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Fertilising for High Yield and Quality

CEREALS

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Fertilising small-grain cereals for sustainable yield and high quality

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E.John Wibberley, Shaldon, Devon, UK
October 2006

Biographical Note: Professor John Wibberley is an independent consultant with a portfolio role in agriculture and rural development working internationally. He holds degrees of the University of Reading, England in agriculture and soil microbiology and his PhD is in agronomy extension through farmers' groups. Previously Head of Agriculture at the Royal Agricultural College, Cirencester, England, he is now a visiting Professor there and elsewhere. Since 1994, he has been a Visiting Fellow in International and Rural Development at the University of Reading. He serves in Africa with RURCON an otherwise all-African team of development practitioners. John is an international Nuffield Farming Scholar and a Fellow of the Royal Agricultural Societies in the UK where he lives with his wife Jane and family.

Introduction

Small-grain cereals include wheat, barley, oats, rye, triticale, some millets and rice. Large grain cereals include maize and sorghums. All cereals make up a high proportion of most human diets (typically half daily intakes) and thus have a strategic place in many farming systems internationally. After the first chapter, the scope of this book covers small-grain cereals, excluding rice.

Soils and sites vary in their capacities to provide the required quantities of all necessary plant nutrients to supply the crops. Soil fertility is the ability of land to produce and go on producing useful crop yields. In order to maintain this long-term ability, it is essential to feed the soil itself not just the crop growing on it at a particular time. Fertilisers, manures, composts, green manure crops and legumes grown in rotation all offer strategic means for supplementing the supplies of plant nutrients. The potential influence of nutrient supplies upon plant physiology and performance is huge. An understanding of how the different cereals respond to nutrients – both extant in the soil and applied, especially as fertilisers – is vital to proper management of crops.

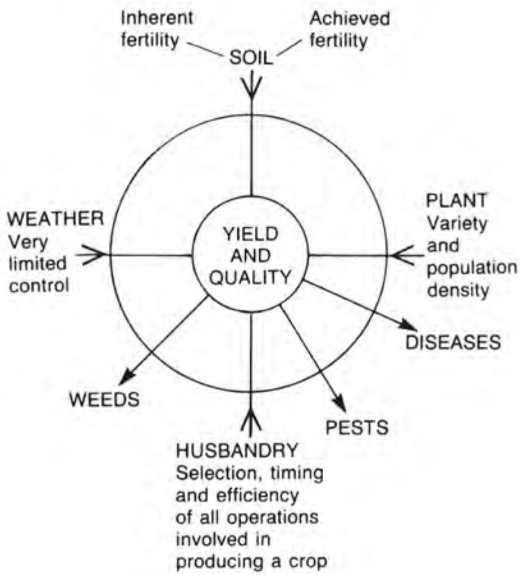
Small-grain cereals vary in yield not only because of their differing genotypes and cultivars of those, but also owing to differences in the ecology of their growing environments. It is important that yields are attained which can be repeated reliably and coupled with good quality characteristics for particular, ethnically dependent end-uses. The concept of sustainability implies productivity without exploitation and exhaustion of the production base – the soil. Fertilisers themselves are a scarce resource, either because they come directly from a finite mineral reserve in the earth’s crust or because their production requires substantial expenditure of fossil fuels. Thus it may not be a matter of maximising but rather of optimising yield in order to retain suitable grain quality, to use fertilisers wisely and to protect soil conditions. Very high input systems carry high economic risks and the quality of the cereal grain product tends to suffer when yields are maximised. There is a key influence of fertiliser type, dose and timing in relation to soil and crop management.

Fertiliser application management needs to be integrated with plant protection and with cropping sequences including cereals. Consideration needs to be given to the place of small-grain cereals within whole local systems of farming and food security in which they have a particularly central role.

Each chapter is intended to be self-contained but such that the whole interlinks. Chapter 1 seeks to explain the vital international importance of cereals. Chapter 2 presents an outline of their botanical and physiological characteristics in order to enable an understanding of the small-grain cereal crops to be managed. Chapter 3 focuses on the responses of cereal crops to nutrients while Chapter 4 discusses nutrient supply via soil and crop uptake patterns. Chapter 5 gives an international overview of cereal cultivation in relation to the agro-ecological context of climates and soils. Chapter 6 covers fertiliser effects on yield and quality, while Chapter 7 discusses the impacts of cropping systems on cereal nutrition and Chapter 8 concludes on fertiliser practice for cereal growers.

Concepts of sustainability have been much discussed and are central to the attainment of food security. They are summarised below and can be related to optimised yields of cereals consistent with the simultaneous pursuit of quality. There is legitimate concern that the world is becoming too dependent on wheat as a dietary species and, within that, on a narrowing range of highly bred genotypes, with current quests for genetically modified improvements and development of hybrid varieties (Bodson *et al.*, 1997) tempting investors to maximise their markets for the seed. Exacerbating this threat to true food security is the worldwide exodus of farmers and the assault on local food cultures of obesity-inducing ‘fast foods’ (Schlosser, 2002). By contrast, proper nutrient management using all available local sources, correctly supplemented by fertilisers where necessary, offers a real contribution to sustainable food security.

Farmers and agronomists/advisers need to understand, observe, monitor and manage the variables affecting crop yield and quality on a field by field basis over time as shown in the panel below. Keeping records to inform this is important.



Concepts of Sustainability (after Wibberley, 1995)

Provision	For 'grandchildren' by cropping in a way that they can follow
Relationship Conservation	'Community values' of local food chains
Local self-reliance	Including indigenous technical knowledge (ITK)
Productivity	Supplying present needs without compromising future capacity
Profitability	Surplus wealth to share and use to care for consumers and land
Reliability	Steady performance from year to year of the overall crop rotation
Resilience	Flexibility/'elastic' behaviour under stress with a range of crops
Appropriate	Technology suitable for both user (farmer) and place
Replenishment	Of the renewable resource base by optimising nutrient cycles
Protection	Environment neither eroded nor polluted
Biodiversity	Maintain range & balance of wild & farmed species & cultivars
Adaptability	To change, notably impacts of globalisation and global warming

Too much research and experimental data is not applied to field practice. Findings and principles need to be accessed. Accordingly, this book attempts to clarify understanding and to provide practical information for action in the hope of improved nutrient resource management for small-grain cereal crops so that they may be effectively produced for better food security with improved farm returns.

Chapter 1: Global Importance of Small-Grain Cereals

1.1. Defining cereals

The chief temperate cereals are wheat, barley, oats and rye plus durum wheat and triticale, whilst those of the subtropical and tropical areas are chiefly rice, sorghum, maize and various millets, especially pearl millet (*Pennisetum typhoides*) and finger millet (*Eleusine coracana*). Cereals include several locally vital but internationally insignificant grains such as tef (*Eragrostis tef*) in Ethiopia. Acha – also called fonio or 'hungry rice' (*Digitaria exilis*) in certain parts of West Africa, including Jos Plateau in Nigeria, and Northern Sierra Leone - provides a good entry crop grown before another staple food crop of sweet potatoes. Grain is strictly a wider term than cereal because it includes legumes and other edible seeds such as beans. Oilseed crops are *not* cereals; neither is buckwheat (family *Polygonaceae*), though it is sometimes loosely considered so when grown for its grain to produce flour (*sarrasin* in Brittany, France).

1.2. Origins of cereal cultivation

It is generally agreed that cereal cultivation started some 6,000 years ago in the so-called 'fertile crescent' of the Middle East, probably in Iraq (especially through the valleys of the rivers Tigris and Euphrates), around Jericho Israel, and in Egypt. Barley is reckoned to have been domesticated before wheat. Indeed it was barley which featured in the Biblical case of Ruth gleaning in the fields of Boaz and the miraculous feeding of the five thousand by Jesus using the two fish and five barley loaves of the boy. Barley *(Hordeum sativum)* remains well adapted to less fertile land than wheat and is commonly found in North Africa.

Oats *(Avena sativa)* were probably first noticed as weeds in barley and wheat crops and cultivated later. The wheat first cultivated widely was Emmer (*Triticum dicoccum*), a tetraploid (having double the normal number of chromosomes carrying genetic information in each cell) derived from the wild diploid Spelt wheat (*T. aegilopoides*). These had grains that did not thresh out easily. Thus it was a breakthrough when Rivet wheat *(T. turgidum)* was selected as a freely threshing species. However, the majority of the wheat now cultivated as the world's leading cereal of trade is the hexaploid *T.aestivum* (breadwheat). Plant introduction has spread the types of wheat now commercially important. For instance, Stoskopf *et al.* (1993) draw attention to the statue of the Mennonite farmer in North Newton, Kansas, USA who is credited with introducing hard red winter 'Turkey' wheat from Russia to the USA in 1874, so-named because the Russians had obtained it from a valley in Turkey. Wheat has shared with rice the distinction of being separately classified by the UN Food and Agriculture Organization (FAO), whilst the other cereals are collectively termed ‘coarse grains’.

Rye (*Secale cereale*) cultivation is reckoned to have begun only some 3,000 years ago. It extended habitation northwards into Europe, notably Poland, Russia and Scandinavia. Spring rye is adapted to areas with very short growing seasons. In about 1875 in Scotland, rye (*Secale*) was crossed with wheat (often *Triticum durum* is now used, i.e. durum, pasta or macaroni wheat) to produce triticale. This was further developed in North America after World War II and has been adopted in Europe and the UK more latterly, where Polish cultivars are most popular. Indeed, *Triticum durum* itself has been grown as a minor specialist cereal in the UK since about 1980.

Maize *(Zea mais)* - a large grain cereal - originated in the New World and was adopted as the staple cereal of Indians in the Americas, hence its being called Indian corn or just corn in North America, whilst ‘corn’ in Britain is an all-embracing term for cereals. Rice became the staple cereal of the Asian and humid tropics. It is cultivated as paddy (padi) in wetland, puddled fields. Dryland (upland) rice is grown in the seasonally drier tropics. Sorghums and millets - large grain cereals - of various *genera* fulfil the central dietary role for the dry tropics.

Evidence of breadwheat cultivation in Britain dates back some 5,000 years. Julius Caesar’s men cut corn following their invasion in 55 BC. One of the earliest rotations practised in Britain was autumn-sown cereal (usually wheat), spring-sown cereal (usually barley) and then fallow. Cereals occupied 50 % of the four-course rotation introduced in the seventeenth century by Lord Townshend on his light-textured soils at Raynham, Norfolk, England. Paddy rice has been continuously cultivated on the same terraces for some four thousand years in the Far East, for example in Java, Indonesia and in the Philippines.

1.3. Improved cereal productivity

An expanding understanding of cereal nutrition has played a key role in laying the foundations for productivity improvements. In the mid-nineteenth century, Rothamsted Experimental Station in England began continuous cereal-growing on the same field. Similar trials have been started since and commercial practice has also been to grow continuous cereals as well as those in rotation. Attention has been paid to the whole farming system and its effect on soil restoration for cereal growing.

Early in the twentieth century, Sir George Stapledon, who worked at the Royal Agricultural College, Cirencester, England before starting the Welsh Plant

Breeding Station in 1919, advocated the greater integration of grassland and cereal production in the system of alternate husbandry or ley (short-term grass) farming. Typically, in this system three-year grass leys alternate with two or three years of cereal crops. It is now common to find cereals in rotation with other combinable crops, both oilseeds and pulses. European Union (EU) policy, starting with a voluntary scheme in 1987, has required land to be 'set aside' in order to reduce surplus production and this may also be rotated within the cereal sequence. Overproduction has co-existed with huge need elsewhere in the world.

Wheat yields in Britain almost quadrupled (from 2 t/ha to almost 8 t/ha on average) since 1945, having remained more or less static from 1800 to World War II. These yield improvements arose from:

- Better varieties, notably with a greater grain/straw ratio (so improved *harvest index*).
- Better husbandry, including timely and effective field operations, the promotion of positive factors such as soil potential including fertiliser application, and protection from negative factors (weeds, pests, diseases).

1.4. Cereal importance

The importance of cereals in world agriculture is great. There are some 13,000 million hectares of land in the world of which just over 10% is reckoned by the FAO to be arable. Of this, more than half is occupied by cereals.

World wheat yields still typically average around 2.6 tonnes per hectare, about 33% of the West European level of recent years, and total annual world cereal production is usually around 2,000 Mt (Table 1.1, FAOSTAT data, last accessed February 2006). Of this, something over 550 Mt is wheat, slightly more is rice and almost 640 Mt is maize, and barley only amounts to some 140 Mt, while oats are around 25 Mt; rye and triticale are less than oats. The FAO in 2003 reckoned that between 1995 and 2010, wheat demand will increase by about one third (32%) – equivalent to an extra 180 Mt wheat. World grain stocks have recently declined. However, there is considerable scope with better management on the fertile soils within countries such as Lithuania, Poland, Russia and Ukraine greatly to improve average yields.

