	58.0
Thailand	7.9	12.7	10.2	10.8	22.8	42.0	38.4	50.9	39.1	20.5	22.0	30.0	44.1	35.4	35.6	38.0
Sub-total	53.4	80.7	86.7	104.2	124.0	191.6	223.6	246.9	226.6	243.0	253.4	331.7	387.8	377.1	405.9	423.0
Total for region	243.1	271.6	307.3	370.7	447.9	562.6	691.2	649.4	563.2	702.6	820.9	987.6	1045.1	1121.0	1206.3	1177.0

Source: *TVA and FADINAP [1984]*

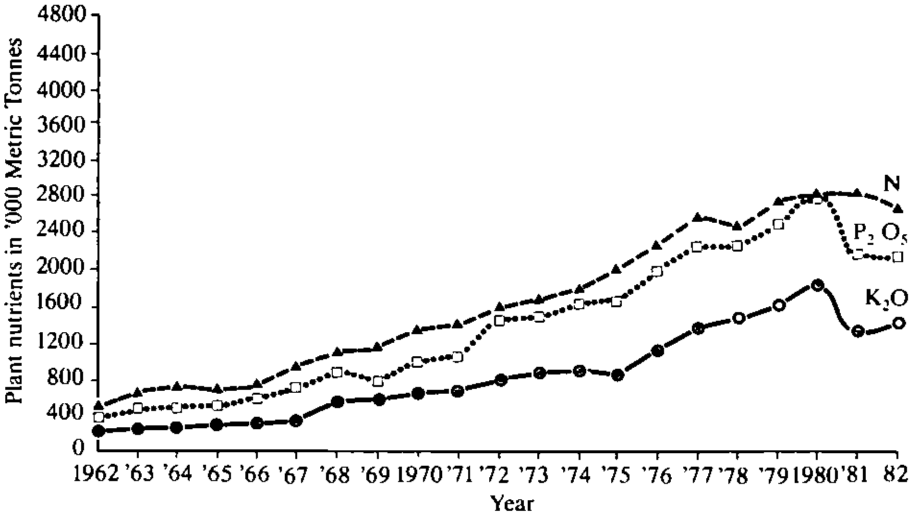


Fig. 2 Fertiliser consumption in Latin America *(Malavolta [1984])*

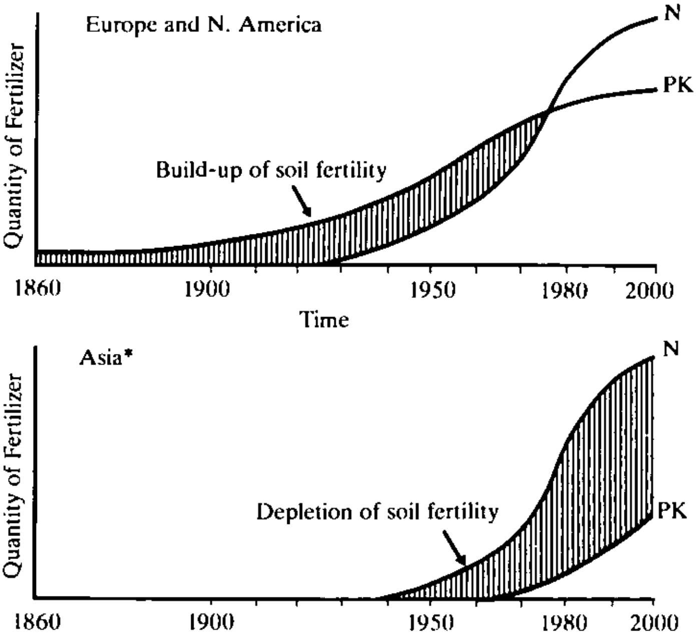
3. Fertiliser consumption by countries

The share of the total fertiliser consumed in tropical Asia is indicated in Table 3. This shows that India, Indonesia and Pakistan account for over 70 % of the NPK consumed in the region and are expected to be the future potential growth areas. A further detailed consideration to assess the fertiliser use and potentials for use would be to evalute the intensity of use of fertiliser or the rate of fertiliser application per unit area of arable land. The values for the selected countries are given in Table 4. This shows that highest use of fertiliser per unit area of land both in the period 1969/1971 and 1981/1982 was Malaysia with 44 and 93 kg NPK respectively during the two periods under consideration. In Sri Lanka, the use of NPK in the earlier period was 50 kg and this grew to 67 kg in the latter period. Indonesia has seen the largest growth in the use of NPK fertilisers per unit area (from about 12 kg in 1969/1971 to 72 kg in 1981/1982).

In Latin America, the growth was from 19.6 kg in 1969/1971 to 44 kg per ha in the latter period.

An important aspect of the consumption of fertilisers would be the nutrient ratios. The fertiliser nutrient consumption ratios for the period 1982-1983 (Table 5), indicate that most of the countries under consideration are using very low levels of potassium; the exceptions in the Asian region being Malaysia and Sri Lanka. On the other hand, the ratio of nutrients used in Latin America may be considered satisfactory.

Uexküll [1984] explains the reasons for this imbalance particularly in the use of excessive N in relation to P and K. This was so because in Asia, the use of N gained momentum in the 1960s, preceding the use of P and K. On the other hand in Europe, K and P fertilisers were used before the nitrogen fertilisers as the inorganic nitrogen fertilisers were introduced or commercially available only in the early 1920s. The contrast is evident in Figure 3. The demand for P and K in Asia has developed partly as a consequence of the increased crop demand for the nutrients, particularly with the intensive use of N.



*Asia minus Japan

Fig. 3 Trends and time sequence in the use of N and PK in Europe and North America as compared to Asia *(von Uexküll [1984])*

Table 3. Share of total Regional fertiliser consumption; 1969 - 1983 (percent)

Country	Year 1969 - 1971	1979 - 1981	1982 / 1983
Bangladesh	3.6	4.2	4.4
India	53.8	56.6	53.8
Indonesia	6.1	11.1	14.0
Malaysia	4.8	4.7	4.2
Pakistan	9.2	11.0	11.4
Philippines	5.8	3.4	3.1
Sri Lanka	2.9	1.6	1.6
Thailand	2.9	2.6	2.3
Vietnam	8.5	2.4	2.9
Other ESCAP countries	2.4	2.4	2.3
Total	100.0	100.0	100.0

Source: *FADINAP [1984]*

Table 4. Average fertiliser nutrient consumption / unit arable Land under permanent crops

Country	1969 - 1971				1981 - 1982			
	N	P_2O_5	K_2O	Total	N	P_2O_5	K_2O	Total
Bangladesh	10	3	1	14	28	13	3	44
Burma	2	1	–	3	9	3	–	12
India	8	2	1	11	23	7	4	34
Indonesia	9	2	–	12	51	16	5	72
Malaysia	16	12	16	44	30	23	40	93
Pakistan	15	2	–	17	41	11	1	53
Philippines	12	5	4	21	21	5	6	32
Sri Lanka	23	10	15	50	35	13	19	67
Thailand	4	3	1	8	7	6	2	15
Vietnam	28	18	6	52	33	5	4	42
Latin America	8.8	6.6	4.2	19.6	17.5	15.0	11.5	44.0
World	23	15	12	49	41	21	16	78

Source: *FADINAP [1984]* and *Malavolta [1984]*

Table 5. Fertiliser nutrient consumption ratio (N = 1) in 1982 / 1983

Country	N	P_2O_5	K_2O
Bangladesh	1	0.43	0.10
Burma	1	0.38	0.09
India	1	0.30	0.15
Indonesia	1	0.34	0.07
Malaysia	1	0.80	1.41
Pakistan	1	0.28	0.03
Philippines	1	0.24	0.25
Sri Lanka	1	0.38	0.55
Thailand	1	0.81	0.17
Vietnam	1	0.15	0.09
Latin America	1	0.85	0.66
World	1	0.50	0.37

At the same time, *Uexküll* has forwarded his theory that use of fertilisers in developing countries is initially limited to a few commercial crops and high value vegetables and tree crops where the NPK is balanced. The second stage is where fertiliser use spreads to food crops. In this way, the consumption of nitrogen moves ahead of the other nutrients. In the third stage, both N and P demands are increasing more, with the P increases at a faster rate than that for nitrogen, and potash needs are found to be evident. In the fourth stage, nitrogen use would be approaching economic and agronomic limits, while with phosphate build-up in the soils, the demand for this nutrient starts levelling off; however the demand for potash grows rapidly. At the final stage, NPK consumption stagnates over time and starts to decline. *Uexküll [1984]* has used these categories and indicated that countries like the Philippines and Thailand are at a stage between Category 1 and 2. Indonesia is at Stage 2, while India is at Stage 3. This would have a bearing on projections for future growth of fertiliser consumption.

Table 6. Estimated percentage share of fertiliser use by major crops in 1975 / 1976 and in 1982 / 1983

Country	Period	Crop / produce				
		Paddy	Wheat	Cotton	Sugar	Others
Bangladesh	1975 / 76	77	–	–	–	Jute / wheat / sugar 10
	1980 / 81	80	–	–	–	Jute / wheat / sugar 14
Burma	1975 / 76	67	–	5	4	– –
	1982 / 83	85	–	2	2	– –
India	1975 / 76	41.4	25.6	5.7	7.1	Groundnuts 2.8
	1982 / 83	40.5	24.2	6.7	8.7	Groundnuts 2.2
Indonesia	1972	61	–	–	–	Rubber, oil palm, sugar 22, Vegetables & maize 13
	1977 / 78	48	–	–	–	Rubber, oil palm, sugar 19, Vegetables & maize 33
Malaysia	1978	9.6	–	–	–	Oil palm 49.8, rubber 26.6
	1980 / 81	14.5	–	–	–	Oil palm 49.5, rubber 22.0
Pakistan	1976 / 77	12	48	16	11	– –
	1982 / 83	10	50	15	8	– –
Philippines	1977	46	–	–	39	Maize 1.7
	1982 / 1983	41	–	–	37	Maize 6.0
Sri Lanka	1975 / 76	34	–	–	–	Tea 42.8
	1982 / 83	48	–	–	–	Tea 22.5, Vegetables 12.9
Thailand	1978	50	–	–	–	Vegetables 7
	1982 / 83	58	–	–	–	Vegetables 12, Fruits 15

Source: *FAO [1984]* and *FADINAP [1984]*

4. Distribution of fertiliser use by crops

It would be of benefit to ascertain the crops on which these fertilisers are used. In most of the countries in the Asian regions considered, paddy accounts for the largest portion of the fertilisers used (Table 6). In Bangladesh, in the 1980/1981 period, 80 % of the fertilisers were used for paddy; in Burma 85 %; in India, paddy and wheat together accounted for 65 % of the total NPK fertilisers used. The only exceptions to a high proportion of fertilisers being used on paddy and cereals was Malaysia where only 14.5 % of the NPK fertilisers in 1980/1981 was used on paddy. A very large proportion, *i.e.* 49.5 % of the NPK was used on oil palm and about 22 % on rubber. In the case of Sri Lanka in 1982/1983 (Table 6), only 48 % of the total fertilisers was used on paddy, while about 23 % was used on tea. This indicates that in trying to evaluate and project fertiliser requirements for this region, these crops would play a dominant role.
For Latin America, *Malavolta [1984]* had shown that the main crops grown were cereals, pulses, roots and tubers, sugar cane, stimulants, fibre and vegetables. In fact, for most of the crops, such as cereals, pulses, root tubers and vegetables, the yields obtained in Latin America were less than 50 % of the maximum yields in other regions. Unfortunately, there is no information available as to the consumption of fertilisers according to the various crops.

5. Food production and role of fertilisers

Another factor to be considered is the need to increase food production and the manner in which the increased food production is to be brought about. *Malavolta [1984]* quotes *FAO [1981]* data based on the study of *«Agriculture Towards 2000»*. The data presented in Table 7 shows that in the Asian region, the increase in agricultural production through increase in cultivated land is minimal with <10 % of the increase being due to increase in new land. However, it is envisaged that about 70 % of the increase of production would be through higher productivity. On the other hand, in Latin America up to the year 2000, 55 % of the increase in production would be through increase in land alienated for cultivation. This particularly emphasises that in Latin America, the continued use of minimum input concept for food production would play a major role during this period.

Table 7. Contributions to increase in Agricultural production in 1975 - 2000

Region	Increase in cultivated land	Crop* intensity	Higher productivity
90 developing countries	26	14	60
Africa	27	22	51
Far east	10	14	76
Near east	6	26	69
Latin America	55	14	31

*Crop occupying land for longer period, *e.g.* moving from shifting to permanent systems or shortening fallows etc.

What are the factors that would play a role in increasing productivity? *Mathieu [1979]* as quoted by *Malavolta [1984]* shows (Table 8) that both in Asia (Far East) and Latin America, average of best responses are well over 70 % and in fact the average benefit / cost ratio of fertiliser inputs was about 5. This implies that appropriate fertiliser use on food crops would be having a beneficial effect.

As stated earlier, particularly in the Asian region, rice is the dominant food crop and accounts for the largest proportion of fertilisers used. Now, in considering productivity increases, it is useful to assess what are the various factors that have contributed to productivity increases in rice in the past. A close scrutiny (Table 9) shows that averaged over the countries under consideration, the contribution by fertilisers in increasing rice production from the years 1965 to 1980 was of the same magnitude as the introduction of high yielding varieties: fertilisers increased production by an average of 24.4 % while high yielding varieties increased production by 23.3 %. Irrigation on the other hand seems to have had the largest effect with about 28.8 % influence. In the contributions of fertilisers to productivity, Thailand experienced the minimum with a 10.6 % increase in production, while India and Philippines had the largest with 30.9 % and 30.8 % increases respectively.

Table 8. Summary of results of fertiliser experiments *(FAO fertiliser programme)*

Regions	No. of Expts. or demonstrations	Average of best responses	Average ratio benefit / cost
Far east	9513	73	5.6
Latin America	10745	99	4.9
All regions	101297	67	4.9

Source: *Mathieu [1979]* quoted by *Malavolta [1984]*

Table 9. Percent contribution of selected countries to increases in rice production from 1965 - 1980 in selected countries

Countries	Factors				Total
	HYV	Fertilisers	Irrigation	Others	
Bangladesh	7.6	23.1	19.6	49.7	100
Burma	34.9	19.1	37.0	9.0	100
India	22.8	30.9	31.9	14.4	100
Indonesia	23.2	19.7	20.4	36.7	100
Philippines	25.9	30.8	24.5	18.8	100
Sri Lanka	23.3	20.8	27.3	30.6	100
Thailand	12.8	10.6	13.6	63.0	100
Total of above	23.3	24.4	28.8	23.5	100

Source: *Amanda Te and Flinn T. C. [1984]*

The use of fertiliser responsive photo-period insensitive varieties from 1966 onwards (*i.e.* variety IR8 or varieties modelled on IR8), has contributed to the yield increase. In 1965 to 1966, only about 42 000 hectares were under these types of varieties. However, in the year 1980/1981, the area was about 32.9 million hectares. With fertiliser responsive varieties being used to a large extent, it would be expected that the fertiliser for the rice fields would also have to be increased. This is reflected in Table 10. The countries showing largest percentage increases in fertiliser use on rice (between 1965 and 1980) were Burma, Indonesia, Pakistan and India. In the case of Malaysia, increases in use of fertilisers was only 143% (Table 10). However, the quantity of fertilisers used per unit area in the year 1980 would be a better indicator of the efficiency of fertiliser used for increased crop production. Table 10 shows that though Burma increased fertiliser used by 1,694% (that is the total fertiliser used); even in 1980, only an average of 10 kg of NPK fertilisers per hectare was used in the paddy fields. The largest use was in Indonesia with 102 kg per hectare. Countries such as India, Malaysia and Pakistan used about 60 kg of NPK fertilisers.