Grain growing for trade as a commodity crop is becoming increasingly concentrated in fewer hands. Kerr (2002) notes that across the Canadian Prairies in just two years (2000-02) the number of grain elevators had more than halved from 660 to 290. Grain trading is becoming a significant factor in the world's political balance, especially between China and the USA. China trebled its wheat production in the past 25 years (1979-2004) and is now the world's fourth biggest cereal exporter after the USA, Germany and Japan, despite the fact that it has diminishing stocks (Table 1.2, USDA 2003). Food safety in grain for export is monitored by the China National Grain Trades Association. China is the most populous country on earth with 1,289 million people, projected (by the USA Bureau of the Census) to increase to 1,394 million by the year 2050 when India will have overtaken it at 1,628 million. National food security for every country, rather than excessive trade, is both necessary and desirable from the points of view of environmental stewardship, farm livelihoods, food cultures and conflict mitigation (Madeley, 2000; Shiva, 2000; Devereux & Maxwell, 2001; Fell, 2004; Wibberley, 2004). In this, cereals have the key food role to play with wheat continuing as 'the staff of life'.

Whilst quantitative terms such as area, yield and production indicate the extent of cereal importance, reasons for this are as follows:

- Cereals are *multipurpose*, providing human diet, livestock feeds and a wide range of farm and industrial raw materials (including starch, oil from maize, and biofuel potential).
- Cereals are *demanded* consistently throughout the world, being a concentrated carbohydrate source with useful protein, fat, mineral, vitamin and fibre content. They have proved fairly stable-priced commodities to trade although the past decade has seen some considerable price squeeze.
- They are easily *storable* after drying to around 14% moisture content or less.
- They are *transferable* both in terms of ease of transportation and in terms of convertibility to various end-products for different markets. This contrasts with a commodity like butter which sensibly has only restricted use as such.

Table 1.1. World area, yield and production data for cereals in 2005.

Cereal	Area (Mha)	Yield (t/ha)	Production (Mt)
World total	681.7	3.25	2219.3
Wheat	216.2	2.90	626.5
Barley	56.5	2.45	138.3
Oats	11.8	2.08	24.6
Rye	6.6	2.27	15.0
Triticale	3.5	3.83	13.5
Rice (paddy)	153.5	4.00	614.6
Maize	147.0	4.71	692.0
Sorghum	42.7	1.33	56.9
Millets	35.9	0.76	27.3
Acha (or Fonio)	0.3	0.71	0.2
Mixed grain	1.8	2.75	4.9

Adapted from: FAOSTAT data, last accessed February 2006.

Table 1.2. China: Wheat and coarse grain production, stock and trade (Mt).

Year	Cereal	Start stocks	Prodn.	Imports	Use	Exports	End stocks
2001/2	Wheat	91.88	93.87	1.09	108.74	1.50	76.59
	Coarse	81.66	122.27	1.96	133.08	8.63	64.19
2002/3	Wheat	76.59	90.29	0.43	105.20	1.72	60.39
	Coarse	64.19	129.15	1.92	136.27	14.59	44.40
2003/4	Wheat	60.39	87.00	0.50	104.50	1.30	42.09
	Coarse	44.40	121.30	2.31	137.71	8.53	21.77

Adapted from: USDA.

1.5. Uses of cereals

Human dietary uses lead in significance. Cereals consumed directly account for about 55% of the average human diet; they also provide around half the dietary protein intake of humans. Indirectly, they contribute more owing to their inclusion in livestock diets producing meat, eggs, milk and dairy products. The proportion of diet contributed by direct cereal consumption generally increases the poorer the country, amounting to over 90% of diets in the poorest areas.

A country like India supplies some 150 kg of cereal grain per person per year (around 0.4 kg/day) – more than is available per person in Sub-Saharan Africa. Less developed countries contain over 75% of the world's population but produce less than 50% of world grain; over 80% of grain supply in them is eaten directly, whereas industrially advanced countries feed over two-thirds of their cereal grain supplies to animals. Millstone & Lang (2003) note that it can take up to 930 kg of cereal grain per person per year to sustain a meat-based diet.

Cereals are fairly well balanced nutritionally, and whole grains are a valuable source of fibre which is considered particularly protective against constipation. By providing bulk, dietary fibre also protects against excessive energy intake and absorption with its resultant obesity and diabetes. Recent surveys indicate that some 30% of North Americans are obese and some 22% of Britons. Furthermore, adequate fibre protects from diseases related to cholesterol and bile acid metabolism such as gallstones and certain forms of heart disease. Western man's typical fibre intake of 20 grams per day stands at one-third to one-sixth of that in rural tropical societies. Broadly, for western people, a doubling of fibre and starch intake, halving of salt and sugar intake and reduction of one-third in the present fat intake is recommended. An increased consumption of whole (unrefined though physically processed) cereals can achieve much of this adjustment at once. There is reckoned to be a 10% per annum growth rate in the demand for whole-grain products in the UK and even higher for those organically grown (by alternative methods of nutrient supply and weed control with minimal or nil synthetic chemical inputs). Only the tiny minority who suffer from coeliac disease (sprue syndrome) cannot cope with cereal protein (especially gluten) since it generates toxins in the bowels.

Livestock feeds account for much use of all cereals. Some cereal crops, such as rye, are grown as forages to be either grazed at the vegetative stage by sheep or cattle or else cut and carted to them. Cereals may be fed as whole grains, ground, crushed, rolled, acid-treated or caustic soda treated. Whole crop cereal silage may be made by cutting crops when the grains are soft cheesy-ripe. Some crops are grown deliberately for this purpose and may include other species, notably vetches or other legumes. The bulk produced may be good but cereals alone give a low protein silage by contrast with pasture grass alternatives. Heavily diseased or irregular crops may be taken for silage as a second choice, especially if patches in a crop have been filled by later-sown seeds. Green oats are made into hay in some regions such as Israel.

Cereal straw provides both feed and bedding, to some extent simultaneously, especially for loose-housed cattle and other livestock. It may be fed fresh or ammonia- or caustic soda-treated to improve its nutritional value for ruminants. Processed straw has also been incorporated into compound feeds.

Industrial uses of cereals may well increase both as a means of diversifying market opportunities in regions where cereals can be in surplus, such as Europe, and also as a sustainable means of providing renewable goods including biofuels. Cereals may be harvested as whole, near-ripe crops and fractionated industrially. Apart from the physical properties which make grains a source of adhesives and fillers for various purposes, they are also sources of specific chemicals, notably starch and dextrin. As concentrated energy sources, their starch can be converted to sugars and then alcohol for use as fuel, and starch can also be made into biodegradable plastics and other goods. Straw is a potential fuel. Some 1,000 million tonnes are produced annually in the world, only part of which is used for animal feeding and bedding. This could be very important since yields of 4 t/ha are equivalent to the annual incremental growth of temperate mixed forest. Fuelwood supplies in less developed countries are increasingly even more critically short than food supplies from a land conservation point of view. The problem in any industrial usage of straw is its bulk and the separation of supply from areas of demand with consequent high energy costs for collection and re-use. Even wider adoption of high-density balers would help greatly.

The fibre content of straw is high and makes it a potential material for manufacture of coarse paper, pulp, packaging, insulation board and construction board. In addition, straw crafts are important rural industries in many countries, not only for aesthetic items but also for useful goods such as straw mats and ropes. Staniforth (1982) thoroughly reviewed the commercial uses of straw.

1.6. Distribution of cereals

Cereals are adaptable, the different species and varieties tolerating a wide range of soil, climatic and agronomic conditions.

They are an integral part of most arable systems of cropping. It is difficult to devise sensible arable rotations which omit cereals.

Location of strategic supplies is vital in world politics and in food security.

Wheat is important over the widest range of latitudes of any cereal. Though principally a temperate cereal, it is also cultivated in the highland tropics. It requires greater sunshine receipts and higher soil fertility to perform well than do the other temperate cereals. It needs an early start to the growing season and plenty of summer sunshine to ripen; it is more resistant to winter frost than barley and much more so than oats. Wheat responds more to heavier and richer land while barley is grown on lighter land. Oats respond to better soils than they are often given and are found in more northerly, cooler, wetter latitudes, while rye is the northern-most cultivated cereal, quite often on poor soils though again capable of responding to richer ones. See Chapter 5 for more on distribution, especially in relation to nutrient management.

1.7. Cereal production and system policy issues

They are relatively easy to produce in that a total failure of crop or markets is very unlikely by contrast with many crops. The labour requirement is fairly low per tonne produced.

Cereals have proved fairly straightforward to mechanise. This arises partly from the harvest fraction being above ground and also from their widespread cultivation which has justified the development costs of improved harvesters.

Relatively low capital investment per hectare is needed for a cereal production enterprise.

A cereal gives a relatively good ratio of energy output to energy input per hectare to produce it. It also gives a good yield in relation to seed planted (for instance, 40:1 or so for wheat in contrast with peas at around 15:1).

In order of quantity of production, wheat ranks first, closely followed by rice and maize, then barley, sorghum, oats and rye. Other cereals are of relatively minor importance overall though they may provide the staple diet in particular districts. Wheat can produce up to 12 tonnes per hectare commercially on good land. Irrigated rice crops (paddy) using short-strawed, quick-maturing (90-day) varieties can produce four crops per year with a total yield in excess of 20 t/ha.

World food supplies hinge on cereal production, trade and reserve stocks of grain. Before 1940, every region except Western Europe was a net grain exporter; now Africa, Asia, Latin America, and Eastern Europe are net importers. Never before has there been so much information about supplies or so much grain transported for trade and aid to poorer areas of the world. Yet supplies can be very vulnerable to droughts, as in Australia where the normal harvest of approaching 25 million tonnes of wheat and some 7 million tonnes of feed and malting barley - much of it usually a major part of world exports – has been cut to around 40% of normal production by drought in 2002/3, necessitating imports to Australia. Meanwhile, in Africa, one child in three dies from hunger and related diseases before attaining school age. Despite HIV/AIDS, Africa has had a rapid population growth - with some countries having a population doubling time of less than 18 years - but scarcely an overall improvement in food production over the past decade. Food supplies have been drastically short in many regions, owing especially to political turmoil. Over one billion people (one in six of the world's population) are trying to live in absolute poverty on less than US$1 per day, and some 30,000 children die daily from hunger and related causes.

In this context, cereal grain has already become a most significant political weapon in the modern world. North America remains the chief exporter of cereals though the EU is increasingly significant. Whilst Russia is the world's largest wheat producer, she has needed to import during the past twenty years, as has China. However, India and the ASEAN countries (Association of South-East Asian Nations) operate their own grain reserves and have recently more or less maintained self-sufficiency. Far Eastern rice is now exported to Africa in significant amounts and is the only rice regularly obtainable in some West African local markets.

Overall, world cereal supplies have kept pace with population increase though still some 850 million people go to bed hungry every night. The problem of regulating the expansion of cereal surpluses elsewhere has become of huge political and agricultural significance. Having been encouraged to produce and having succeeded in doing so, some farmers now often feel superfluous, yet they struggle with wheat prices that have fallen to around one-third of their level of two decades ago. However, Jonathan Swift (1667-1745) wrote the now-famous lines in *Gulliver's Travels,* 'whoever could make two ears of corn or two blades of grass to grow upon a spot of ground where only one grew before, would deserve better of mankind and do more essential service to his country than the whole race of politicians put together.' Certainly the challenge of good husbandry for both sustainable yield and quality has never been greater for farmers. The challenge of guiding overall production has never been greater politically. WTO policies of non-discrimination against imports are leading to least cost production pressures in order to grab markets – whoever is there already and no matter how far the grain is carted. Ironically, and in complete though welcome contradiction of this, the world community is being urged to 'protect the environment' by reducing energy consumption. Sustainable livelihoods need approaching in an integrated manner - environmentally, economically, socially, politically and spiritually. In this context, an internationally agreed *Highway Code* for agricultural trade is urgently needed. (Gorringe & Wibberley, 2002; Appleby *et al.*, 2003; Ray *et al.*, 2003; Lang & Heasman, 2004; Clover, 2004; Tudge, 2004; Wibberley, 2004; Hodges, 2005).

It can be argued that world hunger and unemployment problems have the mutual solution of more labour-intensive agriculture yet many farmers are leaving agriculture worldwide. However, closer crop observation, the ability to cultivate crop mixtures, cultural weed control plus the greater recycling of nutrients in labour-intensive systems can enhance output and significantly improve the energy-efficiency of farming systems. An integrated, farming systems development approach is needed (Duckham & Masefield, 1970; FAO, 1989; Dixon & Gulliver, 2001). A summary of the essentials of this is given in Table 1.3 (Wibberley, 1995).

Table 1.3. Essentials of a farming systems development approach.

IT IS **NOT**	IT IS
Farm only	Farm-household based
Linear process emphasis	Cyclical process based
'Blueprint' approach	Location-specific
1st capital-intensive	1st Management-intensive
External input oriented	Local resource based
Subsidy dependent	Effort dependent
Finite and exhaustive	Sustainable
Outsider-led (but outsider-served)	Farmer-dominant
Market first	Family 1^{st} ; animals 2^{nd} ; market 3^{rd}

Adapted from: Wibberley, 1995.

1.8. Biotechnology and genetically - modified (GM) cereals

Biotechnology is a wide, multi-disciplinary field of science dealing with the use of micro-organisms, genes and biochemical components of cells to produce goods or provide services. Genetically modified (GM) crops have become widespread, especially in the Americas, and accounted for some 5% of global cropland in 2004 (James, 2005). However, they are controversial (Farmers' Link, 1998; Runge, 1998; Barton & Dracup, 2000; Bruce & Horrocks, 2001; Sharma, 2003).