Table 10. Fertiliser use on rice 1965-1980

Countries	('000 t NPK)[a] 1965	 1980	Growth (%) 1965-1980
Bangladesh	17.3 (2)	132.9 (13)	668
Burma	4.7 (1)	84.3 (18)	1694
India	251.1 (7)	2305.9 (57)	818
Indonesia	74.2 (10)	922.1 (102)	1143
Malaysia	18.5 (33)	45.0 (61)	143
Pakistan	7.1 (5)	129.0 (67)	1717
Philippines	26.5 (9)	132.6 (38)	400
Sri Lanka	11.4 (23)	85.0 (104)	646
Thailand	13.3 (2)	153.5 (17)	1054

a) Figure in ( ) = kg NPK / ha

Source: *Amanda Te and Flinn, J. C. [1984]*

What is the impact of such rates of fertiliser use? Table 11 shows that the countries using the most fertilisers generally tend to have the largest yield of paddy. For example Indonesia which had apparently used an average of 102 kg of NPK in 1980, used about 54 kg of NPK in 1981/1982. They obtained yield levels of 3317 kg in 1981/1982 and

3780 kg in the following year. Malaysia which had in the year 1980 used an average of 61 kg, but increased the fertiliser use in 1981/1982 to 104 kg, obtained the next highest yield of 2833 kg in the 1981/1982 period and 2856 kg in the 1982/1983 period. Thailand, which had used 17 kg in 1980 and 1981/1982, obtained average yield levels of 1933 kg in 1981/1982 period and 1835 kg in the 1982/1983 period. The overall average for the developing countries in the *ESCAP* region was 2816 kg and 2990 kg during the 2 years under consideration. The average fertiliser use in the year 1981/1982 was 68 kg NPK per hectare. This therefore clearly implies that fertiliser inputs has a role in increasing productivity and the rates of fertiliser seem to have an effect on the yields obtained.

Table 11. Average fertiliser use on paddy (1981 / 1982) and yield

Countries	NPK fertiliser (kg / ha)	Yield (kg / ha) 1981 / 1982	Yield (kg / ha) 1982 / 1983
Indonesia	54	3317	3780
Malaysia	104	2833	2856
Burma	10	2549	3166
Pakistan	51	2450	2587
Sri Lanka	74	2514	2890
Bangladesh	45	1977	2014
India	30	1890	1851
Philippines	34	2196	2362
Thailand	17	1933	1835
Developing countries (ESCAP)	68	2816	2990

Source: *FADINAP [1984]*

6. Requirements for potassium up to year 1992

For the 10 countries in Asia considered, the easiest method to project the fertiliser requirement is to evaluate the growth rates that had taken place in the preceding years. Two approaches were made; one using the growth rate for the last 5 years for which data is available, i.e. 1977-1982 and the other was to use the growth rate over a longer period of time, *i.e.* 1972-1982. As is evident from Table 12, the growth rates vary for the different periods under consideration. Generally, for Bangladesh, India, Pakistan and Malaysia, the growth rates per year considered over a longer period of time of 1972-1982, was higher than when the growth rates between 1977-1982 were considered. In the case of Vietnam, in fact there has been a decline in the fertiliser potassium consumption. The decline was larger in the period 1977-1982 than in the period 1972-1982. In the case of Thailand, there was a decline between 1972-1982.

When the projections of fertiliser requirement for 1992 are based on the growth rates from 1977-1982, a total of 2 720 000 tonnes of K_2O would be required. However, when the projection is based on the growth rate averaged over a 10 year period, the total K requirement is estimated to be 3 200 000 tonnes of K_2O (Table 12).

Table 12. Growth rates in fertiliser consumption and projection of requirements in 1992

Country	Growth rates of K_2O (% / year)			Consumption of K_2O ('000 t)		
					Projected for year 1992	
	1972 - 1977	1977 - 1982	1972 - 1982	Actual in 1982	Based on growth rates for: 1977 - 1982	1972 - 1982
Bagladesh	24.5	2.2	14.8	28.0	30	70
India	10.9	5.8	9.9	622.0	980	1240
Pakistan	67.2	69.6	185.0	26.0	210	510
Sri Lanka	5.2	15.4	12.4	45.0	110	100
Burma	5.3	94.6	63.3	11.0	115	80
Vietnam	1.5	3.5	1.1	22.0	15	20
Indonesia	5.6	49.3	34.3	133.0	790	590
Malaysia	16.4	6.4	14.0	194.0	320	465
Philippines	3.7	5.3	4.9	58.0	90	90
Thailand	9.5	5.4	1.0	38.0	60	35
Total				1177.0	2720	3200

However, in any final projections, the crop requirements and cropping patterns would also have to be taken into consideration. Earlier (Table 6), it was pointed out that in the 10 countries in the tropics in Asia considered, in almost all the countries with the exception of Malaysia and Pakistan, paddy played a dominant role. Thus the use of fertilisers in paddy will to a large extent be the determinant of the potential use of fertilisers in the future. In order to consider the changes in fertiliser requirements for paddy cultivation, it is pertinent to consider the changes in cultivation practices. Currently, with the high yielding varieties and multiple cropping, often the straw is removed or is burnt in the field. If burnt, it is done in heaps and hence there is a non-effective distribution of the ash and hence the K. In some countries, the straw is removed and used for fuel. With this in mind, an attempt was made to do a fertiliser budget for paddy cultivation in the countries considered (Table 13). Firstly, it is evident that for most of the countries, the average use of NPK per hectare of crop land in 1981/1982 was almost the average of the NPK used in paddy cultivation. It is therefore assumed that the fertiliser nutrient ratios used on paddy were identical to the average use of NPK on the crop lands.

Table 13. Fertiliser inputs and deficits in fertiliser use

Country	Average use of NPK (kg / ha) of crop land (1981 / 1982)[a]	For paddy			
		NPK (kg / ha) 1981 / 1982[b]	Nutrient removed (kg/ha) in crop year 1981 / 1982[c] K_2O	NPK	Deficits of NPK[d] (kg/ha/yr)
Bangladesh	44 (3)	45	43	84	39
India	34 (4)	30	41	80	50
Pakistan	53 (1)	51	54	104	53
Sri Lanka	67 (19)	74	55	107	33
Burma	12 (0)	10	56	108	98
Indonesia	72 (5)	54	73	141	87
Malaysia	93 (40)	104	62	120	16
Philippines	32 (6)	34	48	93	59
Thailand	15 (2)	17	42	82	65

(a) From Table 4. Figures in ( ) = kg K_2O

(b) From Table 11

(c) Based on yields in Table 11. Nutrients removed based on assumption *(v. Uexkull [1984]), i.e.* 1000 kg grain removes 16.8 kg N, 3.83 kg P_2O_5 and 21.9 kg kg K_2O

(d) Deficit = crop removal less amount applied

Based on the yields obtained during the crop year 1981/1982 (Table 11) and using the average nutrient drainage as forwarded by *Uexküll [1985]*, the nutrient removed from the area during the cropping year (1981/1982) has been estimated (Table 13). This clearly shows that in most of the countries, there are large deficits. The deficits in the year under consideration was a minimum of 16 kg NPK for Malaysia and as high as 98 kg in Burma. If the nutrient deficits per year are projected for a long period, then it would not be unlikely to observe very rapid declines in yield due to loss in fertility. An important

feature is the large amounts of nutrient K being removed. Almost 50% of the nutrient drained is in the form of K. Therefore, it is imperative that to sustain productivity, let alone increase the productivity to meet demands for this staple crop, fertiliser use should be increased. From the information presented in Table 13, it is evident that potassium is a major nutrient, the use of which in rice cultivation in particular in South-East Asia, would have to be increased. Using this assumption and requirements of other dominant crops, estimates of the K requirement in 1992 was evaluated. The assumptions and calculations are given in Appendix 1. This shows the projected requirements would be: Bangladesh 76000 tonnes K_2O, India 1130000 tonnes, Sri Lanka 75000 tonnes, Burma 60000 tonnes, Indonesia 400000 tonnes, Malaysia 320000 tonnes, Philippines 90000 tonnes and Thailand 80000 tonnes. This gives a total of 2.2 million tonnes of K_2O as the requirement. Generally therefore, the expected consumption of potassium (as K_2O) in the 10 countries in the Asian tropics would range from about 2.2 million to 3.2 million tonnes in the year 1992. The actual consumption would be dictated by crop production which is dependent on weather conditions. In the case of countries such as Malaysia, Thailand, Philippines and Indonesia which are also growing industrial crops, such as oil palm, rubber, sugar cane and coconuts, the consumption of fertilisers would again be dependent on the price that the agricultural produce obtains in the international markets. Nevertheless, it could be safe to project that a minimum of 2 million tonnes of K_2O would be consumed in the 10 countries under consideration in the Asian region.
For Latin America, *Malavolta [1984]* estimated that the annual nutrient export or removal was about 30 kg of N, 10 kg of P_2O_5 and 20 kg of K_2O per hectare. With 1.62 million hectares of arable land under cultivation, the total removal of nutrients is:—

$$N = 4860000 \text{ tonnes}$$
$$P_2O_5 = 1620000 \text{ tonnes}$$
$$K_2O = 3240000 \text{ tonnes}$$

In 1980, the total consumption of the respective nutrients, N, P_2O_5, K_2O was 3150000 tonnes, 2860000 tonnes and 2130000 tonnes. Based on this consideration alone, there was a deficit of 1.1 million tonnes of K_2O. Thus merely in order to replenish the current nutrients removed (ignoring leaching losses etc.), the consumption of potash would have to be increased. With the view to correcting the shortfall and to further increase productivity, the amount of K_2O used by 1990 would have to be at least double that of the amount used in 1980. The consumption should therefore be at least about 4.2 million tonnes of K_2O.
On the other hand, growth in consumption of K_2O in Brazil from the year 1962-1963 to year 1980, averages 39% per year. If this annual average increase is maintained, the consumption by the year 1990 should be 8.3 million tonnes of K_2O. Based on economic and other considerations, the earlier value of about 5 million tonnes of K_2O is a more likely consumption figure for the year 1990 in Latin America.

7. Conclusion

In the countries considered in Asia, growth in consumption of N, P_2O_5 and K_2O has been in the order of 16.3, 16.7 and 10.9% per year in the period 1972-1982; the growth rate for K being lower than that observed for N and P. In Latin America, the growth rate for K was slightly larger than that for N.

Evaluation of export of K in crops indicates the likelihood of reduced soil fertility setting in, as the nutrient K added was less than that removed.

In the humid tropics, rice cultivation alone accounts for a major portion of the fertilisers consumed.

It is projected that the 10 countries in Asia would consume at least 2.2 million tonnes of K_2O by 1992, while in Latin America, this is likely to be about 5 million tonnes.

Acknowledgements

I would like to thank the *International Potash Institute for* the invitation to present this paper. The valuable assistance of Dr. *von Uexkull,* Dr. *A. von Peter* and *H. Künzli* in providing some of the references is acknowledged. The *Director* and *Board* of the *Rubber Research Institute of Malaysia* are thanked for the permission to present the paper.

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Appendix 1. Estimation of projected consumption for K_2O in the year 1992 based on crop requirements

Country	Crop	Assumptions Use of K_2O (kg/ha) 1982	 1992	Use in 1982 '000 t K_2O	Projected 1992 '000 t K_2O
Bangladesh	Rice	3	9	22.4	70
	Other crops	?	?	5.6	6
	Total			28.0	76
India	Rice	4	12	250	750
	Others	?	?	372	380
	Total			622	1130
Sri Lanka	Rice	19	38	21.6	40
	Tea[a]	43	90	10.0	20
	Others	?	?	13.4	15
	Total			45.0	75
Burma	Rice	0.8	5	9	55
	Others	?	?	2	5
	Total			11	60
Indonesia	Rice	5	15	64	200
	Others[b]	–	–	69	200
	Total			133	400
Malaysia	Oil palm			100	140
	Others[c]			94	180
	Total			194	320
Philippines	Rice	6	12	24	50
	Others	–	–	34	40
	Total			58	90
Thailand	Rice	2	6	22	60
	Others			16	20
	Total			38	80

(a) *Kemmler [1984]* showed that the low rates of K used in Sri Lanka was a contributor to low yields.

(b) In others, it is projected that area under oil palm and rubber will increase substantially.

(c) Use of fertilisers in cocoa, rice & rubber is projected to increase. Currently, about 500 000 ha of mature rubber does not use fertilisers. These areas are to be developed as mini estates.

Co-ordinator's Report on the 4th Session

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Research and Extension in South East Asia and their Implications for the Use of Potassium

In most parts of South East Asia, agricultural production can and must be pushed up to meet the food, fibre and fuel needs of its growing population and for export. Crops grown in this region are of two kinds. In the first category are the high value plantation crops like tea, coffee, rubber and palm-oil. Much of these are grown on highly leached soils, known to be deficient in potassium. Although poor in native fertility, these are carefully nurtured since these are owned by resourceful, knowledgeable farmers or business houses. Farming there is done for profit and in such situations, fertilizers and potassium are seldom neglected. Questions of potassium use in these areas revolve around a moving target of rising yields. Thus, although average yield of tea in South India now is approx. 2000 kg, many tea estates produce 4000 kg made tea. Theoretical optimum is in the neighbourhood of 20 tons, but 30-40 per cent of this theoretical optimum may become achievable in the not too-distant future. In the second category are the cereals, edible oils other than palm oil and legume grains. Grown on a variety of soils and by relatively resourceless farmers, who own small chunks of lands, these crops suffer for want of adequate nutrition and other inputs. *Von Uexküll* has drawn attention to the problems of soil fertility management in recently cleared lands. Addition of plant nutrients to these soils for obtaining increased yields appears to be an essential step in most situations. Since fertilizers are non-renewable resources requiring expenditure of energy to produce and transport, they are expensive and there «must» be sufficient economic incentive for the farmer to apply them. So long as yields are low, nitrogen generally is the only fertilizer nutrient which is economically attractive to use. As yields rise, with the availability of irrigation or better water management, seed of high yielding crop cultivars, and appropriate Government pricing policies, needs for phosphorus and potassium are increasingly felt.

Lin Bao, Liang De-Yin and Wu Rong-Gui have discussed in their papers, data from large number of experiments on major crops carried out in recent years in parts of China. It is very interesting to learn that yields of all crops – food, fibre, sugar, oil and fruit – increased with the application of potassium, and that the beneficial effects of potassium on the yield of these crops were associated with perceptible gains in plant height, number and size of productive heads, grain weight and quality in food crops; bolls per plant, their reduced shedding and better size and quality in cotton; yield of cane and sucrose content in sugarcane; plant height, branches and fertile pods per plant in rape seed; yield in-

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creases due to potassium application were invariably large in hybrid and high yielding varieties than in local, tall rice varieties, and grain quality in terms of total amino acid content also increased along with the yield. *Xie Jian-Chang* presented a similar picture in his paper on the potassium status of soils in South China. Emanating from a country where all agricultural wastes are carefully recycled, these observations are very significant.