Biotechnology includes:

- *Genetic engineering*, for instance, incorporating genes for improved gluten quality in wheat and threonine (an amino acid) content in barley and using recombinant DNA to give more durable disease resistance. This includes forming new combinations of genetic material by the insertion of nucleic acid molecules produced by whatever means outside an organism, into any virus, bacterial plasmid or other vector system and their incorporation into a host organism in which they do not naturally occur but in which they are capable of continued propagation. It also includes various techniques for the direct injection of heritable material prepared outside the organism or the use of cell or protoplast fusion which could not occur by natural means. In theory, this might mean the admixture of anything living with anything else (already deep sea fish genetic material has been incorporated into Sugar Beet to make it more frost-hardy). Forms of genetic engineering which alter the natural rate of genetic variation in order to diversify or accelerate the natural breeding programme are much more ethically acceptable. These include cell fusion between organisms which could breed naturally too, induced polyploidy and mutagenesis (long used, though there should surely be limits to the kind of pressures to which an organism ought to be exposed). It is important in evaluating on a case-by-case basis to distinguish what is actually meant by 'genetic engineering' in that particular case.
- *Tissue culture*, for example, immature wheat embryos have been cultured at Rothamsted to produce hundreds of plantlets which can be assessed subsequently in normal field trials. These plants show considerable variation from which new cultivars of wheat may emerge, so diversifying and accelerating the plant breeding process.
- *Fermentation*, for instance, at the Plant Breeding Institute in Cambridge, UK, the enzyme *alpha*-amylase from wheat, which hydrolyses starch (and makes for low Hagberg numbers in wheat), has been incorporated into yeast by transferring the gene which controls this enzyme. The yeasts may then be used to digest starch from cereals in the commercial production of ethyl alcohol (ethanol, an industrial alcohol).
- The possibility of *nitrogen-fixing* nodules on cereals is being further investigated; certainly pearl millet can fix nitrogen symbiotically when a *Spirillum* bacterium is there.

Already, some 90% of maize grown in the Midwest of the USA is genetically modified in some way and, controversially, sold into commodity markets largely unlabelled. Pressure is mounting from corporate owners of GM technology for a relaxation of European regulations on GM development and marketing.

Key long-term issues at stake in genetic modification of cereals (as for other crops) are:

- Are the products safe for consumers?
- What are the consequences for the environment given that irreversible escape is inevitable?
- How far should one cross more than very closely related species boundaries in gene transfer?
- What effects on the structure of farming may arise given that larger businesses tend to use GM?
- Who really controls it – this is a big issue – since the Trans-National Corporations (TNCs) 'own' GM?

The case for and against GM crops can be summarised as follows:

GM crops - the case *for*:

- *Multiple gene copies* - Can be easily made for desirable characteristics.
- *Rapid breeding* - Can accelerate the provision of improved crop varieties.
- *Wide species choice* - Genes from virtually anywhere can be drawn upon.
- *Reduced chemical use?* - But practice so far does not meet expectations.
- *Nutraceuticals* - Scope to make pharmaceutical and nutritional products.
- *Stress resistance* - To suit dry or saline or other harsh environments.
- *Feed the world?* - Scope to breed adaptable high-yielding varieties (HYVs).

GM crops – the case *against*:

- *Boundaries?* - God created everything 'after its kind'; should we interfere?
- *Safety?* - Meddling with components threatens people of allergenic susceptibility.
- *Environment?* - Once released, it is difficult to recapture or control destinations.
- *Structure?* - Larger businesses dare not refuse GM for fear of losing markets.
- *Control?* - Is already alarmingly supranational, beyond democracy within TNCs.

- *Commoditisation?* - Already accelerating e.g. ‘fast food’ GM cereals.
- *Alternative?* - Sustainable, energy-efficient, productive non-GM systems exist.

It seems unreasonable and unnecessary to rule out everything which is described as 'genetic engineering'. However, it is essential that the techniques are refined before field release and that some applications are ruled out - such as those whereby herbicide-resistant varieties of cross-pollinating species are generally released. We are clearly on the threshold of something that demands extreme caution in view of the unpredictable biological, ecological and rural community economic knock-on effects. Use in controlled environments of accelerated breeding techniques for intractable medical and intermediate plant breeding purposes seems a legitimate cause to pursue further. Clear labelling is a paramount requirement so that consumers know what they are buying and eating. The whole issue of GM certainly needs to be governed correctly, especially as regards the poorer countries (Paarlberg, 2000). It is here deemed better first to support local sourcing of sustainably produced food and farm products grown on well managed soils adequately enriched with nutrients.

1.9. Cereals and food security

Quantitatively, cereals dominate among all foods. Strategically, food reserves are often held as grain and overall food supplies are expressed in ‘grain equivalents’.

Brown (1998) notes that ‘feeding 80 million more people each year means expanding the world grain harvest by 26 million tons, or 71,000 tons a day’; this assumes the current world population growth rate is sustained. World population in 2004 is 6.3 billion but predicted as 9.4 billion by 2050, and urbanising. Of course, sustainable consumption is as important as sustainable production of food (and other resources).

Real food security is based on optimising locally grown supplies with associated local land care for future generations to enjoy that security, together with a strategic reserve policy. The International Food Policy Research Institute, USA (IFPRI) 2020 vision is of a world where ‘every person has access to sufficient food to sustain a healthy and productive life, where malnutrition is absent and where food originates from efficient, effective, low-cost food systems compatible with sustainable natural resource use’. Nowhere is this more urgent than in Africa (Devereux & Maxwell, 2001; Wibberley, 2004).

Food security depends upon respect for land and natural resources as God-given, covenanted place (rather than contextless space for technological exploitation) designed for harmonious relationships between Creator, humans and other creatures (Wibberley, 2004).

Food security at household, village, national and international level requires:

- *Availability* of adequate quantity and quality of locally-grown agricultural produce.
- *Accessibility* of supplies for urban/land-remote areas (food attainable, affordable).
- *Appreciation* of the close link between nutrition and health for work and enjoyment.
- *Avoidance* of undue risk through livelihood vulnerability, hazard and shock.

Agricultural research and extension needs to be geared to foster sustainable farming systems with better local marketing. To achieve greater food security, farmers in each village/district need to produce a variety of crops - especially cereals - as mixtures and in rotation, control erosion, maintain soil fertility, keep some animals between them and reduce losses of food in storage. From Farm Asset Resource Management Study (FARMS) groups various forms of Farmer-Controlled Business can spring - not because told by government or by private entrepreneur to co-operate, but because the members themselves decide to do so (Wibberley, 1993, 1997). This strengthens capacity to deliver and sustain food security at village/district level and to market concertedly to nearby towns, to contribute to national food reserve stocks, and to sell in a moderate way into international niche markets.

Proper nutrient management is critical to the achievement of the above food security aspirations, and cereal crops are central to its focus. The aim of chapter 2 is to present an overview of the botany and physiology of these crops in order to enable clearer understanding of their nutrient responses and their husbandry requirements.

Chapter 2: Botany and Physiology of Small-Grain Cereals

2.1. Cereal classification

Cereals belong to the botanical family *Gramineae*, a large monocotyledonous family of some 600 genera and around 10,000 species. They are named 'cerealia' after annual offerings made to the Roman goddess Ceres, giver of grain. Cereals are members of the grass family with relatively large edible grains. The grain is strictly a one-seeded fruit called a caryopsis in which the pericarp (fruit-coat) is thin, translucent and fused to the seed-coat or testa. Perennial cereals exist such as perennial maize and *Agrotricum*, which is a cross between wheat and couch grass, but only annuals are commercially important. Each cereal exists in many varieties. Rice, for instance, has some 7,000 varieties of which only a few are cultivated (cultivars).

2.2. Cereal identification

The various parts of the different cereal species must be identified, their functioning (physiology) considered and their growth stages (GS) through the life cycle described if one is to understand the basis of sustainable yield and high quality determination and thus employ sound crop husbandry.

Space does not permit exhaustive diagrams and photographs of all cereals, but key parts are covered: grains and germination (Fig. 2.1); vegetative recognition of cereal plants (Fig. 2.2); features of some cereal heads (Fig. 2.3).

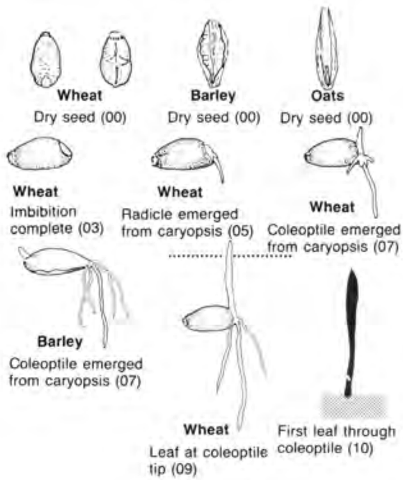


Fig. 2.1. Seed, germination and seeding growth (Tottmann, 1987).

A hand lens is vital equipment when examining cereals. Attention to detail underpins good husbandry, which starts with close observation of the crop. It is essential to have a basic grasp of the design and functioning of a living creature in order to begin to manage it effectively.

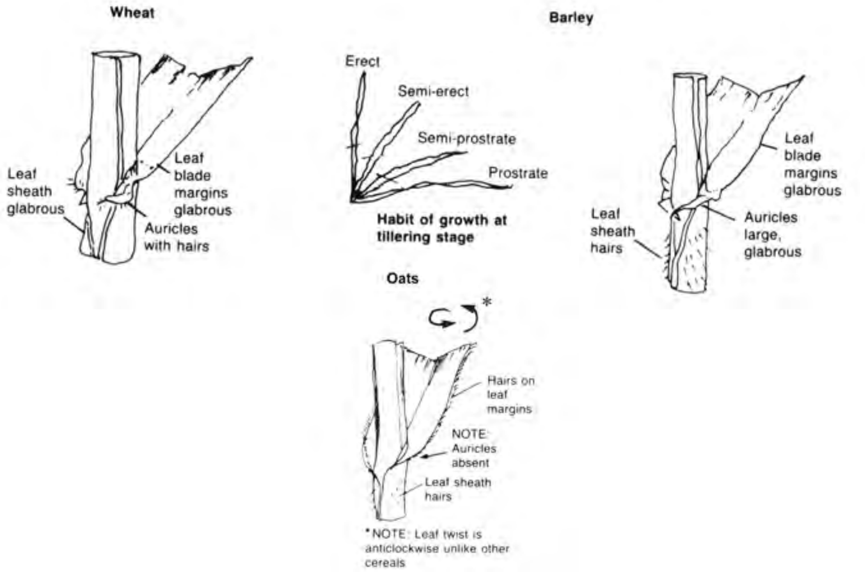


Fig. 2.2. Vegetative recognition of cereal species (Wibberley, 1989).

Fig. 2.3. Recognition of some cereal heads.
A = Rye, B = Spelt, C = Two-ranked Barley, D = Wheat
(Strasburger, A Text Book of Botany, 3rd edn., 1908, Macmillan and Co. Ltd., reproduced with permission of Palgrave Macmillan).

2.3. Basic cereal physiology

The basic process upon which all green plant production, including cereals rests is photosynthesis. This process not only provides the majority of the food consumed by man and livestock, since carbon dioxide derivatives provide over 90% of cereal yield, but also it replenishes oxygen depleted by respiration. Total *biological yield* or biomass (all plant parts) has advanced little if any in modern cereal varieties. What has improved is *economic yield* through better crop management of varieties bred for increased grain: straw ratios and disease resistance. Grain:straw can now be as favourable as 2:1 and is often 1:1; only recently it was 1:2 and it still remains as poor as 1:5 in some traditional varieties of sorghum and millet in Africa and Asia.

Harvest index (percentage of above-ground DM) yield which is grain is measured as:

$$\frac{\text{DM in grain x 100}}{\text{Total DM}}$$

Harvest index varies in practice between 30 and almost 60% for currently grown wheat and barley cultivars. Dwarf varieties based on the Rht (reduced height) genes have contributed significantly to the so-called ‘green revolution’ in both wheat and rice yields and have the higher indexes.

There is considerable variation in net photosynthesis in the field owing to:

- *Low and variable efficiency of light interception*

  Commonly only 1% (but up to 3%) of total incident solar radiation is actually trapped by the crop, though this could be trebled in the field by timely development of an optimum-density leaf canopy and by selecting the most efficient cultivars.

- *Variation in photosynthetic rate*

  The biggest distinction identified relates to the speed of the biochemical pathway between the one-carbon (Cl) molecule of carbon dioxide and the six-carbon (C6) glucose in photosynthesis. Those which rapidly act to produce a C_4 molecule are maize, sorghum and millet, whilst the less efficient C_3 cereals - wheat, barley, oats, rye and rice - use a slower biochemical pathway. (C_4 cereals respond up to double the light intensity of C_3 cereals, tolerate higher temperatures and use water twice as efficiently; transpiration ratios - kilograms of water used per kilogram of DM yield - are 300-350 for C_4 by contrast with 500-700 for C_3). In addition, C_3 cereals are actually inhibited by normal atmospheric oxygen content at 21%. Maize and other C_4 cereals have a photosynthetic rate some 55% greater than wheat (C_3), double the translocation rate (movement of products of photosynthesis to grains) and some 60% greater crop growth rate (CGR) than wheat - exceeding the photosynthetic rate differential because C_4 cereals do not suffer photo-respiration (loss of carbohydrate by respiration in daylight) as do C_3 plants, and thus net assimilation rate (NAR) is higher for C_4 cereals. This greater efficiency of maize explains the interest in using genetic engineering to try to incorporate genes for this into wheat and other small-grain cereals.

Considering the cereal crop as analogous to a business, the fundamental question is, 'By how much does the weight gain by photosynthesis exceed all the processes of loss, notably respiration?' A business analysis of the cereal crop might include the following:

- *Capital value* = *total crop DM.*
- *Productive capital* = *LAI*, i.e. area of leaf per unit area of ground (around 7.5 seems ideal for wheat on good land).
- *Factory production span* = *leaf area duration* (LAD), i.e. days of green leaf area survival between sowing and harvest. Varieties differ significantly in leaf production characteristics, and extra nutrients, especially nitrogen, can influence leaf area and colour.
- *Net production* = *CGR*, i.e. dry weight increase over time.
- *Investment programme* = *DM Distribution* (DMD), i.e. to grain for the next generation of the crop.
- *Efficiency measure* = *NAR* = grams extra DM per gram of leaf DM, i.e. NAR = CGR/LAI.

2.4. Cereal growth stages

The cereal plant is described as determinate; that is, it has a vegetative phase of root and leaf production giving way to a reproductive phase that ends with production of ripe grain. It uses its accumulating DM (growth) to enable it to pass through the various stages of its life cycle (development). Recognisable external and internal changes in the plant accompany these stages, though the two do not necessarily correspond in different cultivars. The temperate cereals develop flowers in response to increasing day length (that is, they are photoperiodic); what actually triggers them is the duration of darkness rather than light. Tropical maize cultivars are sensitive to short days but temperate ones are bred to be less sensitive. Development in response to environment (phenology) is affected by factors such as temperature. The stress of high temperature accelerates flowering but with lower resultant yield, whilst true winter varieties of cereal need to experience a prior cold period to trigger ultimate flowering and grain formation (this is called the vernalisation requirement). Most varieties have now been bred to be less critically dependent upon this vernalisation requirement.

Growth does not proceed in exact step with calendar dates from season to season and in any case varies with sowing date and soil conditions. An appropriate frame of reference was needed to describe growth stages of cereals. Feekes and also Large, (1954), first produced a descriptive scale of growth for cereals for the purpose of defining disease severity in relation to recognisable stages of the plant. This was adopted in the early l970s when systemic fungicides, hormone weed killers and plant growth regulators (PGRs) were becoming more widely used and effects varied with stage of crop at application time. However, the scale was awkward and imprecise, running from 1-11.4. Zadoks *et al.* (1974) introduced a more precise decimal key to 100 growth stages (GS 0-99) for the purposes of analysing both weed competition and responses to weed control at different stages. This scale is internationally recognised for all cereals and grasses as descriptive for all identification purposes and as an important agronomic management tool (Fig. 2.4).

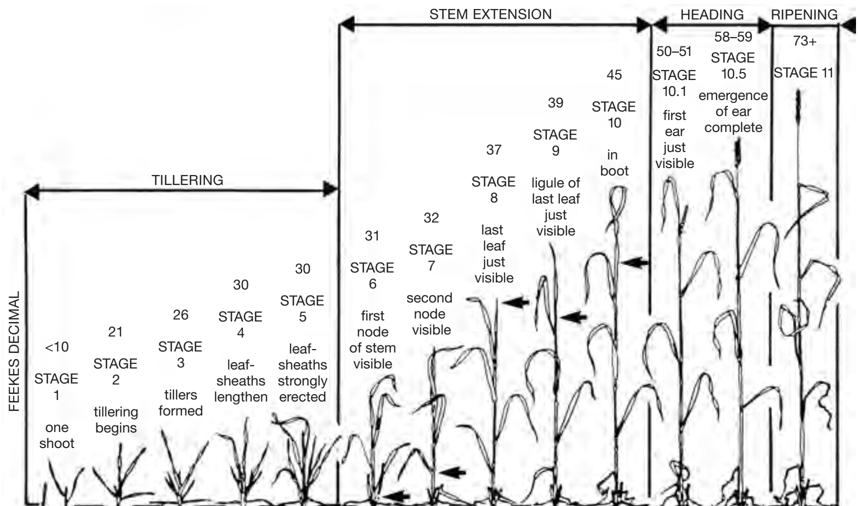


Fig. 2.4. Growth stages and internal cereal development (Wibberley, 1989 after Large, 1954 and Zadoks *et al.*, 1974).

2.5. Description of the sequence of cereal development

The description below of the sequence of stages is universally applicable though the dates and duration of phases are here described as observed in the field in the UK. Their incidence needs to be monitored by farmers in each place where crops are grown in order to provide detailed management. This hundred-point decimal scale divides neatly into ten phases of the life cycle (with secondary numbers to represent relevant recognisable stages within each) as follows:

Germination

These ten initial stages enable researchers on seed physiology to describe precise points in water imbibition, hormone and enzyme action and activation of the germ (embryo plant) within the seed. Germination rate is environmentally dependent, notably on temperature, oxygen and moisture supply. Evidence that germination has taken place is the emergence at GS 05 of the young root (radicle) closely followed at GS 07 by the coleoptile (thin sheath which protects the young shoot or plumule and which disintegrates by about the four-leaf stage). The optimum temperature for germination of the small-grain cereals is around 20-25°C with minima of around 4°C (with rye able to germinate at as low as 1°C) and maxima of around 30°C, though wheat may germinate at slightly higher temperatures. At 15-20°C, all should show radicle emergence within two days, though oats may be slower and rye swifter.

Seedling growth

These stages describe the early development of the main shoot as it produces its leaves and moves from dependence on ‘deposit account’ reserves of food from the seed to ‘current account’ production from its own leaves.

Winter barley, for instance, initiates its ear primordium once the second leaf has unfolded and completes laying down all its grain sites by the six-leaf stage. Winter wheat begins the same process only at the four-leaf stage and completes it by the second node stage (GS 32). In March-sown UK spring barley in England, rate of leaf appearance is steady at about one every five days, each successive one being larger than its predecessor (until developing ear competition takes effect later on). Cereal leaves grow from their bases so the tips are older, making the plant less susceptible to canopy surface damage – such as might occur from liquid fertiliser application during changeable (warm/cold) weather.

The fibrous root system is developing critically during this vulnerable, juvenile phase. The code is logical, e.g. 13 = seedling with main shoot and three leaves unfolded (i.e. with ligule visible at the base of the leaf blade), 14 = with four leaves, and so on. Younger leaves emerge like a telescope from within the sheath of the next older one below. The value of the scale is now becoming more apparent for the vigilant farmer who monitors the rate of progress of his different crops. If seed is too deeply sown, for instance, development rate will be slower.

Tillering

Tillering is the production of extra side shoots. These arise from buds in the axils where leaf sheaths join the stem at the base of the cereal plant at ground level (the crown). This process is also known as stooling or suckering in some countries and is the basis for sometimes ratooning rice and sorghum crops in the wet tropics (i.e. cutting successive harvests from only one initial sowing). Some cereal breeders have thought tillering undesirable and, indeed, most maize cultivars scarcely produce tillers at all, whereas original types gave ten or twelve. A uniculm (main shoot only) variety of barley exists but has not proved commercially successful since it lacks standing power and the capacity to compensate for poor conditions that its tillering cousins possess and that results in higher, more reliable yields for them. Tillering allows crops to compensate for low density of established plants arising either from deliberate sowing of low seedrates with expensive seed or from high seedling losses.

The amount of tillering depends on cultivar and growing conditions such as timing of nitrogen fertiliser. Given no competition from surrounding plants, a single barley seed might produce 30 or more tillers, but in a crop with 325 plants per square metre, it may produce only 5. Of total tillers, it is critical to achieve a high proportion going on to develop their own associated root systems and to bear ears. Generally, tillering capacity is greater in winter rather than spring varieties, in two-row rather than six-row barleys and in dwarf rather than tall wheats. Leaf number per tiller is more or less constant for any particular variety so controlling tiller density to achieve an optimum ear population is the critical factor. Excessive tillering will not only prove competitive, reducing the proportion of ear-bearing tillers, but also creates a dense crop in which a favourable microclimate exists for many diseases. On the other hand, inadequate ear density limits yield, so a compromise is sought as so often in husbandry decisions. Wheat compensates more effectively than barley for low ear density. In any one variety, few tillers die if fast DM accumulation per plant is sustained from the time of maximum tiller production up to anthesis. Early nitrogen application during the tillering phase encourages greater tiller numbers to form, and at maximum tiller stage, nitrogen and other inputs to maintain growth rate will encourage tiller survival. Varieties that have limited tillering ability very often have strong apical dominance (overpowering influence of the main shoot exerted through its own internal hormone concentration). This apical dominance can be lost either if the main shoot is damaged by pest attack or affected by early lodging (stem collapse) or if PGRs suppress it deliberately or by accident. A late phase of secondary tillering in such circumstances can greatly inconvenience harvesting since there is usually a wide differential in ripening between oldest and youngest ear-bearing tillers; however, the process does compensate somewhat in yield terms.

A plant can now be described as at GS 14, 22 (main shoot with four leaves and two tillers), i.e. given a double, full description. The description GS 24 is logical, i.e. main shoot plus four tillers; GS 25 plus five tillers, and so on. Until the end of tillering, the ear primordium (growing point) stays below soil surface level, where it is protected.

Stem elongation

The plant is now fully tillered. Tillering ceases sometime in early April for early October-sown winter wheat in Southern Britain. This is triggered by the internally developing ears, which now begin to compete in earnest for their share of the plant's resources. First the plant assumes a more upright posture loosely known as pseudo-stem erect stage (with some 5 cm length of main shoot leaf sheath in winter wheat, about 7 cm in barley). Then the first node (joint) is detectable (GS 31), quite soon followed by the second (GS 32) and so on to GS 35 usually (Fig. 2.5).

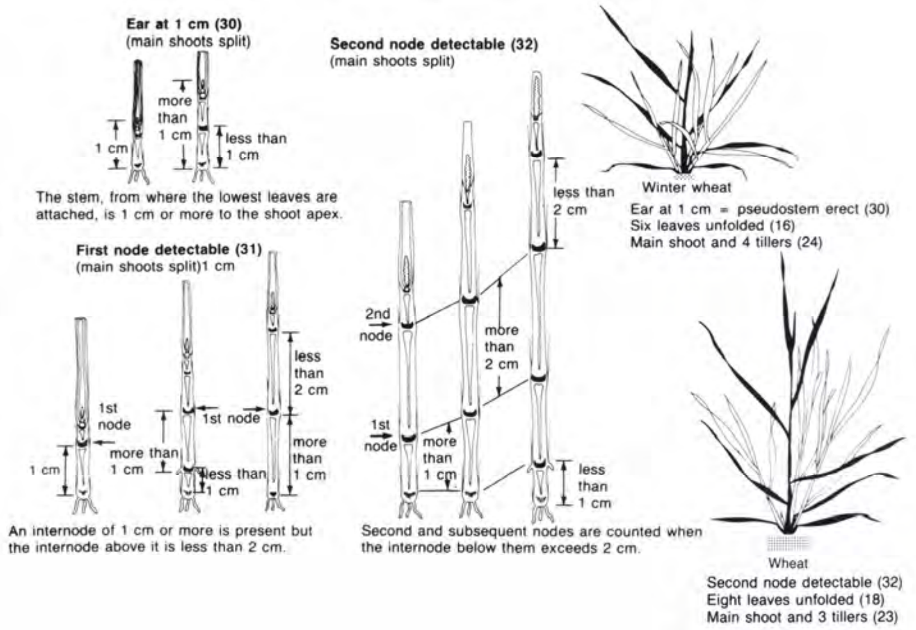


Fig. 2.5. Key internal changes at onset of exponential growth and nutrient demand (Tottman, 1987).

Nodes are 'roundabouts in the traffic-flow system of the plant', as well as possessing the capacity to help re-erect early-lodged crops as long as the node is green and active. Stems, apart from those of maize and sorghum, are hollow except at the nodes. Plants must be dissected to examine ear development because it can vary some tenfold in size at this stage even though varieties appear at the same GS externally. PGR applications are sometimes used in an attempt to restrict excessive stem extension and so have more photosynthates for the grain as well as enabling the stem cells to remain more fortified, thus providing a stronger stem against any threats to lodge (knock over) the crop. Hormone weedkillers applied after GS 30-31 can damage ears and induce shrivelled grain. Leaf area of the plants increases greatly from this time (in the winter wheat crop cited above to a June peak target of around LAI 7.5). Ear development is proceeding and grain numbers retained per ear are determined. The crop normally grows very quickly during this phase.

Booting

GS 45 marks the stage where the developing ear is swelling visibly inside the leaf sheath of the flag (top) leaf. It is important to continue to protect the crop carefully from diseases during this phase. It is a period of continuing death of superfluous tillers, and the last-formed spikelets and florets also abort to leave a number which the crop has the capacity to sustain through to harvest. The pattern of primordia production varies considerably between species and according to sowing dates.