In his introduction to the colloquium, *Cooke* alluded to large nutrient removal of both phosphorus and potassium, consequent upon introduction of high yielding rice cultivars and stressed on the need for careful assessment of the soil reserves of K, so that K fertilizer gets applied when soil reserves are insufficient.

In discussing their results, *Lin Bao, Liang De-Yin and Wu Rong-Gui* stated the names of provinces and the locations where the experiments were conducted, but information on soil characterization, variability in K supply characteristics of the general area and the distribution of sub-areas; significantly differing from each other in these characteristics, were not presented.

In describing the FAO experience in South and East Asian countries, *Ho* stated that in Bangladesh, crop responses ranged between 4.4-10.8 kg rough rice per kg K_2O but that in one series of experiments, exceptionally high responses of 24 kg grain/kg K_2O were obtained. His results on the Eutric Gleysols and Calcic Gleysols and Gleyic Cambisols were also interesting. The first group of soils had about 17.5 FPI against 10 of the second group, with an application of 40 kg K_2O/ha. It is essential to identify soils which differ in FPI as widely as 4, 10, 17 and 24; Mapped with an acceptable degree of confidence, it should be easy enough to extend the use of potassium on the last 3 categories of soils with advantage to all concerned.

Greenland's observations concerning experimental approaches in defining the needs for potassium are, therefore, unexceptional. Development agencies charged with the responsibility of extending the results of research often feel handicapped owing to inadequate definition of responsive soils. *Greenland* has drawn attention to the fact that though the exchangeable potassium content correlates moderately well with potassium supply to crops, yet crop requirements considerably exceed the exchangeable potassium content of soils and hence the rate at which non-exchangeable reserves become available must be taken into account together with accretions through irrigation water for better understanding of the responsiveness of soils to applied potassium. The importance of field experiments to define the needs for potassium and various nutrient interactions is also appropriately emphasized. Some of these experiments must be long-term, which conducted on well characterized soils, should permit confident extrapolation in time and space. However, their number also should correspond to various categories of potassium availability. Too few experiments, if they happen to be located in high K situations, may convey an erroneous impression and lead to questionable judgements.

Potash Research Institute of India made a modest beginning in 1983 for laboratory characterization of bench-mark soils from soil series widely occuring in intensively cultivated agricultural areas. Thus, it becomes possible to examine together several estimates of potassium availability and permit a better understanding of potassium supplying characteristics of soil series and soil types. Accordingly, it was found that two alfisols, which occured in the area earlier regarded to possess a modest supply of K, were fairly low in potassium availability. *Grimme* in his paper on the dynamics of potassium in soil-plant system pointed out that differences in soil texture could result in highly dissimilar reduction in solution K concentration around the plant roots. When soils are adequately characterized according to soil taxonomy into soil series and soil types, the parameters of soil physical conditions like moisture holding capacity, pore size distribution for which attention was drawn by *Walsh,* are integrated and it becomes possible to translate the results of *S.A. Barber's* or *H. Grimme's* observations into fertilizer recommendations. Thus, potassium can be used most profitably in the soils which are adequately defined. This would instil much greater confidence in the minds of the farmes and the marketeers. Hence the need to encourage coordination between scientists engaged in soil fertility and soil survey.

Mamaril has described the *INSFFER programme* to illustrate how scientists from several nations cooperate to develop collaborative research trials. He mentioned advantages and disadvantages of a coordinated programme. With time and understanding, disadvantages can be minimized or even eliminated, and advantages of harnessing the talents and facilities of developed countries or international agricultural research programmes retained to help solve essentially national problems. *IPI* and *PPI missions* have done much in the past, by way of injecting purposeful ideas and funneling assistance to do relevant work. Both institutes have made strong suggestions for maximum yield research. Efforts to develop meaningful options for obtaining yields all along the ascending yield curve on well characterized bench-mark sites, should be invigorated. This will help meet the challenges of crucial decades ahead.

Puspharajah has reviewed the trends in fertilizer consumption, especially potassium in the humid tropics. He has drawn attention to a relatively large increase in the use of fertilizers and pointed out the possibility of substantially higher potassium requirements in the future, in order to maintain and increase productivity. Evidently, many countries need better infrastructure by way of transport, credit facilities and pricing policies, besides dissemination of agricultural technology to support a more productive agriculture. This demands a shared approach between the agricultural and social scientists and the decision makers in individual nations. *Amon* has already dwelt at considerable length on the need for continuous education of policy makers.

Considerations of maintaining a favourable trade balance and protecting the environment will goad the nations to do an effective recycling of wastes in agriculture. Chinese experience and careful experiments both show that the current and emerging needs of the people in the densely populated countries are such that in the foreseeable future, the needs of fertilizer and potassium would keep growing.

When soils are adequately characterized in respect of their potassium supplying capacities, it would enable the farmers to make more intelligent least-cost options in their drive for maximizing yields. In the long run, such a research is neither costly nor more time-consuming. It only needs planning and organization. But the rewards for such an effort are attractive; the results from the laboratory and the experimental fields can be extended faster.

Chairman of the 5th Session

Dr. *G. W. Cooke,* Honorary Scientist, Rothamsted Experimental Station, Harpenden, Herts/United Kingdom; member of the Scientific Board of the International Potash Institute; Chairman of the 19th IPI-Colloquium

5th Session

Conclusions

The Role and Importance of Potassium in the Agricultural Systems of the Humid Tropics: the Way Forward

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Summary

The humid tropics have the potential to produce very high yields of agricultural produce because their climates encourage plants to make the maximum possible growth. These potentials are only achieved when all constraints to plant growth are removed; most important is the constraint imposed over large areas by inadequate supplies of plant nutrients in the soils. The Colloquium held in Bangkok in November 1985 examined the evidence available in southeast Asia on the need to increase the use of fertilizers, and particularly of potassium fertilizers, to overcome the nutritional constraints which now limit productivity. Changes in the amounts of fertilizers used in Thailand are typical of much of the region; there have been very large increases in the amounts of nitrogen (N) used, some increase in the phosphate (P) used, but very little change in the potassium (K) used. The lack of balance between the N and K fertilizers used is a cause for concern. The Colloquium had the task of assessing the scientific, agricultural, and economic justifications for increasing the supply of K, and discussed how these fertilizers should be used efficiently to provide adequate returns to the farmers who apply them and to the nation that supplies them. The *Conclusions of the Colloquium* should help in developing policies and recommendations that will increase productivity to the required levels while reducing costs of unit produce so that food costs are minimised and competitiveness in export trades is improved. To secure the best returns from increased fertilizer supplies will also require attention to problems associated with land and soil management and the availability of irrigation, and also socio-economic problems such as prices of crops and fertilizers and the provision of credit to help farmers to apply improved technologies.

The first need is to develop fertilizer policies at both national and local levels which are based on nutrient balances in the whole agricultural system and on the properties of the soils used and the crops that are grown. Nutrient balances for Thailand are given as an example of a national study. The agricultural products that are exported from Thailand remove more potassium than is applied in the whole country. The total amounts of K which would be used if current recommendations were put into practice for the important arable and plantation crops are less than the amounts taken up by these crops but are about 20 times greater than the total amounts of K used as fertilizer in the whole country. The risk of serious nutritional deficiency causing reductions in yields is much greater for K than for N and P while fertilizer use continues at present levels.

Local nutrient balances are essential for developing advice to farmers. Results of long-term experiments on the cropping systems used assist in constructing these balances. Account must be taken of local practices and factors such as soil type, the return of nutrients in crop wastes and manures, the amounts supplied by irrigation waters, and possible losses by leaching and surface run-off.

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The intensification of agricultural systems to achieve production nearer to recognised potentials will often involve changes in the farming systems and the plant materials grown; it will always involve practices and inputs to overcome constraints caused by shortages of water and nutrients and by weeds, pests and diseases. Of these inputs fertilizers to supply extra nutrients are the most important as inadequately nourished plants cannot respond fully to other inputs. High-yielding varieties of crops will be grown; these varieties take up much more K than traditional varieties do and require correct balances between NP and K fertilization. Multiple cropping systems can greatly increase production but to achieve this requires calculations of the nutrient balances for the system. Experiments in India have shown that current fertilizer recommendations applied to multiple cropping systems have resulted in very serious deficiencies of potassium. Where root crops are grown in tropical systems it must be recognised that they remove considerable amounts of nutrients, and especially large amounts of K from the soil. Cassava is notable in this respect and if it is not adequately fertilized it removes so much K that following crop yields are diminished. Adequate fertilizing also helps crops to resist diseases and pests.

Export crops are very important sources of national prosperity in many regions of the humid tropics. Thus tapioca (from cassava) is a very important export from Thailand and from Brazil. These exports remove large amounts of nutrients from the country and these must be replaced by fertilizers. The nutrition of tea for export from Sri Lanka and from South India is discussed. Considerable increases in the total nutrients applied, and in the $N:K_2O$ ratio (now 1:1) in India greatly increased average yields in the 1955-1980 period and they are now twice as large as average yields in Sri Lanka where there has been little increase in the quantities of fertilizers used and the $N:K_2O$ ratio is unchanged at about 2:1.

When tropical forests are cleared for crop production nutrient balances in soils and cropping systems must be studied. Continuous cropping can provide good yields provided adequate fertilizer is applied, and large amounts of potassium will be needed. High inputs to these systems are essential; if minimum inputs are applied the land resources will deteriorate and may be destroyed.

In assessing the need for fertilizers the interactions that exist between nutrients and other inputs must be recognised. These interactions build up yields and increase the efficiencies of the inputs; for example applying fertilizers with irrigation increases water use efficiency, and the water increases the efficiency of the fertilizers.

Estimates of the future use of fertilizers were presented to the Colloquium. The best estimates are made by calculating nutrient balances, taking account of the requirements of crops and the cropping and marketing systems used. Assessments were made for the croplands of eight countries in southeast Asia which used a total of 1.1 million tonnes of K_2O in 1982; in all the countries the quantities of N, P and K applied were much less than the amounts the crops removed. To remedy this situation it was estimated that a total of 2.2 million tonnes of K_2O will be required in 1992. In Thailand, where 38000 tonnes of K_2O were used in 1982/83, it was estimated that 80000 tonnes of K_2O will need to be used by 1992 to maintain agricultural productivity and therefore national prosperity. An estimate for Latin America, where 2.1 million tonnes of K_2O were used in 1980, was that 5 million tonnes will be needed annually by 1992.

The research on soils and crops which is required to support the intensification of production and the efficient use of fertilizers was discussed. It is necessary to have an adequate survey and classification of the soils of a region to plan cropping and to aid the transfer of new technologies from field experiments to farmers' land. The *Fertility Capability Classification* system seems to have considerable merits for this purpose. Full information on soil composition, including measurements of minerals present and available nutrients, will be required to develop logical fertilizer policies. Long-term field experiments of a multidisciplinary character need to be established on the major soil types in each country. These experiments will guide extension work to help farmers by providing data on nutrient cycles and on responses to fertilizers and other inputs (such as irrigation or pesticides), and on the interactions between these inputs. There is a case for establishing coordinated international schemes of experiments testing fertilizer-K as has been done with N-fertilizers used for rice. Experiments on special topics, such as timing of application of K-fertilizers, will also be needed.

The field experiments will also provide working material for other research that is required to determine the best methods of soil and plant analysis which are needed to diagnose deficiencies and establish advice to farmers. In particular work is needed on methods for estimating the reserves of potentially-useful potassium in soils and subsoils. Work in the field of crop physiology is needed to aid understanding of the means by which fertilizers raise yields and of the nutrient balances that promote best growth.

The papers presented to the Colloquium showed that the soils of southeast Asia rarely contain sufficient potassium for the continuous production of yields near the economic maximum. K-fertilizer increased yields in most of the experiments reported and the value/cost ratios (VCRs) were often so large that the work indicated that using K-fertilizers would be very profitable to the farmers. China was a good example of a country where K-fertilizers have been increasingly needed as agriculture has been intensified by using high-yield varieties, multiple cropping, and increased amounts of N and P fertilizers.

While most research on fertilizer use has been done on arable and perennial crops there is an increasing interest in the tropics in the production of forage for livestock; at present animals produce rather little because their food is often limited in quantity and is of poor quality. Improved animal production will require the use of fertilizers and lime to provide minerals for both plants and animals and also to encourage the growth of legumes which will fix nitrogen and so improve the whole of the pasture.

Economic aspects of the use of potash were examined by using the results of the *FAO/Thailand Fertilizer Programme Project* in which 271 experiments had been made on farmers' fields, covering the main soil and climatic conditions of the country. Such experiments are valuable in identifying areas of soils deficient in potassium and in relating the K-status of the soils to crop responses to fertilizers. These experiments in Thailand and similar experiments in other countries of southeast Asia showed that responses to K-fertilizers occured on all types of crops in all the series of trials that were reported. These responses also showed that VCRs were positive indicating that using potash would bring considerable profit to farmers. Whether farmers can put into practice advice on the use of fertilizers depends very much on the economics of the situation as determined by fertilizer costs and the prices farmers receive for the crops they grow. The success of a fertilizer policy based on nutrient balance studies and on experimental results will depend on its acceptance by farmers and their decisions will depend on the crop and fertilizer prices which determine the size of the return they receive on their spending on fertilizers. Several international studies have shown that the highest fertilizer usages and the highest national average yields are recorded in countries such as Korea and Japan where the crop/fertilizer price ratio was most favourable to the farmer. Where the ratio is much less favourable, as in Philippines and Thailand, farmers use much less fertilizer and average crop yields are much smaller. Although N-fertilizers often have an immediate effect on crop growth it does not follow that applying N is more profitable than applying K. Thus in one study in India the returns from expenditure on K-fertilizers for gram and for sorghum were several times larger than the returns from using N and P fertilizers.

The evidence presented to the Colloquium and discussed there indicated that Governments should be aware of the constraints to the use of fertilizers, and particularly the use of potassium, since these constraints could become obstacles to achieving national plans to produce enough food for the local population and to provide products for industry and exports. These constraints include lack of credit for farmers to adopt inputs such as fertilizers, lack of other inputs such as water for irrigation, lack of information on crops and soils, lack of supplies of fertilizers in remote areas, and unsatisfactory crop/fertilizer price ratios. Social and economic factors that lead to these constraints should be remedied by action by Governments which should also support research on soil and crop systems and then ensure that the results of this work are applied to practical farming.

1. The expansion of agricultural production

It is generally agreed that in many countries expansion of the amounts of food produced will largely depend on increasing the production from land that is now cropped since the areas of land that are available for conversion to agriculture are limited. In his Introductory paper to the 19th IPI-Colloquium *Yookti Sarikaphuti* described the present levels and future trends in agricultural production in South East Asia. He stated the directions of policy to improve productivity in Thailand required to implement the *Fifth National Economic and Social Development Plan (1982-1986).* On technical aspects of the policy he wrote as follows:

«Restructure the agricultural production process by shifting from extensive agriculture to «intensive agriculture», *i.e.,* placing a heavier emphasis on yield improvement. This could be achieved by increasing the efficiency in the utilisation of land in both irrigated areas and non-irrigated areas, water resources, and forestry resources to give maximum economic returns, including the conservation of natural resources to reduce their deterioration. Furthermore, the government will promote the cropping pattern appropriate with soil quality and will provide necessary inputs like fertilizer, high yield seeds, and credit simultaneously with appropriate production technology in order to allow farmers to increase agricultural yield and rural labour utilization».

Other policy questions dealt with by *Yookti* were concerned with prices and with economic and social matters. Comprehensive development measures were planned to improve the efficiency of using natural resources, particularly water, and land and forests. Research and extension would be speeded up using modern technology. Credit would be provided to encourage farmers to use the new technologies because: «Adoption of new production technology by farmers in Thailand, (like farmers elsewhere) depends largely on economic incentives rather than on yield incentives alone. The level of basic knowledge and the economic status of farmers are major constraints to the acceptance of technology and its applications».

All developments to improve the productivity of agriculture will require effective management of water and land resources, the use of improved varieties of crops, and the use of pesticides and fertilizers. Certainly the increased yields needed will not be achieved unless the supplies of nutrients are adequate. My purpose here is to indicate how we can assess the need for increased supplies of fertilizers in a country, and then to discuss how we can ensure that these fertilizers are used efficiently so that they bring adequate returns to the farmers who use them and to the nation.

It is appropriate to draw attention to the relevance of the major points that I shall make to the country which hosted the Colloquium. I do hope that our conclusions will help those who are responsible for the planning of agricultural productivity in Thailand to develop policies and recommendations that will increase productivity to the required levels while reducing costs per unit of produce so that competiveness in the export trade is improved.

Fertilizers have been a major input to agricultural development in Thailand for many years. The changes which have occurred during the last 20 years in the total amounts of nutrients used are shown in Figure 1. The amounts of nitrogen used have increased enormously and the phosphate used has also increased considerably, but the increases in the potash used have been much smaller and, as was pointed out in the Introduction, the amounts used are much too small to match the large amounts of N-fertilizers that are available. *FAO (1983)* reports that in 1982 the amounts of fertilizers applied in Thailand on average of the whole area of arable and permanent crops were 9.5 kg/ha of N, 6.9 kg/ha of P_2O_5, and 1.9 kg/ha of K_2O; the average figures for Asia as a whole were 50.0, 16.9, and 5.6 kg/ha respectively of N, P_2O_5, and K_2O.

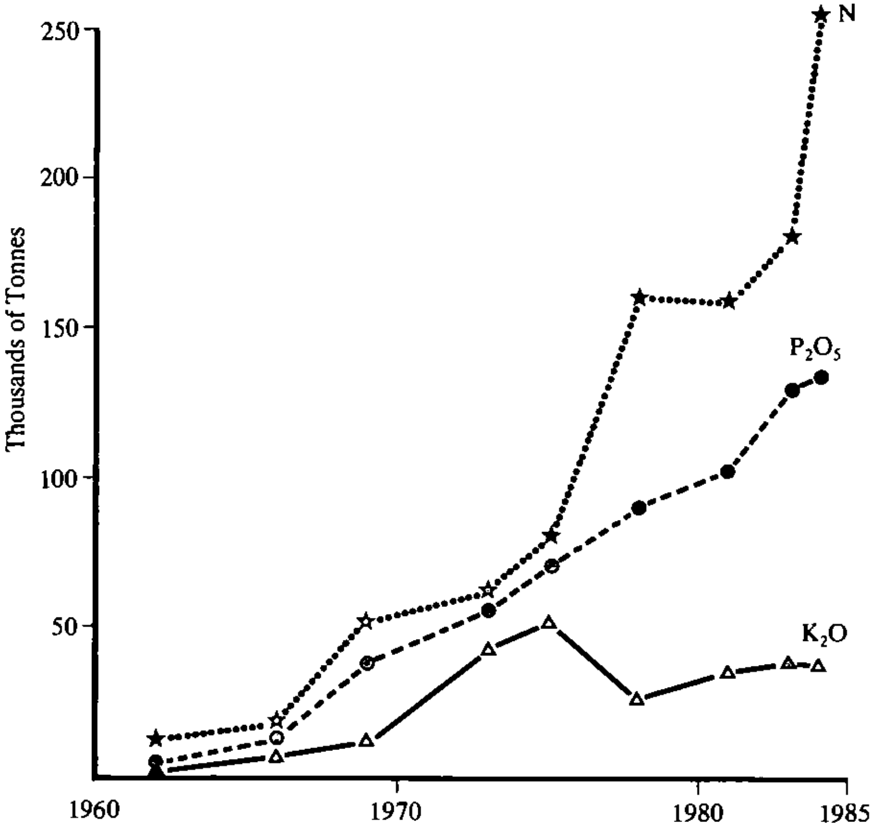

Figure 1. Changes in the use of fertilizers in Thailand, 1962-1984 (data from Fertilizer Yearbooks published by (FAO)

Reasons that have been stated as being responsible for the relatively low use of fertilizers in Thailand are:

1) Environmental problems of climate, soil, topography and the availability of irrigation. 2) Socio-economic problems such as fertilizer prices, low prices for farm products, land tenure and tradition. 3) Technical problems which require increased research and the facilities to extend the results to farming. Apart from the chemical problems that we are aware of, the soils in this region have physical problems, being sensitive to both com-

paction and erosion; recommended practices are to maintain a constant cover of organic mulch and to minimise disturbance of the soil. In this context *Boonyaruk Suebsiri [1984]* gave an account of soil conservation in Thailand. 17.2 million hectares, that is 33% of the country's area, has been moderately to severely eroded, particularly in sloping uplands. It is estimated that 27 million tonnes of sediment is lost annually. This is a serious matter as topsoil is lost in erosion and this soil contains much organic matter and plant nutrients, including potassium. If we assume that most of the erosion is from upland soils, and that on average the content of total K in the soils is 2000 ppm (the paper to the Colloquium by *Samnao Phetchawee et al* reported the wide ranges of total K in Thailand soils) the annual loss will be 54000 tonnes of K (equivalent to 65000 tonnes of K_2O which approaches twice the amount of fertilizer-K_2O used in 1982). The author states «This insidious loss of soil to the farmers in the country is a problem that will keep them poor unless adequately addressed. The farmers are poor and cannot afford to replace lost nutrients».

I will now discuss the activities which I think are required to ensure efficient and profitable intensification of agricultural production by the use of more fertilizers, with special reference to potassium — the subject of the Colloquium held in Bangkok.

2. Fertilizer policies at national and local levels

2.1 National policies

The first need is to develop a national fertilizer policy since many of the scientific and agronomic questions that will arise must be discussed against the background of economics and public policy. The overall need for the production of crops to provide food for the local population, for industrial processing, and for export, will indicate the yields that are needed. Soil capability assessments, which I will discuss later, will indicate where this food is best produced; these assessments aided by studies on the crops and soils, together with the results of long-term field experiments, will show how much fertilizer is required to initiate the improvement in productivity that is needed. To ensure that the fertilizers are used efficiently, and that soil fertility is maintained, will require more detailed and continued studies on the nutrient balances and work on soils and crops. In planning the long-term maintenance of soil fertility to produce the maximum economic yields it is essential to make studies of national nutrient balances. These balances will guide decisions on investments in fertilizer factories, on imports, and the exploitation of local mineral resources to supply nutrients.

2.2 Nutrient balances in Thailand

I have already referred in my Introduction to the Colloquium to the large amounts of nutrients that are removed in produce that is exported and have shown that the exports from Thailand remove four times as much potassium as is used as fertilizer in the whole country. I have pursued this subject further by calculating the amounts of nutrients removed in the major crops grown in Thailand.

2.2.1. Arable crops

I used the data for Thailand published by *FAO [1985]* showing the areas grown and the production of each crop. The calculations were restricted to the ten crops which occupied more than 100000 ha each in 1984; these crops are rice (paddy), maize, sorghum, cassava, (dry) beans, soybeans, groundnuts, seed cotton, sugar cane, and fibre crops (jute and others). These ten crops occupy 14588000 ha, which is 84% of the arable area of Thailand. The results of these calculations are detailed in Appendix 1, and the total nutrient uptakes are summarised here in Table 1. If, for the present, we ignore the other arable crops and the plantation crops grown in Thailand we can say that the fertilizers used in the whole country supplied 37% of the N, 48% of the P, and only 4% of the K, taken up by these 10 crops. It is clear that the risk of serious nutritional deficiency causing reductions in yields is much greater for K than for N and P while the fertilizer use continues at present levels.

This situation for the ten most important crops was further examined by calculating the amounts which would have been applied if current recommendations given by *De Datta* (this Colloquium) for rice, and by *Ho and Sittibusaya [1984]* for the other crops, were applied. The total nutrients recommended for the areas of crops given by *FAO [1985]* are also summarised in Table 1. The recommendations made for the crops would have supplied more N and P than the total amounts taken up, but only 83% of the K uptake. Comparing the totals of the recommendations with the amounts of fertilizers used in Thailand in 1983/1984 we see that the total amounts of fertilizers used at present would supply only 19% of the N, 35% of the P, and 5% of the K that would be recommended.

Table 1. Amounts of nutrients taken up by the ten most important arable crops grown in Thailand in 1984, the amounts recommended for these crops and the fertilizers used in 1983/84.

	N	P_2O_5 tonnes	K_2O
Removed in total crops	683861	282409	940726
Amounts recommended	1323845	381740	784415
Fertilizers used in country	255000	135500	36800

2.2.2 Plantation crops

The calculations noted above have ignored the minor arable crops (occupying 16% of the arable area and which include crops such as the heavily-fertilized tobacco occupying 91000 ha [0.5% of the total arable area]). Some account must be taken of the large area of plantation crops. *(FAO [1985]* states that «permanent crops» occupy 1970000 ha, equivalent to 11% of the arable area). For some of the plantation crops Appendix 2 gives total production in 1984 recorded by *FAO,* and estimates of the nutrients removed in these yields. The total amounts of nutrients removed from the land by the 1984 crops were equivalent to:

	Tonnes
N	18864
P_2O_5	7181
K_2O	28982

These are only small fractions of the amounts removed by the arable crops shown in Table 1; nevertheless these removals are important in the areas where the perennial crops are grown.

2.3 Local nutrient balances

Extension workers should be prepared to calculate nutrient cycles for the cropping systems on farms in the areas they serve. Much guidance in constructing balance sheets will be given by the results of long-term experiments. *Sekhon* and *Subba Rao* indicated to the Colloquium the value of such studies of input/output relationships in relation to the K-fertilizer used in south India. *Ho* showed how essential it is to secure balance in fertilizer application; the results of experiments on cassava which he quoted showed that when only N and P were applied the yields were depressed below those of unfertilized crops but when K was applied as well the yields were increased. Local practices and other local factors such as those of soil type and climate should be taken into account in constructing local nutrient balances, some examples are noted below. *Sekhon [1982]* has discussed potassium cycles in agricultural systems. He gave data for uptake by plants, leaching through soil, fixation by soil and release from soil, and the supplies in irrigation water and in organic wastes.

2.3.1 Re-use of crop wastes and residues

Particular attention should be paid to the use made of fractions of the crop or their fate on the farm. Where the straw or stover of grain crops is ploughed in or burned on the field the P and K contained in these fractions will be returned to the soil, but if they are removed from the land extra nutrients must be applied to balance these losses. *Sudjadi and his colleagues* cited in their paper the benefits obtained by returning rice straw directly, or burning it on the site, in supplying potassium for paddy.

If rice straw is burned in heaps the return of P and K will not be uniform over the soil surface. In some countries straw is removed and used as fuel, attempts should be made to return the ashes to the soil. In Bangladesh both rice roots and the stubble are used as fuel. Similar considerations apply to some plantations crops. The crop residues left after extracting sugar from cane should be returned to the land where is this possible. Oil palm fruit contain much N, P and K, these fruit are processed in factories to extract the oil. The residues from the extraction contain most of the nutrients that were in the fruit bunches; if these residues are burned (as I have seen in practice) the N will be lost but the ash will contain K and P and efforts should be made to return this to the plantations where practicable. Appendix 2 indicates how much nutrients there are in the residues of banana and pineapple crops left after the fruit is removed for sale.

2.3.2. Potassium in irrigation waters

The quality of irrigation water affects the fertility of paddy soils. This subject was discussed by *Kawaguchi and Kyuma [1977]*. If a crop requires 1000 mm of water, 1 ppm of an element in the irrigation water will supply 10 kg/ha of that element. If the water contains 2 ppm of K^+ the supply of K will be about 25 kg/ha of K_2O. In Japan it was found that irrigation water could supply 17% of the crop's need for potassium. The amounts of Si, Ca and Mg supplied are significant but the N and P supplied are «negligibly small». Data are given which show that river waters in Thailand contain from 1.1 to 4.4 mg/l of K^+, in Indonesia from 1.7 to 5.7 mg/l of K^+, and the world average for river water is 2.3 mg/l of K^+. Other publications agree that about 20 kg K/ha may be supplied when a rice paddy receives 1000 mm of water. In his paper to the Colloquium *Sudjadi and his colleagues* have shown how important is the K contributed by irrigation water in Java. They showed that if the rice used 1000 mm of irrigation the K supplied depended on the region of Indonesia, ranging from 4 kg K/ha in Sumatra to 26 kg K/ha in West Java, and to 52 kg K/ha in East Java. *Sekhon [1982]* also considered that irrigation makes a significant contribution to supplies of K, the actual amount depended on the amount and frequency of the irrigation, often 30-70 kg K_2O/ha would be supplied. We should also remember that these figures for K in irrigation water are an indication of the amounts of K that are lost from the upland soils where the river waters originate, they are removed from the surface soils by leaching and surface run-off and some is derived from weathering of the minerals in subsoils and deeper strata where reserves are situated.

Although much potassium is supplied by irrigation water, the movement of this water down the soil profile leaches away much of the potassium ions present in the soil solution. *Feng and Chang [1965]* reported on the losses of potassium from lowland rice soils in Taiwan. They found that where soils are maintained in flooded conditions most of the added potassium was leached away during the four-month growing season. Where reserves of potassium in the soil were small the K-fertilizer that was required needed to be applied in split dressings to avoid losses by leaching.

Paolo Sequi [1981] discussed the removal of soluble potassium in water draining from rice paddies in Italy. The input of potassium in irrigation water amounted to 222 kg/ha of K_2O, but the drainage water removed 132 kg/ha of K_2O, so during the course of a year's irrigation 90 kg/ha of K_2O was lost from the system.

3. The intensification of agricultural systems

The very high potential of the humid tropics to produce large crop yields was discussed with the Colloquium by *van Keulen* and *Corley*. *Van Keulen* quotes the results of a maximum annual production trial and writes — «simulation of the latter trial, which involved continuous cropping of four rice crops within one year, resulted in a total yield of 33000 kg/ha, illustrating that very high production levels are possible in the humid tropics, provided that unfavourable effects of water or nutrient shortages and weeds, pests and diseases can be avoided». In estimating how far a country can go in approaching such potentials local facilities must be assessed and comparisons of present levels of production with levels achieved in other countries can provide some guidance.