Ear emergence

Ears emerge in response to shorter nights. This stage marks the end of leaf expansion and the onset of leaf senescence except for the flag leaf and leaf two. Stem sugar content decreases rapidly. Ear emergence results typically in a main shoot plus two or three ear-bearing tillers in two-row barley, main shoot panicle plus one or two others in oats and main shoot plus maybe one (occasionally two or three) in wheat. Six-row barley behaves much more like wheat. The two-row ears of the most widely cultivated barleys arise from the infertility of the side spikelet rows so that only the central spikelet row is fertile on opposite sides of the rachis (inflorescence central stalk). Two-row barley will abort between 30 and 50% of its potential grain sites but retain some 95% of remaining fertile florets to produce grains. Wheat similarly loses around 40% of its floret initials but only produces grain from some 80% of its retained florets, giving about 3.5 grains per spikelet on average at harvest. Thus, ears/m^2 varies more for barley than for wheat, whilst grains/ear varies more for wheat. Everything now hinges on grain growth, the grain itself acting as a ‘sink’ – in crop physiologists’ language - to receive carbohydrate from the various ‘sources’ in the plant. Most of the carbohydrate stored in cereal grains is produced by photosynthesis after ear emergence. The percentage of assimilates actually deposited in the wheat grain in the various stages from ear emergence can be reckoned:

> Ear emergence to flowering, 5%; flowering to milk ripe, 25%; milk ripe to cheesy ripe, 53%; and cheesy ripe to mature, 17%.

Stem sugar content decreases rapidly during senescence though barley typically retains reserves which can be mobilised to supply up to half the ultimate grain carbohydrate, thus buffering it well in drought.

Anthesis (flowering)

Self-pollination leading to self-fertilisation is usual in barley, wheat, oats, rice and triticale. However, they can all be induced to cross for breeding purposes. Protogyny (development of the ovaries much earlier than the anthers) ensures the need for cross-pollination in pearl millet. Maize, sorghum and rye are also normally cross-pollinated though they can be selfed for breeding purposes. The lodicules swell to open the pales to allow extrusion of the anthers to release pollen onto the wind.

Wheat, for example, exhibits anthesis once the ear has emerged so that its base is some 5 cm clear of the flag leaf ligule. An individual ear can complete the visible process amazingly quickly, often early in the morning. Stamens dangle, anthers split, pollen is released and it takes but five minutes to germinate on the feathery stigma of the 'home' ovary and about an hour to send down a pollen tube into it. This contains three nuclei, two of which fuse within the day with ovary nuclei to produce, respectively, the embryo or young plant and the endosperm or carbohydrate store of the grain.

The whole crop may take around a week to complete anthesis if it is uniform. In the north of Britain rather than the south, and in a crop of rye rather than wheat, the process takes more than twice as long to ensure maximum chance of cross-pollination; this explains the prevalence of ergot disease (*Claviceps purpurea*) in rye ears grown in the north and so exposed to risk for a longer period.

Milk development

This is an absolutely critical phase for storing up the grain carbohydrate. Therefore, it is important to monitor the potential raids of late aphids that can dramatically reduce yield. Typically, the ears of crops with high yield potential will already have received a protective fungicide or ear protectant wash as necessary.

Dough development

Ample time to mobilise all possible reserves into the grain is now critical to yield. Early death of the plant through drought or disease can be very damaging.

Ripening

Grains will normally fill to between 25 mg for the thinnest barley and up to 65 mg for the plumpest wheat.

An overview of key stages in cereal development from emergence to completion of heading and anthesis is provided in Fig. 2.6.

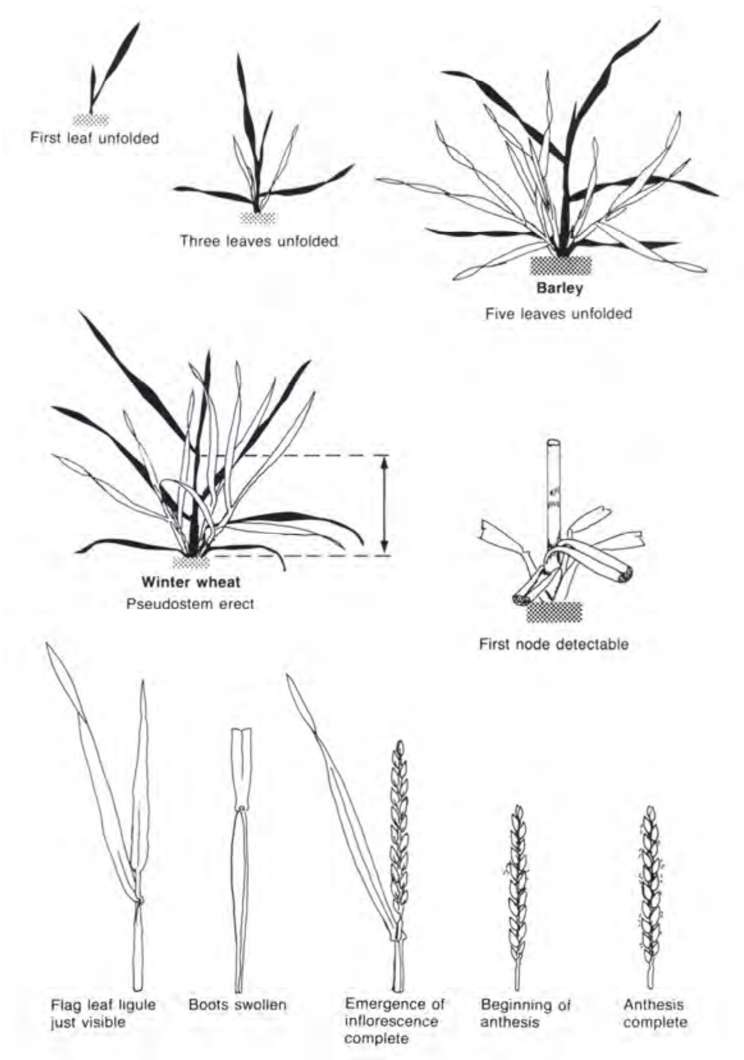


Fig. 2.6. Key growth stages of cereals (Tottman, 1987).

2.6. Cereal root development

Roots merit special consideration because shoots demand a disproportionate amount of attention anyway, and the decimal GS scale omits monitoring of root progress.

- Cereal roots grow actively from their tips, by contrast with cereal leaves which grow from their bases. They can remain active as far as half a metre behind the tip.
- Seminal or primary roots are the first ‘seed’ roots to emerge; three to six of them support the plant during the first month or so of life. They develop first-, second- and third-order lateral branches and penetrate to considerable depth. They may amount to a total length of 5 metres by the time a winter wheat crop is a month old, though they never occupy more than 5-10% of the total root volume of a fully grown crop.
- The secondary root system usually develops properly one to two months after germination. These thicker roots (300-700μ or 0.3-0.7 mm c.f. seminal roots at 220-400μ) arise at the crown and are also called nodal or adventitious roots (Fig. 2.7).

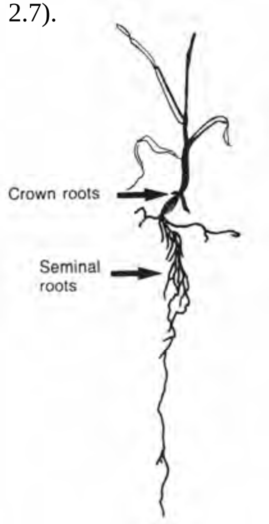


Fig. 2.7. Young barley seedling (GS 13) showing seminal and crown roots.

- Lateral roots develop from the main roots to produce a fibrous system overall with abundant root hairs. They are finer (100-200μ) and tend to occupy a greater proportion of the total system if compacted soils restrict the larger roots. They are vulnerable to local soil nutrient deficiencies whereas the main roots survive unless the whole plant is deficient. They normally spread sideways up to 1 metre. Maize also develops prop roots from just above the crown which help to support it.

- Roots may occupy between 1% and 5% of the total soil volume to 15 cm depth. What matters is development of good ‘root length density’ i.e. cm root/cm^3 soil; winter cereals, especially wheat, are particularly effective at this while spring cereals have less opportunity to achieve dense colonisation.
- Most roots are concentrated in the top 25 cm of the soil profile. In October-sown winter wheat, depth of rooting extends to 0.5 m by February, to 1 metre by the five-leaf stage/end of tillering and to as much as 2 metres at peak root development. In Britain, this coincides with full ear emergence (GS 59) during June when total root length may exceed 80 metres.
- Root growth rate accelerates from up to 5 mm per day over winter to 25 mm or so per day during the growing season.
- Root development is obviously correlated with seasons and soil depth. Root production is more consistent than shoot production. Variations in soil depth and therefore in rooting can make considerable visible differences to the uniformity of ripening on shallow soils such as many soils over chalk or limestone.
- Root functions for the cereal crop include:
  - Anchorage and support.
  - Production of hormones to control growth patterns.
  - Production of exudates; These are organic substances that leak out of active roots continuously, attracting beneficial microorganisms that help to protect roots from pathogens as well as assisting in crop nutrition. These exudates may account for as much as 10% of the total loss of photosynthates generated by a crop.
  - Water absorption - drawn from as far as 100 mm away from the root surface (rhizoplane) and critically assisted by the deepest roots.
  - Nutrient absorption - closely allied with water absorption. Whilst very mobile ions like nitrate can reach a root from 100 mm away, the least mobile like phosphate ($H_2PO_{4^-}$) need to be within 1 mm.
  - Both root formation and activity are restricted by oxygen deficiency in the soil and by extremes of pH.

2.7. Yield components

Yield (Y) is the product of several factors which can be influenced by crop management, though capacity to affect the crop in this way decreases as it matures and grain filling is very weather-dependent except in rare cases where irrigation is possible. Fig. 2.8 presents an overview of yield development used for crop modelling purposes. The components of cereal yield are:

Y = plants/hectare x tillers/plant x % ear-bearing tillers x grains/ear x weight/grain (mg)

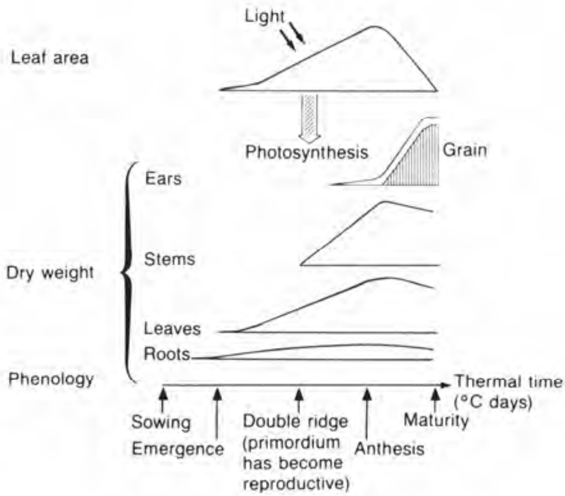


Fig. 2.8. Overview of changes in the cereal plant over time (used in the modelling of crops at Rothamsted IACR, England).

2.8. Cereal quality

Apart from yield alone, farmers need to heed quality requirements for different cereal uses and markets, especially in times of oversupply. Quality refers to suitability for end-use. Standards are liable to change either to control market supply (relaxed in times of shortages; tightened in times of surpluses) or to satisfy novel markets. Many aspects of quality are subjective and locality- or market-specific. Farmers should always check before growing a particular variety in a specific way. Quality is generally dependent on appropriate choice of variety and good husbandry - especially lodging prevention, timely harvesting and careful cleaning, drying and storage.

General physical measurements applicable to all cereals:

- *Purity* (degree of freedom from all matter other than the grain concerned) – measured as percentage by weight and stating the contaminants present.
- *Entirety* of grains (i.e. proportion of broken and sprouted grains present).

- *Colour* of sample (still a lot of mystique about this in the malting barley trade).
- Grain *size.* The proportion of small-grains (2 mm screenings) is relevant. A high figure not only shows a poor sample but probably many shed in the field too.
- Grain *weight* (absolute weight) adjusted to a specified moisture content. (Beware: yields and other results vary considerably between dry weights of 13 and 14% moisture or 'as harvested' moistures) The weight is usually expressed as that of one thousand grains in grams (TGW). It can be depressed significantly by high levels of late-applied nitrogen.
- Grain *density.* This was based on the Anglo-Saxon bushel measure (roughly 8 gallons or 36 litres). Pounds per bushel vary widely for the different cereal species; add to that the variation in accepted weight of wheat meant from district to district and it becomes clear that 'bushels per acre' is an unsatisfactory *quantitative* (yield) measure. Yet it is still used as such in North America. It is a very useful *qualitative* measure and has now been metricated into SI units, viz. kilograms per hectolitre (loosely called kph but correctly abbreviated kg/hl). Instead of using large weights and hundred-litre measures the figures are actually derived from grams occupying half-litre test measures. Grain that is not well filled will not pack tightly in the measure so will weigh less. The term 'specific weight' is used now for kg/hl and in some countries 'test weight' is more usual. It is sometimes also abbreviated HLW for 'hectolitre weight'. In practice, many markets require a minimum of 76 kg/hl for wheats, and for barleys, 64 kg/hl is now the accepted minimum target.

General chemical measurements applicable to all cereals:

- Moisture content (mc) is the first consideration because by difference it indicates the true amount of the more valuable DM present and it affects the keeping and processing qualities of the grain. The normal level required is 14%, and low levels often attract a premium.
- Other chemical constituents vary not only according to species but also with special market requirements within each species. Note the high protein content of the top-quality Canadian (Manitoba) wheat, the high fat content of oats and the high fibre and mineral content of barley.
- More detailed chemical information often relates to an assessment of protein quality, viz. the proportions of the various constituent amino acids present. There are cultivar differences and breeders can select for some very specific chemical components.
- Following this overview on cereal botany and physiology, chapter 3 now examines cereal nutritional behaviour.