Agriculture is already a very important industry in Thailand. In 1983 it contributed 21.8% of the G.D.P. (Gross Domestic Product) and about two-thirds of its exports and provided work for 61% of the country's labour force. The potential for increasing yields of the major arable crops grown in Thailand may be seen from comparisons of average yields given by *FAO [1985]* for the World, for Asia and for Thailand, these are noted in

Appendix 3. For six of the ten crops (paddy rice, maize, soybeans, seed cotton, sugar cane, and fibre crops) average yields in Thailand were less than the averages for the world or for Asia. But for cassava the average yield in Thailand is much larger than the ASEAN and world averages.

Intensification is of course achieved by the increased use of fertilizers and the introduction of other inputs such as irrigation or agrochemicals to control pests and diseases. But much may be achieved by changes in crops, the varieties grown, and in cropping systems. I will concentrate on these aspects in this section.

3.1 High-yielding varieties

The introduction of improved plant material with greater potential for yield is very important. Generally these varieties take up more K than traditional varieties do and they require a correct balance between NP and K fertilization as *Liang Deyin* and *Lin Bao* have showed the Colloquium. Such work emphasises the need to assess nutrient cycles whenever agriculture is intensified, whatever the means that are adopted for this purpose.

3.2 Multiple cropping systems

These systems hold great promise of increased production in the humid tropics. *Ismunadji and his colleagues* showed how important mixed cropping was for diversifying cropping and producing more food. In the Indonesian experiments mixed crops of maize and soybean produced much more grain than when each crop was grown alone; adequate supplies of potassium were essential to achieve this greater potential. *Li Shi-ye* and *Zhan Chang-gung* discussed the soil characteristics which affect the supply of K in multiple cropping systems in south China where multiple cropping is applied on more than two-thirds of the total area of paddy. They emphasised that soil alone cannot supply all the K needed by three crops in a year and that other sources (manures and fertilizers) are required to make up the balance. The results of long-term experiments are needed to measure the effects of multiple cropping on soil potassium reserves and to calculate how much more K must be supplied.

Deka et al [1984] described an experiment at Pantnagar which tested six crop rotations over a four-year period. All the crops were grown by recommended practices and received recommended fertilizer dressings. The economics of the systems were calculated and nett returns are shown in Table 2. The highest total return was from the rice-wheat-maize-cowpea rotation, but the highest return per rupee invested was from a rice-berseem rotation.

Deka and Singh [1984] reported the nutrient balances established over a two-year period of this experiment, results are shown in Table 2. The rice-wheat-maize + cowpea rotation resulted in higher uptakes of P (107.8 kg/ha of P in 2 years) and higher uptakes of K (510.3 kg/ha of K in 2 years) than occurred in the other rotations. Among individual crops berseem removed most K (104 kg/ha of K in 1 year). The nutrient balances calculated (from additions in fertilizers minus removals in crops) are shown in Table 2.

Only the rice-wheat rotation showed a gain in N (in the other rotations the legumes fix their own N and the crops removed are rich in N). All rotations gained in P, but the balance for K was negative in all rotations and the maximum deficit was in the rice-wheat-maize + cowpea rotation which was also the most profitable overall. This balance points to the need for a reassessment of recommendations in such a rotation since the negative balance for K occurred when standard recommendations were applied.

Table 2. Nett returns from different crop rotations over a four-year period and the nutrient balance over two years of this period.

Rotation	Nett returns, mean/year		Nutrient balance per year, kg/ha		
	Rs/ha	Rs/Re invested	N	P	K
Rice-wheat	3919	0.54	+44.2	+19.4	−106.2
Rice-lentil	2919	0.54	− 51.9	+19.1	− 77.6
Rice-berseem	5426	0.86	−133.6	+13.0	−141.4
Rice-wheat-green gram	4705	0.53	− 20.6	+31.3	−142.6
Rice-wheat-maize + cowpea	6345	0.73	− 24.8	+ 7.7	−173.3
Rice-mustard-green gram	4067	0.53	− 7.9	+39.7	− 87.1

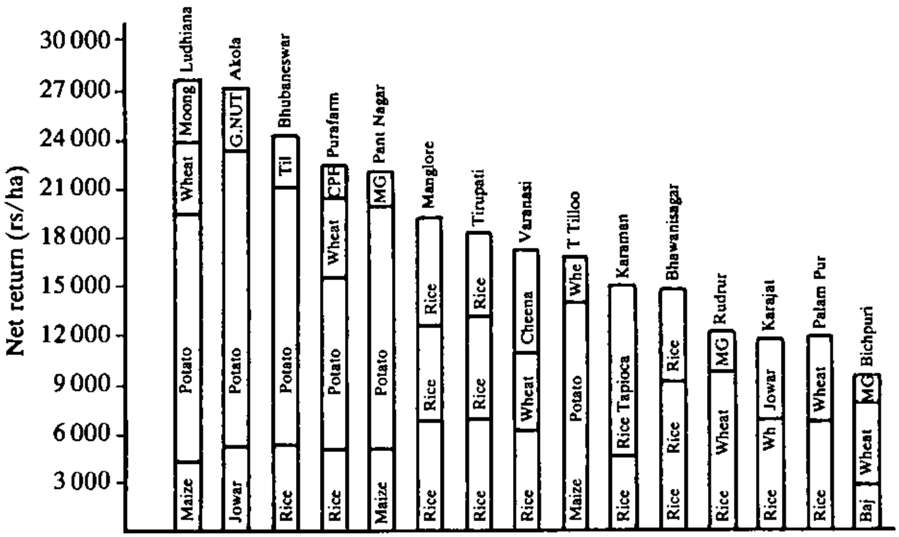

Figure 2. Nutrient achieved in various crop rotations at range of centres in India (from *Soni and Kaur [1984]*

One point that should be recognised in relation to multiple cropping is that growing one species frequently increases the risk of loss from soil-borne pests and diseases. Adequate fertilizing reduces this risk since the higher the standard of nutrition the greater will be the crop's resistance. Some examples are given later in this paper and the subject has also been discussed by *Kanwar [1975]* and by *von Uexküll [1982].*
More work is required on multiple cropping systems as they offer great promise for improving food production in the humid tropics. Thus *Soni* and *Kaur [1984]* reported the results of 3 years of study of systems established at 15 centres in India. Suitable sequences provided 10 — 12 t/ha of food grains each year. Figure 2 (from *Soni* and *Kaur's* paper) indicates the yields obtained at some of the centres with various rotation.

3.2 Tropical root crops

These crops are being increasingly grown in the tropics as they have a potential for very high yields of starch; in addition some, such as potatoes, provide good quality protein and vitamins and minerals. *C.I.P. [1984]* has emphasised how much production of root crops has expanded in recent years; thus in developing countries production of all root crops increased by 44% in the period 1961/65 — 1979. *Cock [1985]* quoted a list of tropical food crops in terms of the food energy they provide. Cassava was at the head of the list with a maximum annual yield of 71 t/ha of tubers and the ability to provide 250 kcal/ha of food energy per day. In the present context these crops are important because they take up large quantities of potassium and most of this is in the tubers which are removed from the farm.
In the paper that *Juo* prepared for the Colloquium he reviewed recent information on the responses of cassava, sweet potato and yams to K-fertilizers. In the experimental work done in Africa and Asia which he referred to there had been good response to potash by both cassava and sweet potato. Yams are normally grown on the more fertile soils and it appeared that there was little response to K-fertilizer except on very deficient soils. *Juo* considered the future expansion of yam production would be limited because of the high costs incurred in preparing the land and growing the crop. But he envisaged rapid expansion in the growing of cassava and sweet potato as these can be grown on marginal soils where high production can be achieved with adequate fertilizers and particularly with potassium.
Cassava is the important root crop in this region of Asia. *C.I.P. [1984]* showed that the country with the largest production in the world was Brazil (24.5 million tonnes [mt]/year) this was followed by Thailand (14.5 mt/year) and Indonesia (13.7 mt/year). Although cassava grows well on poor soils and often receives no fertilizer the potassium it removes depletes the reserves in soils so that responses to K-fertilizer occur where cropping is continued, and the depletion of K means that other crops which follow will suffer unless they receive K-fertilizer.
Potassium not only increases the yields of cassava but it can also improve the health of the crop as the following example shows. *Kang* and *Okeke [1984]* reported the responses of cassava grown on an Alfisol in the forest zone of southwestern Nigeria to N and K fertilizers. Nitrogen increased the yield of tops but not of tubers, potassium increased the yields of both tops and tubers; this response to K occurred in the second year of continuous cropping with one variety and in the third year with the other variety tested. Where no K was applied the crops suffered severely from bacterial blight, and applying N without K increased the disease and severely reduced yields.

Cock [1985] has described the important export industry of cassava from Thailand. He states that although average yields are high there are signs of decline and he comments on the future as follows: «The Thai cassava industry is based on a supply of cheap fresh roots, which in turn is dependent on good yields, so more farmers must begin to use fertilizers and improved technology in the future or the Thai industry could lose its competitive advantage». This is valuable advice which will help to ensure the success of ‹agribusiness› based on cassava in Thailand.

3.3 Tea for export

Experience in other countries with crops intended for export confirms the need to maintain sound fertilizer practices to improve productivity — this improvement is needed to increase the bulk of crop available for export and also to lessen the cost of unit produce and so improve competiveness. This example deals with tea and is based on an account of a Symposium (reported by *T.R.I.* of Sri Lanka in 1983) held to discuss the decline in production in Sri Lanka. In the 1950s yields increased steadily because of the adoption of sound agricultural practices including the use of balanced fertilizer mixtures. In the 1960s economic and social problems led to less satisfactory management of the crops including inadequate fertilizing. The Report stated «Very few estates seem to have a properly worked out fertilizer programme and apply fertilizer without adequate attention to the yield potential of the field». As a result since 1965 yields have steadily declined. In the discussion on these problems it was stated that the fertilizer policy should be reviewed especially in respect of potash as less was being used than was applied in the 1960s. The question of uptake by shade trees was also raised; *Grevillea* trees took up 101 kg N, 34 kg P_2O_5 and 168 kg K_2O per hectare and returned only 34 kg N, 7 kg P_2O_5 and 28 kg K_2O per hectare as leaf droppings; since shade was now being reestablished to improve the growth of the tea extra potash would be needed to ensure that the tea had sufficient.

Kemmler [1984] discussed the N and K nutrition of tea in South India and in Sri Lanka — the two most important tea exporting countries. Recent average yields have been 1748 kg/ha of made tea in South India but only 832 kg/ha in Sri Lanka. Experiments in Sri Lanka in the 1940s showed that after several pruning cycles the response to K could be as large as to N. Research in India in the same period indicated that K was a yield stabilising factor. *Kemmler* also illustrated the stagnation and then the recent decline in yields in Sri Lanka since the peak period in the early 1960s. By contrast yields in all of India have increased by about 40% in this period; these changes in yields and differences between the two countries were associated with differences in practical fertilizer policies which are shown in Table 3.

The changes in both total quantities of fertilizers and in the $N:K_2O$ ratios applied are associated with considerable increases in yields in India, and with the failure to increase yields in Sri Lanka since the 1960s. The average use of fertilizer in South India in 1977-81 was 406 kg/ha (of $N + P_2O_5 + K_2O$) with a $N:K_2O$ ratio of 1:1. The comparable average in Sri Lanka for 1979-81 was only 141 kg/ha with a ratio of $N:K_2O$ of only 1:0.52. *Kemmler* concludes that differences between yields of tea in Sri Lanka and in South India may be due in part to other factors such as soil and climatic conditions and to management of the crops. While the supply of potassium may not be the major factor limiting yields in Sri Lanka, where much N-fertilizer is being applied an increase in the amount of K applied should aid the crops tolerance to drought and recovery after pruning so leading to higher and more stable yields.

Table 3. Estimated annual fertilizer use for tea in Sri Lanka and in South India (amounts of nutrients in kg/ha)

	Sri Lanka			South India		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
1955	60	28	34	67	34	34
1961-65	87	22	60			
1970*	74	14	42	108	34	54
1980**	82	16	43	180	42	184

* Sri Lanka: 3-year average

**Sri Lanka: 3-year average, South India: 1977-81

3.4 Clearing of forests for cropping

Nutrient balances must also be considered when tropical forest is cleared for crop production. An example of clearing rainforest in Peru was published by *Sanchez et al [1983]*. Changes in soil properties and nutrient balance were studied over a period of 8 years when 3 crops per year were being grown. Ash from the burnt forest increased all nutrients in the soil and reduced acidity but deficiencies soon developed as cropping proceeded and so fertilizers were applied. Thus exchangeable K in the soil increased rapidly after burning the forest but then decreased and in less than a year was below the level in the soil in the undisturbed forest. The nutrient balances over the 8 years of continuous cultivation were calculated, they were:

	N	P kilogrammes/hectare	K
Fertilizer additions	1480	850	1740
Crop uptakes	1916	279	1837
Balance	−436	+571	−97

The crops extracted more N than was applied, probably because the soybeans grown fixed much N. P accumulated in the soils. Inputs and outputs of K were nearly balanced, the authors state that this suggests «rather tenuous balance between fertilizer additions plus soil release *versus* plant uptake and leaching losses». Exchangeable K in the soils did not increase. It was pointed out that continuous cropping with proper fertilizing and agronomic practices produces satisfactory yields and improves soil chemical properties.

The authors state «Following nutrient dynamics with time has been the key to developing appropriate fertilizer recommendations for continuous crop production on a sustained basis in an Ultisol representative of large areas of the humid tropics».
von Uexküll presented to the Colloquium a very thorough account of how the acid soils under tropical forest can be managed so that soil fertility is improved and continuous cropping is possible. He described how the original topsoil fertility is maintained by clearing methods and how subsoil properties are improved. Continuous cropping is then possible, provided that large amounts of potash (500-600 kg K_2O/ha) are applied, and 15-20 t/ha of grain can then be grown annually in a three-crop rotation. To achieve this the nutrient cycle of the cropping system must be evaluated so that adequate fertilizer dressings are used. He concluded that a full effort with high inputs is required; minimum input systems will result in the deterioration of these tropical land resources or possibly to their destruction.

3.5 Interactions with other inputs

Changes in other inputs that are applied to intensify production systems will always require a reassessment of nutrient cycles. Thus it is well established that where irrigation is applied to provide extra water needed for full crop growth the uptake of nutrients by the larger crop will require the use of more fertilizer, and the water will increase the efficiency of the fertilizer *(Cooke [1986])*. A good example of the interaction of another input with fertilizer is provided by the use of stimulants in rubber production; the stimulants improve yields, but also increase the nutrients removed in the latex. *von Uexküll and Cohen [1979]* quoted results obtained in Malaysia. With a yield of 2000 kg of dry rubber/ha, the K removed was only 20 kg/ha: with stimulation applied the yield was raised to 5796 kg/ha of dry rubber in 10 months of tapping when the K removed reached 63 kg/ha. The data below show that while Ethrel stimulation increased the yield by over 50%, the loss of K was increased by 3 times (and the N and P lost were increased by about 2½ times).

	Yield of rubber	Nutrients drained, kg/ha		
	kg/ha	N	P	K
Without stimulation	1454	7.6	1.7	5.1
With Ethrel Stimulant	2269	19.3	4.7	15.8

4. Estimates of the future use of fertilizers

4.1 Use in south-east Asia

Pushparajah has discussed with the Colloquium estimates of the amounts of K-fertilizer which will be needed later in this century. The following two estimates were obtained for 10 countries of south-east Asia where 1177000 tonnes of K_2O were used in 1982:

i) When based on growth rates for the period 1977-1982 the total needed in 1992 would be 2720000 tonnes of K_2O
ii) But when based on the 10 years 1972-1982 total requirements for the 10 countries would be 3200000 tonnes of K_2O.

In Thailand where 38000 t K_2O were used in 1982, the forecast based on the 1977-1982 growth rates would be for 60000 tonnes to be used in 1992, but forecasting on the 10-year basis, 1972-1982, only 35000 t would be needed.

Using the past changes in fertilizer use is an unsatisfactory basis for assessing future needs since it takes no account of current lack of nutrient balance, or of the special needs of the soils and the farming systems for potassium to support other inputs; the assumption is that change in farming systems and practices will continue as in the past. *Pushparajah* emphasised that crop requirements and cropping patterns must be taken into account. He had calculated the nutrient cycles for paddy cropping in the following south-eastern Asia countries: Bangladesh, India, Sri Lanka, Burma, Indonesia, Malaysia, Philippines and Thailand. All the countries had deficits (calculated from amounts removed in paddy crops minus amounts of fertilizers applied) which ranged from 16 kg/ha (of $N + P_2O_5 + K_2O$) in Malaysia to 98 kg/ha in Burma per year; the deficit in Thailand was 65 kg/ha of $N + P_2O_5 + K_2O$ per year. The amount of potash removed by paddy in Thailand in the 1981/82 crop year was estimated to be 42 kg/ha of K_2O, the fertilizer used supplied 2 kg/ha of K_2O so there was a large annual deficit of 40 kg/ha of K_2O (which has to be supplied by soil and irrigation water, a situation which may not continue indefinitely as soil reserves become depleted). By assuming that the fertilizer nutrient ratios used on paddy were the same as the average use on the whole cropland the requirements for potash in the 8 countries in 1992 were estimated, these are stated in Table 4. The total amount of potash needed in 1992 for the whole of the 8 countries will be about 2.2 million tonnes of K_2O. So *Pushparajah* concluded that the consumption of potash in the Asian tropics is expected to range from 2.2 to 3.2 million tonnes of K_2O; the actual amounts used will depend largely on weather, crop production, and prices of crops and fertilizers.

Table 4. Amounts of potash used in 1982 in eight countries of south-east Asia and estimates of the amounts which will be required in 1992, based on crop requirements (from *Pushparajah's* paper to the Colloquium)

	Use in 1982	Estimate of use in 1992
	Thousands of tonnes of K_2O	
Bangladesh	28	76
India	622	1130
Sri Lanka	45	75
Burma	11	60
Indonesia	133	400
Malaysia	194	320
Philippines	58	90
Thailand	38	80

4.2 Use in Thailand

Pushparajah stated that 58% of all the fertilizer used in Thailand in 1982/83 was applied to rice, fruits received 15% of the total and 12% was applied to vegetables. His estimates of the future use of potash by the year 1992 are:

	Tonnes of K_2O
Forecast based on	
1972-1982 changes	35000
1977-1982 changes	60000
nutrient balance studies	80000
Actual use in 1982-1983	38000

The estimate of use in 1992 based on nutrient balance studies envisages a doubling of the K-fertilizer now used in Thailand. But even this increased use of K in 1992 would provide only about one-tenth of the total amount which is now recommended for the 10 crops discussed earlier (Table 1 in Section 2.2.1.) and 8.5% of the K which these crops take up. The difference between this estimate of the K needed in the future and the total amount which would be recommended for only part of the crops grown in Thailand indicates that there is a serious need to assess the amounts of K which will be essential to maintain agricultural productivity and therefore national prosperity in Thailand. Similar considerations apply to other countries of the humid tropics.

4.3 Use in Latin America

Pushparajah quoted data published from Latin America which showed a large deficit of K_2O, calculated on the basis of crops removed from the land or exported minus the fertilizer-K applied. The amount of potash applied in the region needs to be increased to meet this deficit. *Pushparajah* concluded that by 1992 about 5 million tonnes of K_2O will be needed each year in Latin America. (The total used in 1980 was only 2130000 tonnes of K_2O).

5. Research on soils and crops to aid the intensification of production and the efficient use of fertilizers

When national fertilizer policies have been established there will be a need to plan so that the scientific information on soils and crops is sufficient to ensure that the fertilizers that will be used are used efficiently and give a good return to farmers and to the nation on the outlay involved.

5.1 Soil classification

The first need is for an adequate classification of soils, supported by databases on the soils, both based on surveys. This information will be needed to plan for more intensive cropping systems, the crops being chosen to suit the soils. It is also needed for the transfer of new technologies; the correlation of the results of field experiments with soil type facilititates the transfer of recommendations derived from the experiments to other areas. Factors that affect the reserves of nutrients in the soils, and those that govern the efficiency of nutrients added as fertilizers, need to be related to soil type.

The *Soil Taxonomy Classification (Soil Survey Staff [1975])* developed in U.S.A. has an important place in this context; the classification takes full account of profile characteristics and the pedogenic processes by which the soil was formed. *Eswaren [1984]* has discussed the use of *Soil Taxonomy* in identifying soil-related potentials and constraints for agriculture.

Relevant statements are quoted here:

> «Detailed knowledge about soils and their behaviour is crucial to successful agricultural exploitation. In addition it is necessary to know the requirements of crops. Matching crop requirements to soil conditions is the key, not only to technology development, but also to agrotechnology transfer ...
>
> In Soil Taxonomy the matching of crop requirements to soil conditions is to some extent built into the system ...
>
> Only when the potentials or constraints to the use of a soil are related to the classification of the soil can the classification system be exploited to the fullest extent possible».

Ho showed us how the soil classification was related to the responses to K-fertilizers measured in the experiments made by *FAO* in this region.

Greenland recommended to the Colloquium the use of the *Fertility Capabilit Classification («FCC»)* developed by *Sanchez, Couto and Buol [1982]*. This is an important point: *«FCC»* is not an alternative to *Soil Taxonomy* but it is a technical system which aids the use of Soil Taxonomy in agricultural planning and extension. *FCC* groups the soils according to the kinds of problems that must be considered when the management of chemical and physical properties is being planned. The *Classification* takes account of the measurement of topsoil and subsoil properties that affect plant growth; the system has three levels: *type* (topsoil texture), *substrata type* (subsoil texture), and 15 *modifiers*. The modifiers are the chemical, physical and pedological characteristics that affect plant growth and are constraints to yield. These modifiers include several factors that affect the potassium supply to crops — cation exchange capacity, K reserves (depending on weatherable minerals), and exchangeable potassium. *Apisit Eiumnoh [1984]* published a very thorough examination of the FCC system applied to problem soils in the south-east coast of Thailand and compared its use with that of *Soil Taxonomy. Char-Fen Lin [1984]* discussed the use of FCC as a guide to the nitrogen fertilization of lowland rice in Taiwan; the conclusion reached was that «the FCC system is a meaningful tool for relating fertility limitation to yield response».

5.2 Minerals in soils

There is a need for information on the minerals present in soil which may contain reserves of K and release them to crops. This information must be related to the results of soil surveys. When interpreting the results of nutrient balance studies it is essential to be able to forecast the extent to which reserves in soil can make up a deficit of K where crops are removing more K than is replaced by fertilizers, crop residues, and organic manures.

It is particularly important to know what types and amounts of 2:1 clay minerals are present in the clay, silt and sand fractions.

Mutscher showed the Colloquium how the supply of potassium to crop roots is linked to soil mineralogy. The presence of clay materials with variable electric charge complicates the behaviour of potassium and makes the management of this nutrient more difficult in the humid than in the drier tropical regions. He recommended studies of Q/I relationships to give a better understanding of K dynamics in these soils since «the interpretive value of exchangeable potassium content in variable charge soils is much less meaningful and reliable according to the dynamics of potassium supply to crops than in soils with permanent charge clays».

An example of a relevant investigation was made by *Fagbami, Ajayi and Ali [1985]*. They examined a cross-section of the basement complex soils in the dry forest of south-western Nigeria. Total potassium in the soils was higher than total Ca and Mg but exchangeable K was very low and much less than exchangeable Ca and Mg. Soils derived from granitic gneiss had the highest capacity to supply K.

In another study in northern Imo State in Nigeria *Unamba-Oparah [1985]* investigated the potassium status of sandy soils. Kaolinite was the dominant clay mineral but significant amounts of a 2:1 intergrade mineral were also present. The soils were highly weathered and were poor in K; such K as was released came from the fine sand and silt fractions which contained muscovite or mica flakes. The reserves were mainly contained in the subsoil, this was attributed to the leaching of K from the upper horizons by heavy rain; only deep-rooted plants could utilise these reserves. The soils had been intensively cultivated for years without adequate K-fertilization and the reserves of K had become so depleted that large quantities of K fertilizer were needed for better crop performance. Since leaching is severe in these soils the K-fertilizers should be applied in small dressings frequently.

Greenland discussed with the Colloquium the value of mineralogical characterisation of soils in relation to the supply of potassium; in particular he drew attention to the role of vermiculite which occurs frequently in lowland clays. Elsewhere *Greenland and De Datta [1985]* have reported on the constraints to rice production in relation to wetland soil characteristics. Most rice-growing soils in the Philippines are geologically young and release much K from the weathering of primary minerals. Nevertheless under continuous cropping with modern rice varieties responses to K-fertilizer are increasing in many lowland soils.

5.3 The need for long-term field experiments to manage crop nutrition

The foregoing Sections point to the need for long-term multidisciplinary field experiments to be established on sites that are typical of the major soil types in each country as classified by the FCC System. These experiments will provide the basic information needed to guide extension work which is aimed at improving the productivity, efficiency, and profitability of agricultural systems. They will provide information on the following topics:

1) Basic data required for the calculation of nutrient cycles discussed above. 2) Information on responses to fertilizers and the interactions between nutrients and between nutrients and other inputs (such as irrigation and/or pesticides) to the system. 3) A basis for the associated work involving soil analysis and crop composition. All of this informa-

tion is required to derive the correct recommendations for the amounts of fertilizers to be used and the times when they should be applied.

This topic was thoroughly discussed with the Colloquium by *Greenland.* As he says the long-term experiments are important because «their results can be extrapolated in time and space with confidence». At present there are too few of these experiments made in the humid tropics and I would insist that they should have the highest priority as they are essential for the correct and efficient management of fertilizers.

Greenland also recommended the use of small-plot experiments *(Joint Experiment and Extension Plots (JEEPS))* sited at many places to support and supplement the main series of field experiments. This fits with my views, we have found small-plot Reference Experiments, which are very accurate and are easily maintained — mostly by hand work, to have great value in advice on fertilizing related to cropping system, soil conditions, and climate; an example of the use made of these experiments is to be published *(Cooke [1985]),* this includes a nutrient balance for three crops grown in England and Wales in 1982 which is reproduced in Table 5.

Table 5. Average yields of wheat, barley and potatoes in UK in 1982, average fertilizer dressings applied to these crops in England and Wales, and estimates of N, P and K in the harvested crops

	National average yield t/ha	Fertilizers[1)] applied on average			Nutrients[1)] in harvested crops		
		N	P	K	N	P	K
		kilogrammes per hectare					
Wheat	6.2 (grain)	166	22	37	118 (87)*	21 (17)*	105 (25)*
Barley	4.9 (grain)	120	19	40	98 (74)*	15 (13)*	88 (23)*
Potatoes	35.8 (tubers)	199	87	222	115	18	161

[1)] In this Table 5 nutrients applied in fertilizers, and removed by crops, are stated in terms of the elements N, P and K.

*quantities in parentheses are those removed in grain only

These data show the very great differences at present in fertilizing cereals and potatoes. Potatoes receive five times as much P as they remove and about 40% more K than is removed, also about 40% more N. Cereals receive 20-30% more N than the harvested crops contain, but little more P than is contained in the grain and straw at harvest. By contrast the cereals receive only about a third to a half as much K as in the total harvest. Data given for the amounts of K removed in cereal grain only emphasise the importance of considering the fate of cereal straw. If all the straw is returned to the land, current applications of fertilizers are sufficient to replace the K which is removed in grain, but if the straw is removed and is not returned in farmyard manure, then soil reserves of K will be speedily depleted by cereal growing. Lack of attention to nutrient balances can result in serious problems with potassium nutrition. The problem does require the results from long-term experiments to provide data for nutrient balance sheets; national assessments of the fertilizers applied, and of the proportions of cereal crops where straw is removed or returned, are also required. On a wider scale for farming systems as a whole other information will be required on crop and urban and industrial wastes applied to land, together with estimates of the plant nutrients which enter a country in imported feeding stuffs. National balance sheets are essential for planning fertilizer use, manufacturing capacity, and imports of raw materials.

Ho, described to the Colloquium *FAO's* very important fertilizer programme where the large numbers of experiments were made on farmers' land in five of the countries of this region. The results are very useful and important giving information on responses to potassium and relations between soil classification and characteristics and available K in the soils with the crop responses to K-fertilizers. These experiments are very useful in that they define and locate the areas that are deficient in potassium.

Mamaril gave the Colloquium a very important and useful account of coordinated schemes of experiments on fertilizers. These involved collaboration between agronomists and soil scientists working in national and international schemes to develop technologies to secure the efficient use of fertilizer inputs. He described the *INSFFER (International Network on Soil Fertility and Fertilizer Evaluation for Rice)* network which was established in 1976 and now involves 19 countries. The work done has concentrated on N-fertilizers. Such international collaboration could profitably be extended to investigate the place of potassium in maintaining soil fertility at levels which consistently produce high economic yields. A chain of experiments to measure nutrient responses and interactions on a long-term basis and to relate the effects measured to soil type and to climate would be valuable in providing the information we need to use potassium efficiently to maintain crop production at required levels. The network would also provide a basis for soil classification methodology and to compare analytical methods so as to establish which ones should be generally applied.

5.3.1. Experiments on the maximisation of yields

De Datta mentioned the value of maximum yield experiments on cereals; these experiments are essential for developing information on the levels of nutrients that are critical for sustaining high yields. The purpose of these experiments is not academic, but it is practical as *De Datta* states — «the adoption of any fertilizer use technology at the farm level will largely depend on integrated nutrient use for sustained high productivity from land and higher income». The experiments that he described showed how increased use of N increased the uptake of K by maize, sorghum and rice. He concluded that high cereal yields are only possible with high fertilizer application rates containing growth-limiting nutrients which lead to higher needs for K.

In Europe where there are surpluses of cereal grains such maximum yield experiments have been criticised by ill-informed administrators, and by members of the general public, as likely to increase such surpluses. Increase in *total* production is not the purpose of such work in developed countries though it has this practical value in regions where food is in short supply. The purpose of the experiments is purely scientific and they represent the culmination and the ultimate test of all research on the factors affecting crop production.

The first duty of the scientist is to identify all the constraints which limit the growth of the crop. He must then identify inputs which will overcome each of the constraints. Then experiments must be done to test rates of these inputs, ranging around the optima, in factorial combination, so that the direct effects of each input and their interactions are measured. The purpose must be to develop the ability to produce the maximum yield that solar radiation received and the genetic capability of the plant material make possible on the particular site. The scientist's work is not complete until he can reliably produce these maximum yields in a series of years.