Chapter 3: The Role of Plant Nutrients in Cereal Physiology

3.1. Crop structure and performance

Yield of a cereal is derived cumulatively and is the product of several factors:

Yield = plants/hectare x tillers/plant x % ear-bearing tillers x grains/ear x weight/grain (mg)

Crop structure in practice can compensate to an extent for lowering of one component by raising of another. The factors determining grain yield include:

- Crop density.
- Light interception: depends on leaf angle, LAI, crop standing power.
- Duration of green leaf survival after ear-emergence (LAD).
- Flag leaf size, especially in wheat.
- Ear size as ‘sink’ and for photosynthesis (especially in barley, including awns).
- Temperature and duration of grain-filling period.

Cereal crop husbandry is about the understanding of crop behaviour, selection and timing of all operations in order to exploit this in an effective management system.

Any one of the following variables can be calculated if the others are known:

$$\text{Yield (t/ha)} = \frac{\text{ears/m}^2 \text{ x grains ear x TGW (g)}}{100{,}000}$$

or:

$$\frac{\text{grains/m}^2 \text{ x mean grain weight}}{100{,}000}$$

Table 3.1 indicates key relationships in this respect for wheat.

Table 3.2 gives an example of crop structure, yield and quality relationships for seventeen winter wheat crops monitored and compared over three seasons (1982-4) in association with a Farmers’ Study Group in the West of England (Wibberley, 1985).

Crop nutrition was not found to be a limiting factor in these crops. Assuming sites of relatively high yield potential and willingness to sustain the ongoing nutrient requirements of the crops, Table 3.3 suggests target head populations per m^2 for the different cereals.

Table 3.1. Wheat: Ear population, ear size, TGW and yield.

Population (ears/m²)	Grains per ear	Yields in t/ha at TGW of 35g	40g	45g	50g
	30	3.2	3.6	4.1	4.5
300	35	3.7	4.2	4.7	5.3
	40	4.2	4.8	5.4	6.0
	30	4.2	4.8	5.4	6.0
400	35	4.9	5.6	6.3	7.0
	40	5.6	6.4	7.2	8.0
	30	5.3	6.0	6.8	7.5
500	35	6.1	7.0	7.9	8.8
	40	7.0	8.0	9.0	10.0
	30	6.3	7.2	8.1	9.0
600	35	7.4	8.4	9.5	10.5
	40	8.4	9.6	10.8	12.0

Table 3.2. Yield, quality and crop structure in winter wheat crops (cv. Avalon).

Season (Means for 17 crops)	1982	1983	1984
Seeds/m²	390	440	420
Plants/m²	328	374	346
Establishment %	84.1	85.0	82.4
Ears/plant	1.29	1.37	1.42
Ears/m²	424	512	493
Grains/ear	35	42	33
Weight/ear (grams)	1.56	1.39	1.55
Actual yield (t/ha)	6.63	7.10	7.66
TGW (grams)	45.97	34.00	47.70
Specific weight (kg/hl)	79.79	79.50	80.83
Protein % (1)	11.08	12.20	12.15
Hagberg Falling Number (HFN) (2)		252 - 482	
Nitrogen applied for top yields (kg/ha)	222	173	208

(1) Range for all crops was 10-12.7
(2) HFN 252-482 was acceptable for all samples

Adapted from: Wibberley, 1985.

Note: All sites had soil index 2+ for P and K.

Table 3.3. Yield, quality and crop structure in winter wheat crops (cv. Avalon).

Cereal		Heads/m^2
Winter wheat		500-600
Spring wheat		700-800
Durum wheat		650-750
Winter barley	Two-row	1,000-1,200
	Six-row	500-650
Spring barley	Two-row	1,000-1,200
Winter oats		650-750
Spring oats		700-800
Rye		700-800
Triticale		600-700

Adapted from: Wibberley, 1989.

Note: In general, richer growing conditions can sustain higher densities and it must be remembered that crops can compensate by grain number and/or grain size for varied head populations. Varieties differ in density optima.

3.2. Plant growth regulators (PGRs)

There is interest within higher input cereal systems in the use of PGRs to manipulate the normal physiology of cereal crops in order to increase their yield or quality. The most significant commercially adopted PGR is chloro-choline chloride or chlormequat (CCC) which shortens and stiffens the internodes of straw allowing softer varieties to be given higher N fertiliser rates than they would normally withstand before lodging (collapsing). It can be applied to all the small-grain cereals, normally between growth stages 22 and 31 (Wibberley, 1989). Crop physiologists are interested in the scope to use PGRs to control all aspects of crop development, such as synchronizing tillering and preventing grain abortion, in order to affect yield partitioning and desired quality characteristics. The paper of Humphries (1968) on CCC remains a seminal work. Original interest in growth regulators for cereals centred on the prevention of lodging. One of the predisposing factors for lodging is a long, weak straw. Whilst this is a matter of variety, it is also a tendency increased by high dosages of nitrogen and soluble NP fertilisers. Suboptimal K supply also predisposes cereals to lodging.

The natural hormones increasing internode length are gibberellins. Thus, in order to counteract their effect, anti gibberellins are needed. Chlormequat is just such a material (2-chloroethyltrimethylammoniumchloride, CCC or chloro-choline chloride). Chlormequat is designed to shorten and strengthen the straw. The visual effect of shortening straw is sought to convince farmers that the treatment works. However, a strengthening effect is the more important. The treatment has been advocated on the grounds of yield protection, including protection of the previous inputs of fertiliser and fungicides. Now, there is growing farmer awareness of the potential effects on growth which have been research aims hitherto, i.e. the use of growth regulators at various stages in crop development in order to modify growth patterns in favourable ways. Earlier applications of chlormequat and other materials are being given to crops in order to try to modify growth and secure higher yields.

3.3. Lodging, yield, fertiliser usage and crop quality

Predisposing factors for lodging incidence are:

- Growing of weak-strawed varieties.
- Fields exposed to high winds and/or heavy rainfall.
- Excessive nitrogen fertiliser application making growth soft and weak.
- Stem-based diseases, notably eyespot, sharp eyespot and *Fusarium* ‘footrot’. Disease is particularly associated with ‘straggling’ when plants twist and fall over in all directions rather than falling over more uniformly when pushed down by a steady wind.

The *consequences* of lodging are:

- Obviously greater the earlier it occurs. However, some crops may go flat early under a heavy thunderstorm but still retain sufficient pliability and strength to stand up again.
- Direct loss of yield.
- Greater variability of grain sample, especially regarding grain size, uniformity of maturity and particularly HFN in milling wheats for breadmaking.
- A more difficult, slower harvesting owing to laid ears close to the ground as well as to secondary tillering and weed growth in the flattened areas.
- Greater incidence of late damage by bird pests which find flattened areas easy to land on for feeding.
- Often higher costs of cleaning and drying grain samples.
- Relative wastage of other treatment costs spent on the crop, notably fertilisers.
- Higher incidence of ‘volunteer’ cereal plants growing from shed grains and shed ears. These incur greater disease carry-over and extra subsequent control costs.

Clearly the circumstances in which lodging is likely merit serious consideration for growth regulator use. A *delay* in lodging can bring worthwhile yield responses even if the treatment fails to prevent it altogether. Mepiquat chloride offers a later chance to try to combat lodging at GS 32 - 39 and ethephon gives a final chance to attempt prevention at GS 39 - 57; it tends to prevent ear loss, especially in barleys, by strengthening the neck.

3.4. Nutrient/plant interactions

As a component of the plant environment, the level of each nutrient can play a defining role in how a crop develops. For each element there is an optimum amount required, with the possibility of deficiency at low levels – subclinical at first but then showing visible deficiency symptoms (Fig. 3.1). Likewise, there is the possibility of excess depressing crop performance, distorting the relative proportions of different plant parts, and interfering with uptake of other elements. In particular, an excess of potassium, ammonium or calcium can marginalise magnesium uptake. In the case of minor or trace elements, the difference between too little and too much may be very small. A correct balance of all essential elements can affect the relative proportions of different plant parts that result. Nitrogen is particularly influential in this regard and has thus especially interested crop physiologists as well as farmers. For instance, a continuing excess of nitrogen will prolong the vegetative phase and can detract from final grain yield.

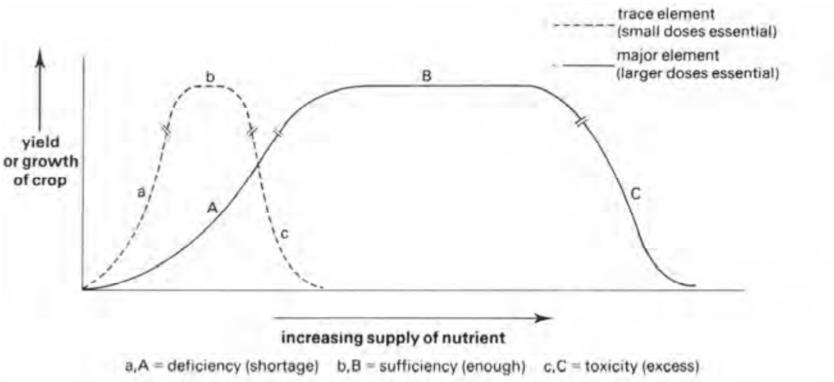


Fig. 3.1. Generalised minor and major nutrient response curves (Wibberley, 1979).

Typical nutrient demand in small-grain cereals is shown in Table 3.4. Essential major elements, required in relatively large amounts, are: nitrogen, phosphorus, potassium, calcium, magnesium and sulphur. Of course, the macro-elements carbon, hydrogen and oxygen are obtained through photosynthesis; they form the bulk of the plant mass as carbohydrates and when combined with N as proteins. The carbon to nitrogen ratio within the plant is crucial for cereal performance and since carbon assimilation is climatically controlled, it is nitrogen supply which can be especially managed by the farmer. Essential minor elements or micronutrients, required in trace amounts, are: iron, manganese, zinc, copper, boron and molybdenum.

Table 3.4. Typical nutrient demand in small-grain cereals.

Removal of major nutrients (kg/t @ 15% mc)						
	N	P	K	Ca	Mg	S
In grain	17.0	3.4	4.7	0.5	1.3	1.3
In straw	6.0	0.7	6.8	3.0	0.8	0.9
Removal of minor nutrients (g/t @ 15% mc)						
	Fe	Mn	Zn	Cu	B	Mo
In grain	40	25	25	4.0	0.8	0.3
In straw	40	60	15	2.5	6.0	0.3

mc = moisture content

Adapted from: Archer, 1985.

Chloride is supplied regularly when crops receive potash as potassium chloride and nitrogen as ammonium chloride. Chloride deficiencies in plants generally occur at inland sites (Fixen, 1987). Substantial responses to Cl containing fertilisers have been reported for different cereal crops in many parts of the world: maize (Heckman, 1995), spring wheat and barley (Fixen *et al.*, 1986; Engel *et al.*, 1994). The probability of Cl deficiency in field situations and thus response to Cl fertilisation, increases in plant species with a high Cl requirement, such as wheat, and in highly leached soils with a low input of Cl from rain and other sources. There is a wide range in the concentration of Cl at which deficiency in plants occurs. In wheat, the Cl concentration of leaf tissue at heading is a good predictor of the response to Cl fertilisation (Engel *et al.*, 1998); the critical range is between 1.5 and 4 g/kg DM, above which no further response is expected. The recommended application rate of Cl is 11-33.6 kg ha-1 when Cl deficiencies are suspected (Mortvedt *et al.*, 1999). On a sandy loam soil, Cl applications of up to 400 kg/ha yielded 500-1500 kg/ha more maize grain than was obtained in the control (Heckman, 1995). Grain yields of maize were positively correlated with increases in Cl concentrations in the leaves. In wheat, there was no yield response to Cl fertilisation when the Cl content was above 70 kg ha-1 in the top 12 cm of soil (Fixen *et al.*, 1987). Yield increases from Cl supplied as KCl, $CaCl_2$, NH_4Cl and NaCl have also been associated with suppression of foliar or root diseases of wheat (Christensen *et al.*, 1981; Engel *et al.*, 1997). Ammonium chloride produced yields of rice that were equal to or larger than those obtained with urea and ammonium sulphate. However, in a glasshouse experiment, rice yields with NH_4Cl were significantly lower than with $(NH_4)_2SO_4$, especially at high salinity levels (Meelu *et al.*, 1990).

Cereals also remove traces of cobalt, silicon and sodium but these have never been shown to be directly limiting to cereal growth although silicon may help to stiffen straw.

Of course, species and varieties differ in nutrient responses, as do different breeds of dog or of cow. For example, durum wheat may remove up to 40 kg N/t yield whilst milling varieties of common wheat may remove 27 kg N/t.

Nutrient uptake typical for a cereal crop is shown in Fig. 3.2. It is not the same as nutrient retention within the plant, especially in the case of potassium. For example, a cereal crop may take up over 300 kg/ha of potash but remove only some 125 kg/ha in grain and straw harvested, or less than 50 kg/ha if straw is chopped and incorporated back into soil. At peak growth rate, wheat can take up some 10 kg/ha/day of potash (Kafkafi and Halevy, 1974).