Economic criticisms of such research are not relevant. Maximum yields minimise the effects of fixed costs of farming on the cost of unit produce. Therefore food is produced more cheaply per unit in a high-input system producing near maximum yields than it is in a low-input system producing much lower yields. This means that high yields provide cheaper food for consumers, and a better competitive position for exports from the Nation.

In situations where surpluses are a problem the remedy is to reduce production by sowing less hectares or milking less cows, those hectares and cows remaining in production should produce from each the maximum yield to minimise the effects of the fixed costs, and the capital involved in the land used or the cattle, on costs of the produce.

In some developing countries money for the imports of inputs may be so limited that lower-input systems have to be considered so that land may be kept in agricultural production and that employment for the agrarian population may be maintained. To maximise the return from limited expenditure under such conditions it is essential to have full scientific information on the direct effect of inputs, and their interactions, on yields to enable those who guide farmers by giving advice to decide on what levels of inputs are essential and on those inputs which may be used at reduced levels or perhaps be omitted. The implications for the use of potassium under such circumstances are obvious; correct decisions at national and farmer levels can only be made when experimental information on the return from potassium fertilizers and their interactions with other inputs is available and this information is best supplied by multidisciplinary multifactorial experiments in which maximum yield is achieved.

It must be stated that whatever the economic circumstances of a country may be the results of research on the maximisation of yields will be required so that the decisions on recommendations for inputs to farming systems have a sound logical, scientific, and economic basis, and also fit the national aspirations and practical capabilities.

5.3.2. Experiments on times of applying potassium fertilizers

Time of application of K-fertilizers is important to ensure that adequate amounts of K^+ are present in the soil solution when crop uptake rates are at maxima, and also to avoid losses of K by leaching. *De Datta* dealt with this topic and noted that split applications have resulted in higher yields in Japan, China, and India. The gains from split dressings occur in warm areas, on soils with low CEC, on poorly drained soils where toxins accumulate, where much N is used, and in coastal areas with high rainfall. In work in Philippines on clay soils with high CEC there was no gain from split applications.

Ho gave the Colloquim the results of other experiments in Philippines where large responses to K-fertilizer were obtained with rice. Generally splitting the total dressing into three gave the best results in both the dry and wet season; the times were: one-third basal before transplanting, one-third 20 days after transplanting, and the remaining third at panicle initiation.

Ram and Prasad [1985] examined this question for wetland rice in India. A few of their results are quoted in Table 6. They found that applying 60 kg K/ha in three equal splits at transplanting, active tillering, and panicle initation; or two splits at transplanting, and active tillering stages, gave the best yields. These gains were related to the maintenance of high concentrations of K in the plants. It appeared that the soil had sufficient K to support the initial growth of the rice but later applications were essential to maintain the concentrations.

Table 6. Effect of time of application of 60 kg of K/ha on the yield of rice and on K uptake.

	Grain yield q/ha	Total K removed kg/ha	K in straw at harvest %
Without K fertilizer	23.85	39.86	0.95
With K fertilizer in 1 dressing			
all at transplanting	33.41	66.70	1.23
all at maximum tillering	34.22	76.95	1.42
all at panicle initiation	33.51	78.66	1.67
With K fertilizer in 3 dressings			
⅓ at transplanting, ⅓ at active tillering ⅓ at panicle initiation	40.43	83.76	1.36
C.D. at 5%	2.41	6.08	0.14

5.4 Soil and plant analysis

Much research is needed on the potassium supplying power of soils and on the effects of potassium on plant growth so that recommendations on the use of K-fertilizers can be made for the important crops, in relations to the soils and climates of the regions where they are grown, to secure the yields that are required and to ensure high efficiency in the use of the K that is applied. This work is best done in association with the long-term field experiments recommended in Section 5.3. In fact work on field experiments should always be supplemented by soil and crop analyses to define the needs for K and the recommendations then developed should be adjusted so that the nutrients in the cropping system are balanced.

5.4.1. Soil analysis

The general value of measurements of exchangeable potassium needs to be determined in particular regions. Thus *Sekhon and Subba Rao* found that ammonium acetate-exchangeable K does not predict responses in Indian soils reliably. Measurements made by electro-ultra filtration (EUF) and by Q/I (Quantity/Intensity) methods were more reliable. Where the method used does appear to be reliable there is a need to establish generally agreed limits for exchangeable K where responses to K-fertilizer are expected. *Greenland* set a limit for many crops at 0.2 me K/100g soil).

Samnao Phetchawee and his colleagues described to the Colloquium the work done on the reserves of K in soils of Thailand in relation to crop responses in experiments. They set up limits for various crops which related exchangeable-K to recommendations for applying K-fertilizer. Other papers presented to the Colloquium have also dealt with this very important subject.

There is also a need to apply methods of determining the reserves of K in soil which are not exchangeable but which may be released to crops. Guidance on this question will be provided where the nature of the minerals present in the soil has been identified. Laboratory methods need to be tested on soils where little information on K reserves exists. The most promising lead appears to come from the use of EUF; extraction with nitric acid (and sometimes with hydrochloric acid) is also used as is the release of K to a calcium resin; these methods need further testing to ascertain their reliability. *Greenland* discussed these problems of potassium availability. His comments on the role of vermiculite in bonding K are an important indication of the need to have mineralogical analyses and a knowledge of the other factors that affect the availability of K, the amounts of exchangeable K and the concentrations of K^+ in the soil solution.

Subsoils must be investigated to determine what reserves of K may be available to deep-rooting crops. *Xie Jian-Chang* showed the Colloquium how the soils of south China have been degraded and the K leached to lower layers; topsoils are now deficient in K but the deep subsoils contain several times as much as the topsoils do.

Organic matter levels in soils should be investigated in relation to soil type and to cropping systems. High organic matter levels generally lead to better yields for some reasons that are still the subject of debate; but we do know that higher organic matter does increase the CEC of the soils and it does aid the management of cation nutrients.

5.4.2. Plant analysis work

The crops from experiments will be analysed to measure uptakes of K and other nutrients; these data are required for calculating balances between inputs and outputs. Tissue analyses will aid in determining the needs for K-fertilizers. Further investigations of the value of these data are required and attempts should be made to establish criteria to interpret the analytical measurements. This may be complicated in the humid tropics by the action of rain which may leach K^+ from plant tissues. It would be worthwhile to test the value of the *Diagnosis and Recommendation Integrated System (DRIS)* which was developed by *Beaufils [1973]* and which is based on nutrient balance (ratios) in the plant. Some workers have shown that the *DRIS* method is more reliable in diagnosing nutrient deficiencies than is the usual method based on the setting up of critical levels in the plant tissue. In a recent paper *Hallmark et al. [1985]* showed that *DRIS* confirmed visual deficiencies and yield responses by soybean more consistently than was achieved by using critical levels. The fertilizer recommendations resulting from *DRIS* could be confidently applied to the next years crop whereas, as the authors state, when normal plant analyses are used it is frequently too late to adjust the fertilizer programme for that season.

5.4.3. Nutrient interactions

Crop analyses are also helpful in understanding the mechanism of interaction. *De Datta* reported to the Colloquium present information on the interaction between K and Zn in rice; concentrations of nutrients in the plants affect this interaction. *Ho* also discussed the effects of combined deficiencies of Zn and K in paddy soils.

It has been reported that potassium deficiency induces iron deficiency in potatoes. *Jolley and Brown [1985]* reported how the response of tomatoes to iron stress was affected by the supply of K. When the plants were grown in K-deficient solution they did not respond by releasing H^+ and reductants from their roots. When K was applied the plants responded and Fe was transported to the plant tops. The mechanism of these effects was explored by analyses of leaves and roots. The authors concluded «Balance of nutrient elements to some degree seems required in order for iron to be made available and to function properly in the plant».

5.4.4 Crop physiology

The other work required on crops grown in the field experiments is in plant physiology. *Liang De-Yin and Lin Bao* reported to the Colloquium how traditional and HYV cultivars of rice performed in relation to their responses to potash. The uptake of K during various growing stages was very different between HYV and local varieties. After full heading the local variety stopped K uptake but the hybrid continued to absorb K right up to ripening stage. A high concentration of K is needed for maximum photosynthesis and it benefits spikelet formation, grain formation and vigorous pollen. The numbers and weights of grain per panicle were increased by applying K. A high K/N ratio in the plant also benefitted nitrogen metabolism and increased the amino acids in the grain. Such work on the components of yield formation is essential to an understanding of how fertilizers raise yields and is important in selecting the amounts of fertilizers to be applied to secure correct balance in the plant.

6. Gains from potassium fertilizers

6.1 Increases in grain yields

It is clear from the papers presented to the Colloquium that the supplies of potassium in the soils of southeast Asia are rarely sufficient for the continuous production of yields that approach the economic maximum that we must aim for. Responses to K-fertilizers have been recorded in most of the countries for which we have reports to the Colloquium.

De Datta reported typical results showing the returns from K-fertilizers used on grain crops, a few examples are given here: In China the increases in rice yields averaged 9.3 kg grain/kg K. While the average responses by wheat were 8 kg grain/kg K in India and 6 kg grain/kg K in Pakistan, very high responses have been measured in some areas of India — 25 kg grain/kg K in the Punjab and 14 kg grain/kg K in Delhi. Also in India maize yields in early experiments were increased at an average of 8 kg grain/kg K but more recent experiments have given responses of 26 kg grain/kg K in the black soils of Coimbatore.

Ho has listed and discussed the responses per kg K_2O and the value/cost ratios (VCR) for rice, wheat, maize and sorghum in the 5 countries where *FAO Fertilizer Experiments* were made in this region. Mostly the responses and VCRs were positive; some VCRs were quite large which indicates that using K-fertilizer would bring much profit to the farmer. *Ho* also showed how the responses were related to available K in the soils, and to soil classification.

Gains from the use of K-fertilizers in China were also reported fully by *Lin Bao, Liang De-Yin and Wu Rong-Gui.* As Chinese agriculture has been intensified K-fertilizers have been increasingly needed because the N and P fertilizers used had increased yields. The yields and qualities of the following crops were all increased by K-fertilizers at these returns per unit of K_2O:

	Kg product per kg of K_2O
Wheat	6.3 (grain)
Maize	8.4 (grain)
Potatoes	15.8 (tubers)
Sweet potatoes	51.4 (tubers)
Cotton	1.3 (lint)
Jute	4.6 (fibre)
Peanuts	8.4 (unshelled nuts)
Rape	2.4 (seed)
Soybean	3.5 (soybeans)
Sugar cane	3.1 (cane)

There are many indications that responses to K have increased greatly in areas where cultivation has been continuous and where HYVs and multiple cropping systems are introduced. A good example was provided by *Lin Bao [1985]* for wetland rice in China. He gave these average figures for a series of 62 experiments in 1958 and 260 experiments in 1982:

	Percentage of trials showing marked responses to			Response to a unit of applied nutrient		
	N	P	K	N	P	K
1958	82	50	29	16.5	5.5	3.8
1982	95	50	63	10.1	3.5	5.8

In the 1950s responses to K were much less frequent and smaller than to N and P. In 1982 average responses to N and P were less than in 1958 but the response to K was greatly increased. In the mid-1960s K-deficiency symptoms appeared in rice in a large area of China.

6.2 Improvements in plant health from the use of potash

Many examples have been published which show that adequate fertilizing assists plants to resist or tolerate diseases and pests. The effect of K-fertilizer in lessening the damage done to cassava by bacterial blight has already been mentioned in Section 3.2. Another example was presented to the *I.I.T.A./I.P.I. Workshop* held in Nigeria in 1980 by *Njoku and Arene* who showed that the severity of anthracnose disease of cassava was halved by applying 150 kg K/ha. The experiments tested K, N, P and Mg fertilizers, only K had any effect in conferring resistance to the disease.

Tea: *Gnanapragasam [1982]* reported that the damage done by the root-lesion nematode of tea *(Pratylenchus loosi)* was alleviated by doubling the application of K-fertilizer from 554 mg/plant/year to 1108 mg/plant/year. The nematode population was suppressed by the higher level of K.

Kanwar [1975] discussed potassium fertilization in the tropics and sub-tropics of Asia at the 10th IPI Congress in 1974. He stated that many plant diseases were accentuated by deficiency of potassium in the plants. Rice, coconut, cassava, groundnut, tea, and sweet potato all exhibit diseases associated with K-deficiency.

6.3 Gains in animal production

There is an increasing interest in many countries in increasing the production of animals to provide milk and/or meat for the population. This is sensible as humans require that a proportion of the protein they ingest should contain the balance of amino acids that animal proteins provide. Although the developing countries have large populations of livestock the average production of food from each animal is very much smaller than in developed countries; for example an average cow in developed countries gives about 5 times as much milk as the average cow in developing countries *(FAO [1985], Balch and Cooke [1982])*. The reason is mainly because both the quantity and the quality of food available to the animals is poor in developing countries. Production from the animal population will be increased by work to improve local grasslands and forage crops and to utilise the wastes from crops grown for human food (straw etc.). As people in the humid tropics become more prosperous they will ask for increased food from animal sources. Better quality protein for children will be supplied economically by milk, with meat as by-product. Pastures to feed these animals can conveniently occupy land that is difficult to cultivate or which is liable to erode when under arable cultivation.

Improved production from such pastures will often require lime to neutralise acidity and to supply calcium for both plants and animals; in addition attention must be given to ensuring that supplies of P and K are adequate for the legumes which are essential for increasing the nitrogen status of the pastures.

Agriculture in Thailand has of course to feed over 50 million people, but also 4.6 million cattle, 6.2 million buffaloes and 4.2 million pigs as well as 75 million chickens and 15 million ducks. (The pigs and poultry may compete with the human population for cereals). The area of permanent pasture in Thailand is reported by *FAO [1985]* as 308000 ha (less than 2% of the area under arable cropping).

Anake Topark-Ngarm [1984] stated that livestock improvement is now a major objective in Thailand by concentrating on up-grading of livestock and the development of pastures by introducing species of grasses and legumes. *Pirmpoon Keerati-Kasikorn [1984]* reported on nutrient deficiencies affecting pasture production in northeast and northern Thailand. Cattle and buffaloes are grazed in these areas on uplands that are unsuitable for cropping. The soils are poor and the vegetation consists of native grasses with small shrubs and bamboos, this is inadequate for livestock; legumes have been introduced to increase stockfeed and build up soil fertility. The low terraces in these areas are used to produce rice. The middle and upper terraces (on grey and red-yellow podzolics, and red-yellow latosols respectively) are under open dipterocarp forests, they are used for grazing; the soils are acid, low in organic matter and with low CEC values. Phosphorus and sulfur are generally deficient; potassium deficiency has been found in many areas and the introduced legumes have responded to K-fertilizer. It is clear that any reserves of K in the soils are quickly depleted; in some areas there has been no response to K-fertilizer in the first year but significant responses in the second year of experiments. Other accounts of recent advances in pasture research and development were given at a Seminar in Thailand in 1983; the above two references are quoted from the volume of proceedings published by *ASPAC [1984b]*.

Chanchai Manidool gave an account of pastures under coconuts in Thailand, unless adequate supplies of nutrients are arranged he stated «there will be adverse effects to both pastures and the palms. Coconut palms are know to require high levels of K for normal growth and high production. Also some species of pasture plants, such as guinea, have a high requirement for this mineral; thus nut yields could be depressed. A similar situation occurs in Sri Lanka. Thus, if these grasses are included in a pasture-coconut program, adequate amounts of K should be applied.» The result of a trial on guinea pasture under coconuts was mentioned by this author: the soil contained 50 ppm of available K before planting the grass, the plots were fertilized with a «15-15-15» compound fertilizer; after 4 cuts were taken available K had fallen to 11 ppm where no fertilizer had been applied and to 16 ppm where 646 kg/ha of this fertilizer had been applied. An experiment using «omission trial techniques» showed that supplies of N, P and K were seriously deficient. Problems in the development of improved pastures in Korea are described in the same volume by *Kee-Jong Lee*. He states that in spite of Government support with subsidies and loans for pasture establishment, farmers did not manage and utilize their pastures efficiently. A survey showed the average fertilizer use on pastures was 78 kg N, 31 kg P_2O_5 and 34 kg K_2O/ha: this level is about one-third of the N, and one-sixth of the P and K usually recommended.

7. Economic aspects of the use of potassium

The increases in yields from the use of K-fertilizers which have been recorded are profitable to the farmers. This is illustrated in Table 7 which abstracts data from a report on the fertilizer requirements on field crops in Thailand made by *C.T. Ho and C. Sittibusaya (1984)* to the *Fifth ASEAN Soil Conference* held in Bangkok in 1984. The report is based on the results of the *FAO/Thai Fertilizer Programme Project* in which large numbers of experiments (271 in all) were made on farmers' fields and which covered the main soil and climatic conditions of the country. Responses to K varied according to the K-status of the soils and other factors such as organic matter contents. The experiments defined the levels of soil K needed for near maximum yields and the fertilizer recommendations (some of which were used in the calculations made for Table 1). Table 7 shows a selection of data giving amounts of K applied, responses (in terms of kg yield per kg K_2O) and

$\frac{\text{value of extra crop}}{\text{cost of fertilizer}}$ ratios (VCR). There were separate sets of experiments on soybean, cassava and cotton. The average data for the whole of each group on a crop is stated in Table 7, together with the average values for the sub-groupings of the experiments (made on the basis of soil characteristics such as K-status or organic matter levels) which showed the best VCRs.

Table 7. Some results of field experiments made on farmers' fields in the FAO/Thailand Fertilizer Programme

	No of trials	Average of whole group of trials			Most profitable subsection group of trials		
		K_2O applied kg/ha	Return, kg of yield/ kg K_2O	VCR	K_2O applied kg/ha	Response kg yield/ kg K_2O	VCR
Sorghum (grain)	21	31	8.4	2.3	31	15.3	4.2
Soybean (beans)	12	38	2.3	1.7	16	4.1	2.9
	33	38	6.8	5.0	33	7.5	5.6
Groundnuts	29	38	4.7	3.9	47	4.9	4.1
Mungbeans	25	38	4.7	3.9	—	—	—
Cassava (tubers)	26						
Regosol soils		100	25	2.1	102	77	6.4
Grey podzolic soils		50	24	—	25	33	2.8
Cotton (lint)	22	38	1.8	2.8	58	5.3	8.3
	7	75	3.8	5.9	—	—	—
Kenaf (fibre)	39	50	12.0	6.0	75	17.8	8.9

That crops in Thailand need supplies of K-fertilizer to produce economic yields is clear from Table 7. That a similar situation prevails in other countries of southeast Asia was clearly shown by *Ho* in the paper which he presented to the Colloquium. He described the results of experiments on rice, wheat, maize and sorghum. The countries involved were Bangladesh, Indonesia, Philippines, Sri Lanka, and Thailand. In all the series listed in the paper the lower rates of K applied increased yields and gave a positive VCR. The only negative effects recorded were when large dressings of K were applied, then in a few series the extra K depressed yields and led to a negative VCR. Gains from potash were recorded in all the experiments on grain legumes, root crops, sugar cane, fibre crops, and vegetables. The higher rates of K were also profitable in many of the experiments on root crops, fibre crops, and vegetables, and in practically all the experiments on maize/legume intercropping.

7.1 Pricing policies

When Governments have reviewed the scientific evidence on the need for fertilizers to be used in their countries to achieve economically the production levels required for home consumption and for export they will develop their national fertilizer policy. It then remains to arrange that farmers receive advice on the fertilizers that they should use. Whether they accept this advice and maintain appropriate levels of fertilization will depend on the economics of the situation which is determined by the costs of the fertilizers and the prices farmers receive for the crops that they grow. Therefore the success of the fertilizer policy, and the acceptance of its practical aspects by farmers, will depend on establishing fertilizer and crop prices which ensure that farmers receive a return on their spending on fertilizers. Examples have been published of the effect of these price relationships on national use of fertilizers and average crop yields in the country. An example, as published by *J. W. Couston [1984]* is in Figure 3; the highest national yields of paddy, in the Republic of Korea and in Indonesia, were associated with small amounts of paddy needed to buy 1 kg of fertilizer. In countries where the price ratio was less favourable to the farmer much less fertilizer was used and national average yields were much smaller. A parallel set of data published by *ASPAC [1984a]* given in Table 8 shows that the highest national average yields were recorded in Korea and Japan where the paddy/ fertilizer price ratios were most favourable to the farmers. The price ratio was least favourable in Philippines and Thailand which had the lowest average fertilizer uses recorded and the lowest national average yields.

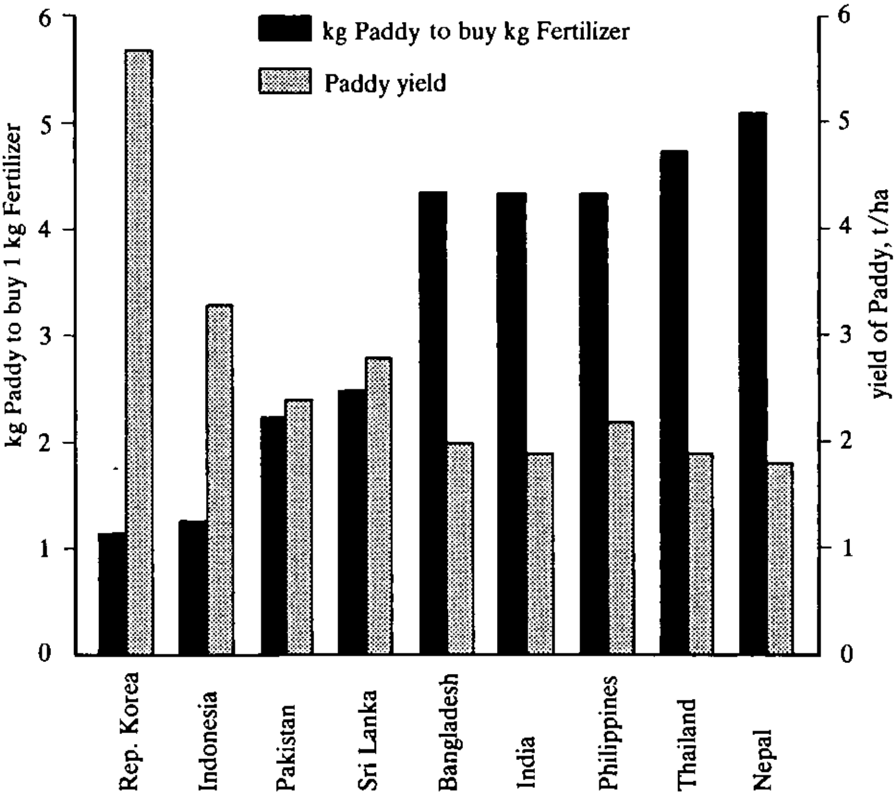

Figure 3. The relationships between the prices of crops and of fertilizers and the yields of paddy rice in countries of South East Asia (from *Couston [1984]*

Table 8. Ratios of prices of paddy and fertilizers, average use of fertilizers, and average yields of paddy, in several countries of southeast Asia in 1981/82

	Ratio of prices of paddy to price of nutrients in fertilizers	Average use of fertilizer kg/ha	Average yield of paddy kg/ha
Indonesia	0.87	54	3317
Japan	1.25	308*	5680**
Korea	1.29	380	5512
Malaysia	0.80	104	2833
Philippines	0.23	34	2196
ROC, Taiwan	0.64	462	3563
Thailand	0.22	17	1933

*308 kg/ha applied to rice, 346 kg/ha applied to cultivated crops as whole.
**Paddy yield was 5680 kg/ha in 1981/82, but 5730 kg/ha in 1982/83.

7.2 Farmers' reactions

Ho reported to the Colloquium that the VCR should be at least 2 to ensure that new technology is adopted by farmers in a developing country. Small farmers with little capital are generally more interested in treatments giving a high VCR than in obtaining very high nett returns. He showed that, with few exceptions, in Thailand where the crop/fertilizer price ratio is one of the least favourable applying 30-40 kg K_2O/ha gave a VCR of more than 2.

Ho also stated that N-fertilizers are preferred by small farmers because they give an immediate effect on the crop and they increase crop yields more than K-fertilizers do. However the use of HYV, and increases in cropping intensity, which had led to more evidence that K was needed, are gradually persuading the farmers to accept the need for potash and to use more of it.

Although N-fertilizers may have an immediate effect on crop growth which is usually more striking than the immediate effect of K-fertilizers, it does not follow that applying N is more profitable than applying K-fertilizer. A study by the *Fertiliser Association of India [1984]* showed that less than half as much paddy was needed to buy 1 kg of K_2O as was needed to buy 1 kg of N or P_2O_5. Consequently the financial return per rupee invested in fertilizer was almost identical for N and for K_2O over the period from 1971/72 to 1984/85. The same study reported the economics of applying N, P, and K for paddy, wheat, gram, and sorghum for the same period. For both paddy and wheat the returns per rupie invested in N and K_2O were very similar and returns from P_2O_5 were much smaller. For both gram and sorghum the returns from expenditure on K_2O were several times larger than the returns from expenditure on N (and applying P_2O_5 tended to be less profitable than applying N). The results of such studies are important and should be widely disseminated among farmers so that they can make rational choices on the fertilizers to be applied which will lead to maximum returns from their expenditure on these inputs.

8. Pathways to progress

Ho listed in the paper he gave to the Colloquium the important constraints which limit the use of potash in the countries that he reported on (and which are listed above in Section 7). These constraints were:

1) Lack of credit
2) Inadequate adoption of other inputs
3) Lack of knowledge and information
4) Uncertainty of crop/fertilizer price ratio
5) Inadequate irrigation
6) Difficulties with the availability of potash in remote areas.

I consider that Governments should be fully aware of these constraints to the use of potash and therefore to the realisation of their targets for agricultural production to feed their own people and for the industrial processing and exports that lead to national prosperity. Governments should do all that they can to remove these constraints which arise from economic and physical reasons; they should also give full support to the work needed in research on the soil/crop system and the application of the results to practical farming. *Ho* considers that future work should concentrate on strengthening extension work on potash and by making simple experiments, such as are done in the *FAO Fertilizer Programme*, to locate potash-deficient soils so that specific recommendations can be made for areas according to their potash status. I agree with him.

It is appropriate to conclude this section by quoting from *van Keulen's* paper which he presented to the Colloquium. Having established the very high potential for crop production in the humid tropics due to the radiation and energy the crops receive, he discussed the obstacles which prevent these potentials being achieved. He stated:

«Sustained high production requires inputs of materials from outside the agricultural community, at reasonable cost ... in many parts of the world, it appears that not so much the physical resources are the limiting factor for agricultural production, but that the economic environment in which the farming community is operating, is a serious limitation to crop production. Such a conclusion may on one hand seem disappointing for agronomists, since it could imply that their possible contribution to alleviation of the problem of hunger and malnutrition is very limited, on the other hand it does require continuous emphasis on the fact that agricultural science can provide solutions, if the economic incentives are strong enough.»

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APPENDIX 1. Yields, total production and the nutrients removed by 10 arable crops grown in Thailand, each crop occupying more than 100 000 ha in 1984.

	Yield kg/ha	Production thousands of tonnes	Nutrients removed per tonne			Nutrients removed by the crops		
			N	P kilogrammes	K	N	P tonnes	K
Rice, paddy	1979	19200	22.2	3.2	26.3	426240	61440	504960
Maize	2500	4150	27.4	4.8	18.1	113710	19920	75115
Sorghum	1366	370	25	1.8	5	9250	666	1850
Cassava	14970	19985	4	1.3	6.2	79940	25980	123907
Dry beans	643	284	31	3.5	6.6	8804	994	1874
Soybeans	1192	192	49	7.2	21	9408	1382	4032
Groundnuts in shells	1206	164	49	5.2	27	8036	853	4428
Seed cotton	1127	123	49.4	9.4	27.6	6076	1156	3395
Sugar cane	43140	24894	0.5	0.3	1.4	12447	7468	34852
Jute-like fibres	1007	199	50	17	133	9950	3383	26467
					Totals	683861	123242	780880

APPENDIX 2. Production of plantation crops in Thailand in 1984 and the nutrients removed in the harvests of some of the crops.

	Production tonnes	Nutrients removed per tonne of product			Nutrients removed in harvest		
		N	P kilo-grammes	K	N	P tonnes	K
Coconuts*	1100000						
Copra	35000	44	12	40	1540	420	1400
Palm oil, in fruit harvested	81361	108	12	87	8787	976	7078
Vegetables and melons*	3109000						
Fruit*	4111000						
Bananas fruit production	2045000						
nutrients in total crop		3.9	0.3	7.6	7976	614	15542
nutrients in fruit only		1.73	0.49	5.0	3538	1002	10225
Pineapples fruit production	1650000						
nutrients in whole plants		3.7	0.45	5.9	6105	742	9735
nutrients in fruit only		0.78	0.13	1.98	1287	214	3267
Natural rubber (nutrients removed in latex)	580000	6.4	0.9	3.6	3712	522	2088
Totals, including whole plants of bananas and pineapples					28120	3274	35843
Totals in produce removed from land					18864	3134	24058

*No data available on crop composition

APPENDIX 3. Average yields of a selection of arable crops in the world, in Asia, and in Thailand in 1984.

	Average yields, kilogrammes per hectare		
	World	Asia	Thailand
Rice, paddy	3186	3268	1979
Maize	3466	2771	2500
Sorghum	1463	1048	1366
Cassava	9117	11988	14970
Dry beans	594	549	643
Soybeans	1727	1231	1192
Groundnuts in shell	1123	1220	1206
Seed cotton	1492	1477	1127
Sugar cane	58873	52871	43140
Jute fibres	1801	1840	1007

APPENDIX 3a. Countries with the highest yields reported by *FAO [1985]*. On the world basis the countries recorded here had more than 1 million hectares of the particular crop. For Asia the country recorded had more than 100000 hectares of the particular crop in 1984.

	World (10^6 ha or more)		Asia (10^5 ha or more)	
	Crop yields in kg/ha			
Paddy rice	Korea Republic	6475	Korea D.P.R.	6506
Maize	U.S.A.	6692	Korea D.P.R.	6143
Sorghum	U.S.A.	3541	China	3157
Cassava	Thailand	14970	Thailand	14970
Dry beans	China	1183	Turkey	1464
Soybeans	Argentine	2601	Japan	1772
Groundnuts (unshelled)	China	2007	China	2007
Seed cotton	China	2642	Syria	2853
Sugar cane	Brazil	62533	Indonesia	85345
Jute fibres	India	1306	China	6587