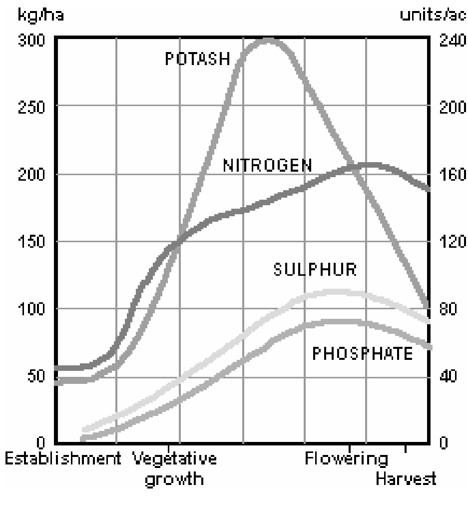


Fig. 3.2. Typical cereal major nutrient uptake curves (PDA).

3.5. Nitrogen (N) and yield physiology

High-yielding, short-strawed cereal varieties (HYVs) – especially of wheat and rice – are bred to respond to nitrogen supply, water and ample light. They were much developed through the pioneering work of Dr Norman Borlaug (1970 Nobel Prize winner for this work and its subsequent effect in overall levels of production achieved in such grain-hungry nations as India and Pakistan).

In the analysis of fully replicated seedling wheat trials over eight weeks at 20^0C with ample moisture at three densities with and without nitrogen at 125 kg/ha, CGR at near-optimum density was increased by 43 % with nitrogen. Leaf to root ratio at this density was increased by nitrogen from just under 1:1 to almost 2:1. However, DM percentage was depressed from a mean of 15.7 to 13.5 per cent and NAR (the difference between photosynthetic production and respiratory losses within the leaves) was cut to only 56.5 % of the efficiency without nitrogen. Nevertheless, nitrogen application improved yield. These data (Wibberley, 1974) illustrate some of the complex nitrogen responses of cereal plants. Reduced plant DM and a denser leaf canopy make for increased water demand by the crop and reduced rooting to satisfy it, while the ‘softer’ crop and moister microclimate within it tend to favour many foliar diseases. In the field, crops of winter barley given ample early N developed higher green leaf area and were taller in mid-April during the spring flush of the English growing season (Fig. 3.3).

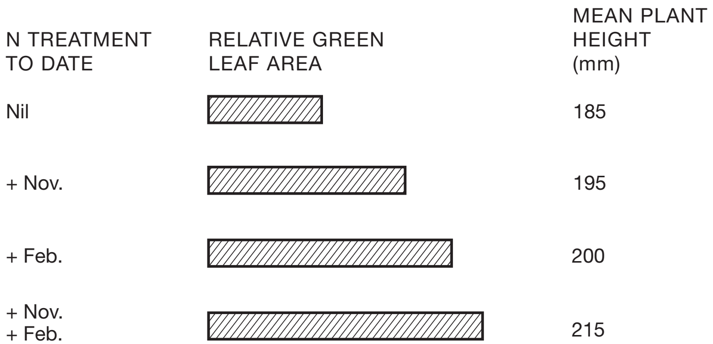


Fig. 3.3. Winter barleys, early nitrogen applications and plant morphology (Jenkinson & Wibberley, 1986).

The amount of tillering depends on cultivar and growing conditions such as timing of nitrogen fertiliser. Early nitrogen application during the tillering phase encourages greater tiller numbers to form, and at maximum tiller stage, nitrogen and other inputs can help to maintain growth rate by encouraging tiller survival. However, there is an optimum tiller population to provide an effective foundation for yield. If too many tillers are formed, then a reduced proportion of them are likely to survive and the crop will be less efficient (Fig. 3.4).

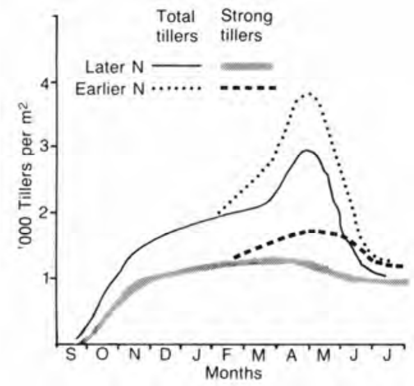


Fig. 3.4. Tillering pattern of winter barley as affected by N fertiliser timing (Jankinson & Wibberley, 1986).

High levels of late-applied nitrogen (Fig. 3.5) can depress TGW significantly. However, extra nitrogen just before ear emergence can boost grain protein, as can foliar urea given just before green leaf disappears. Some 70%+ of N removed by a cereal goes into the grain.

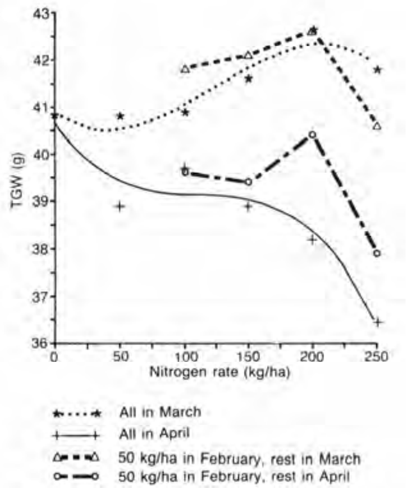


Fig. 3.5. TGW of winter barley as affected by N régime (Jenkinson & Wibberley, 1986).

In short, too little available nitrogen reduces yield by limiting overall DM production while too much leads to excessive vegetative growth at the expense of grain formation and may depress grain quality, especially in dryland farming or in a relatively dry season.

3.6. Phosphorus (P) and cereal physiology

Phosphorus is absorbed largely as $H_2PO_4^-$ anions. Inorganic forms of phosphorus are those chiefly present in the growing plant. However, key organic phosphorus involvements are in:

- Nucleic acids of the plant cell nucleus.
- Adenosine triphosphate (ATP) its main energy-storage compound.
- ATP - a major co-enzyme in CO_2 assimilation during photosynthesis.
- Phosphorylation - plays a key role in other major metabolic processes, including glycolysis, respiration and carbohydrate formation.
- Phospholipids in the middle lamella of the developing cell wall.
- P compounds in mitochondria and chloroplasts.
- Phytin (inositol hexaphosphate) in seed, which is the reserve enabling its later germination and accounts for some 80% of grain P.

In view of these particular ingredients, it is not surprising that phosphorus is especially concerned with the most rapidly growing plant parts – during germination, and then at root tips, shoot tips and in subsequent seed formation. Therefore, the young cereal seedling is especially prone to phosphorus deficiency at the point when it has exhausted its own phytin seed reserves. P is involved in protein metabolism and thus in enzyme formation. Phosphorus is sparingly soluble and so of low mobility in soil typically being present at 1 ppm or less in soil solution. Therefore, the roots have to explore soil adequately in order to reach enough phosphate. P deficiency, with reddish purple leaf discolouration, may arise if the soil status is low and/or the soil conditions poor (e.g. compacted or cold) so impeding root development. In such circumstances, placement of P fertiliser close to the seed may alleviate deficiency.

Phosphorus is mobilised in older tissues and translocated to the ears. Around 70% of P removed by a cereal goes into the grain.

3.7. Potassium (K) and cereal physiology

Potassium fulfils a role in the water/salt (osmotic) balance of every plant cell and is important for healthy metabolism, particularly by supporting efficient N response; it is involved in N metabolism for protein synthesis. It contributes to

CO_2 assimilation and carbohydrate formation in photosynthesis, regulates plant water content, helps the cereal resist stress (climatic, soil, disease or pest-induced), and assists in the movement of products within the plant, especially storage in the grain. However, some 80% of the K finally removed by a cereal crop stays in the straw.

Potassium is absorbed by plants as potassium ions (K) which are cations in the cell sap to counter-balance inorganic anions such as bicarbonates and nitrates as well as organic acid anions. In this way, K critically helps to maintain the turgor of plant cells so enabling water uptake and healthy cell expansion. K is very mobile within the plant being especially concentrated in the phloem sap so that deficiency symptoms (leaf margin and leaf tip chlorosis and browning through cell collapse) first appear in older leaves which have given up their K to supply younger ones. These symptoms could be caused by other factors and so visual diagnosis of K deficiency in cereals is not so straightforward. Since K deficiency may be subclinical (i.e. show no visual symptoms yet still depress yields) it has been called 'the hidden hunger'. Plants short of K are more susceptible to drought, disease and lodging (straw collapse causing plants to lean and fall over) which has a huge overall effect on both yield and quality. Cereal crops may indulge in luxury uptake of K, i.e. they can actively absorb far more K than is needed to maximise yield. Some of this is returned to the soil during growth. This borrowing of surplus K could be important for plants' general health and ability to withstand stress through climatic factors, disease or other causes. The potassium content of winter wheat plant tissues at the outset of the North-West European spring is higher than other nutrients but drops dramatically by harvest time to below the level of N in HYVs (Fig. 3.6 courtesy of G. Wadsworth).

There is a vital relationship between the nitrogen and the potassium nutrition of cereals, which must be kept in balance (Fig. 3.7). Supplying K together with N fertiliser top dressings can help in situations where soil K status is low.

Peak potassium uptake of a cereal crop occurs just after heading before nitrogen uptake peaks, and before phosphate and sulphur uptake peaks during grain filling (Fig. 3.6 above). Off-take per tonne of yield in oats is typically some 10% more than in barley, which removes some 25% more than wheat or rye which are similar in their potassium demand.

By encouraging the synthesis of compounds of high molecular weight in the leaf which are less readily 'digestible' by fungal pathogens and pests, K may confer some general resistance to cereal diseases and pests (Kafkafi, *et al.*, 2001 – esp. section 3.8, p.101).

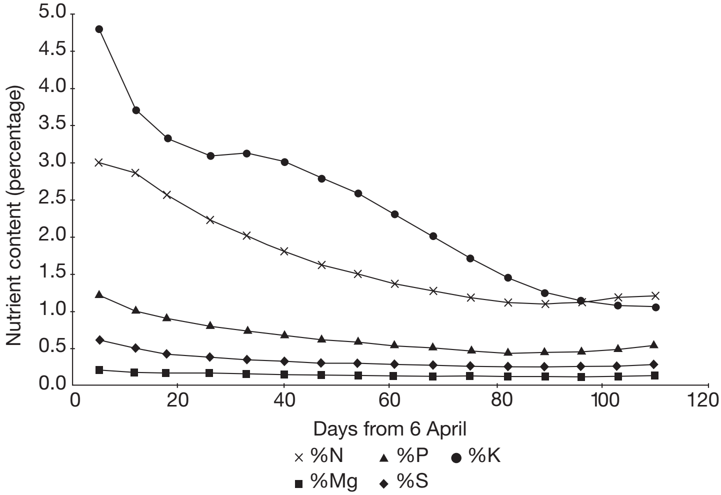


Fig. 3.6. Changing nutrient content (%) of wheat during the growing season.

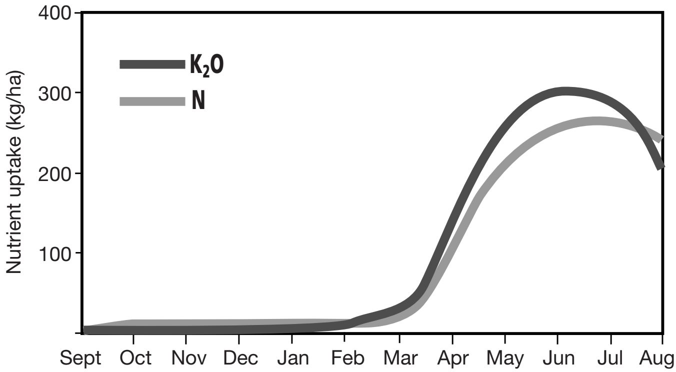


Fig. 3.7. Matching nitrogen and potash to cereal demand (PDA).

3.8. Magnesium (Mg) and calcium (Ca) and cereal physiology

Magnesium is central to the structure of each chlorophyll molecule which accounts for some 15-20% of Mg taken up by cereals. The remainder occurs as cations counter-balancing inorganic and organic acid anions. It also facilitates enzyme functioning. Its uptake can be antagonised by excesses of other cations such as potassium, calcium and ammonium. Classic deficiency symptoms are interveinal chlorosis giving a yellow-striped appearance to leaves.

Calcium requirement of cereals is relatively low by contrast with dicotyledonous crops and most arable soils contain enough for their growth. Deficiencies in plants are usually due to physiological malfunction. Calcium uptake as cations is a largely passive process as is its transport within the xylem transpiration flow of water. However, it is an important constituent of cell walls and membranes (middle lamellae) and once deposited does not move readily within the plant. Calcium deficiency symptoms are shrivelled leaf tips. While calcium deficiency in cereals is very rare, subclinical symptoms may arise from its relative shortage as a liming material keeping the soil pH adequately high for balanced uptake of other essential elements (see chapter 8).

3.9. Sulphur (S) and cereal physiology

The behaviour of sulphur and nitrogen is somewhat similar in both soils and plants. Sulphur is stored in soil organic matter (OM) and taken up as sulphate anions. Like nitrate, sulphate is readily leached from soils. In industrialised countries and regions, much of the sulphur requirement arrives by aerial deposition from sulphur dioxide and sulphates into soils. However, as clean air policies and ‘polluter pays’ principles are adopted, less incidental sulphur deposition occurs. Within the plant, sulphate is converted to sulphur-containing amino acids and thence to proteins. Deficiency of sulphur can thus reduce both yield and quality of cereals (McGrath, 2001). The use of sulphur-containing fertilisers will not only correct this (Conry, 1997) but also may give some contact control of foliar fungal diseases if applied to growing crops. Ample supplies of organic manures can supply most of the sulphur requirement in many cases.

3.10. Micronutrients and cereal physiology

Micronutrients function particularly within enzyme systems of the plant. Most soils, especially those with a vigourous organic cycle, are amply supplied with them so that any deficiency is the result of unavailability rather than absence of micronutrient. The chief factor controlling their availability is pH and most, except molydbenum, become less available at higher pH levels. Some types of slowly decomposing OM can lock up both copper and manganese leading to at least transitory deficiency symptoms. Following test plot trials, it is possible to establish tendencies towards shortage on certain soil types (especially lighter sands) and then carefully to treat crops accordingly. Cereals are especially prone to manganese deficiency and may also suffer from copper and zinc shortages. Manganese can be in temporary deficiency, especially in slow growing conditions. Bleaching and speckling of older leaves is a sign of manganese shortage in cereals (white in wheat; dark brown in barley; grey speck with red-brown tints in oats).

Copper (Cu) may fairly often be seasonally deficient for cereals. At high OM levels (peaty soils), available copper can be short and cereals will have twisted leaf tips, twisted awns in barley and shrivelled grains. At high pH too, copper deficiency occurs, darkening to olive green the leaves of wheat with poor ears resulting. Barley does not darken but fills ears badly. Complete cereal crop failure can occur.

Molybdenum (Mo) deficiency has been reported in Australia and India; regular liming may be all that is needed to correct this. India has also recorded iron (Fe) deficiencies in cereals, but this is typically at higher pH levels. Zinc deficiency occurs on HYVs in India and was found to be a limiting factor in wheat production in Turkey (Cakmak *et al.*, 1996). However, correction of Zn deficiency through its addition to compound fertilisers was found very useful and its application in Turkey contributed economic benefit of 100 million USD (Cakmak, 2004).

Boron (B) deficiency is more prevalent on root crops and should be rectified at that point in the rotation, not onto cereals which have very low boron requirements and can be damaged by direct boron applications (Gupta, 1993). However, incidence of boron deficiency on cereals is more widespread in Asia - including Bangladesh, China and Thailand - and in Brazil (Saunders, 1991),

3.11. Sequential roles of plant nutrients through plant development

After sowing, rapid germination and seedling growth is desirable to pass through the most pest and disease-vulnerable juvenile phase of the crop as quickly as possible. For this, moisture supply is crucial. On-farm seed priming of both barley and wheat - soaking in water for 12 hours overnight - has been reported to benefit yield by as much as 40% in Pakistan, confirmed for wheat in India and Nepal and for barley in Bangladesh (Harris & Hollington, 2001). While seed samples do vary in their vigour, seed reserves of nutrients in good quality seeds are ample for germination. A critical point is when seed reserves of nutrients have been exhausted and the young seedling becomes entirely dependent upon soil water and its mineral content for sustenance. Phosphorus is the key nutrient at this stage but soils low in potassium may also benefit from its placement close to seeds. For rapid early vegetative growth, nitrogen supply is crucial. Placement of a fertiliser containing nitrogen in ammonium or ureic form can be beneficial in making phosphate more available owing to the acid produced by these nitrogen sources; ammonium phosphates are often suitable.

Once seedlings are established, there should follow a period of exponential growth when all essential nutrients will be needed. Steady supply of nitrogen is most critical at this stage in order that it may not limit the attainment of optimum leaf appearance, leaf expansion and tiller initiation. Excess nitrogen inducing too many vegetative tillers is undesirable since a lower proportion of these will later become reproductive, ear-bearing tillers. Excess nitrogen will also produce soft plants vulnerable to infection and stress, especially in conjunction with too little potassium. Thus, a balanced supply of N and K is vital.

As cereal plants approach maturity, nitrogen and phosphorus become concentrated within the grains while potassium accumulates chiefly within the straw. Ample phosphate supplies lead to earlier flowering, earlier grain formation and earlier ripening. Late nitrogen supplementation can delay maturity but for milling varieties of wheat, strategic small doses can directly boost grain crude protein (CP) content. Conversely, where low N is needed in the grain as for malting barleys such effects are to be avoided.

It is now necessary to consider these physiological responses of cereals to nutrients in the more complex context of real field soils. This is the aim of chapter 4.

Chapter 4: Nutrient Requirements of Small-Grain Cereals

4.1. Crop uptake and nutrient off-take

There is a close correlation between crop yield and the supply of readily available nutrients. However, there is no simple relation between soil content of available nutrient and crop uptake so there is no point in expressing available levels of nutrient in kg/ha. It is much better to express them in analytical units such as mg/kg of soil and then correlate these with field experiments to assess and calibrate crop responses. As with humans and animals, there is a correlation between plant growth stage and its nutrient intake demands. Once inside the plant, nutrients are stored in varying concentrations in different parts. Return of nutrients to the soil from a previous crop varies according to how that crop was harvested and utilised. Thus, nutrient off-take may differ from crop uptake, especially according to whether the straw was removed or chopped and reincorporated into the soil. In order to sustain soil nutrient status it is important to balance nutrient off-take with nutrient input from fertilisers and various manures or composts. The different cereals require their own particular balance of all the essential nutrients in order to attain their required yields and qualities. It is one thing to determine these under laboratory or growth cabinet conditions in solution cultures, growing the plants in glass bead media for root support - i.e. hydroponically, quite another to establish responses to rates and dates of application under the complex variables of field soil conditions. It is possible to plot nutrient uptake through the growing season as shown in Fig. 4.1 for winter wheat in Southern England (Courtesy of G. Wadsworth).

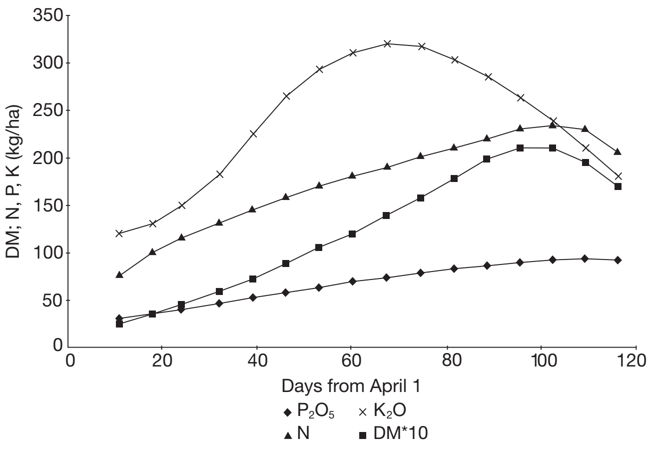


Fig. 4.1. DM accumulation and N, P & K uptake (kg/ha) by wheat.

Long-term experiments are important in relation to fertilisers and crop nutrition (Kemmler & Halicornet, 1989). Fortunately, some field experiments have run for more than a century, such as at Rothamsted UK (Johnston, 1997) but long-term trials are expensive, even impossible adequately to replicate across the diversity of cereal-growing soils worldwide and taking proper account of repeatability from season to varied season. Therefore, correlations have been sought between relatively simple, rapid, inexpensive chemical measurements of soil content, crop uptake and deposition in various plant parts. This chapter attempts to clarify the practical difficulties of this work and to indicate the outcomes of a vast amount of effort worldwide to determine and adjust practical fertiliser nutrient recommendations.

4.2. Soil nutrition and sustainable productivity

The inherent fertility of soil depends upon its proportion of finer clay and silt together with its humus (fully decomposed OM content). Sandier soils and those lower in OM have not only reduced capacity to retain nutrient reserves but also, for the coarser sands, poorer water holding characteristics too. Additions of less soluble, undecomposed OM in the form of manures or the less soluble inorganic fertiliser materials such as rock phosphates take time to become available to crops which actually remove soluble nutrients from soil solution. The factor that controls the relative availability of all the essential nutrient elements for crops is soil pH. This tends to go down (i.e. become more acidic) in many cases rather than up owing to crop removal of calcium and magnesium, leaching during rains and the acidifying effect of many fertilisers. The widely used nitrogenous fertiliser, ammonium nitrate is a particular culprit. While it is true that many latosols and other tropical soils are better buffered against pH falls than many temperate soils, low pH is still a frequent problem. It should be monitored, perhaps through extension officers or advisers offering to test properly randomised, replicated and representative soil samples for farmers. Perhaps this can be done using - as in parts of India - mobile soil testing laboratories to conduct village ‘plant clinics’. The more soluble inorganic fertilisers, such as ammonium nitrate and even the compounds of NPK are vulnerable to leaching when heavier rains come if not removed systematically by a steadily growing crop. It is in this context that the debate about fertiliser recommendations and sources must be set.

Organic manures should be captured as much as possible and ‘pre-digested’ by mixing them with plant residues (crop leaves, soft annual weed leaves, woodash, sprinklings of topsoil). Handling large amounts of manure is laborious. Many small farmers have limited supplies of manures; even the better-off farmers often own only a few livestock per household, and except when kraaled or housed at night, much of their manure is widely dispersed in the bush. Use of human manures, including urine can greatly boost supplies provided that there is good composting and scrupulous hygiene in handling them. The present writer composted the proceeds of 600 students with chopped grass covering in Nigeria during the 1970s and supplied much of the crop nutrient requirements from this source. However, one must not underestimate the taboos in persuading households and communities to adopt and hygienically to manage sewage as fertiliser. Nevertheless, in Chinese and other Far Eastern traditional farming systems, such as in Japan and Korea, maximum human and animal manure capture is key to success (see King, F.H. *Farmers of Forty Centuries*, 1911, reprinted 1977, Rodale Press, USA). Of course, the non-use of soluble inorganic fertilisers attracts a premium for the crops so grown where there is a market for organic produce such as in Europe, and for niche market tropical products (Lampkin, 1990). Adequate nutrients must be obtained for conservation farming (CF) to work, not only to gain adequate yield of food grains but also adequate root activity to depth and ample vegetative residues after harvest to provide sufficient mulch for the next crop.

Clearly, it is unwise and unsustainable to apply more than needed and any added fertiliser should be given to match the yield potential of the crop. It should be applied into a context where other factors affecting yield have been well managed such as water conservation, correct soil preparation, pH, timely planting of the right seeds and established plant populations. By placement of fertiliser near to seeds there is an increased chance of better nutrient recovery and less need per hectare. However, it is equally easy to overdose with yield depressing effect so care in fertiliser use is crucial. There is some debate about using very low levels of fertilisers for the poorest farmers. On the other hand, the *Sasakawa Africa Association* advocates much increased rates for Sub-Saharan Africa, especially on maize, the region's most widely grown food crop covering some 21 Mha but at only around 1.3 t/ha average yield. At these levels, *Sasakawa* reckons on properly applied fertiliser giving some 12-15 kg extra grain per kg applied. Maize provides over 50% of calories in the Malawian diet and approaches similar averages in parts of Zimbabwe. The *Sasakawa* President is Dr. Norman Borlaug the 1970 Nobel prize-winning breeder behind dwarf wheats and rices of the 'green revolution'; it is supported by ex-US President Jimmy Carter and sponsored by The Nippon Foundation. *Sasakawa* calculates that African agriculture must grow at around 5 to 6 % per annum to ensure food security is possible within the continent. Fertilisers judiciously used can certainly help in this, especially in wheat and maize growing areas in Africa.

4.3. Nutrient deficiency symptoms

Cereal crops show characteristic symptoms of nutrient deficiencies (Appendix 1), notably foliage discolouration, but as with human dietary deficiencies, prevention is better than cure. Subclinical depression of growth will occur before symptoms become apparent (see Chapter 3). Various tests of soil and of plant tissues can indicate likely shortages of nutrient supplies before these produce damaging plant symptoms. However, crops can recover from short-term nutrient deficiency symptoms so that undue alarm is not always warranted although avoidance of nutrient shortages is clearly desirable (Appendix 1).

Matching the timing of fertiliser applications to demand is important not only for the crop but also in order that available nutrients are not lost from the soil. Apart from the wastage of a costly input, such fertiliser loss threatens the environment where it arrives – notably in watercourses where leached nutrients can induce *eutrophication,* a process whereby excessive algal and other growth in water depletes oxygen when it dies and decomposes, leading to fish deaths. Nitrates and phosphates are the greatest potential and actual culprits in this process (Addiscott *et al.,* 1991; Edwards & Withers 1998, DEFRA/HGCA, 2002).

4.4. Nutrients needed

Cereal crops need to access balanced supplies of essential nutrients as follows:

Major elements (required in relatively large amounts) are:

- Nitrogen (N)
- Phosphorus (P) - expressed as P_2O_5, phosphate (43% P)
- Potassium (K) - expressed as K_2O, potash (83% K)
- Magnesium (Mg)
- Calcium (Ca)
- Sulphur (S)

Minor (trace) elements (needed in relatively tiny amounts):

- Boron (B)
- Chlorine (Cl)
- Copper (Cu)
- Iron (Fe)
- Manganese (Mn)
- Molybdenum (Mo)
- Sodium (Na)
- Zinc (Zn)

Other elements taken up by cereals but not shown to be essential include selenium (Se), aluminium (Al) and silicon (Si) which, as silicates, stiffens straw.

Particular trace elements may be short in certain soils and districts and are to be monitored accordingly. Most are usually so well supplied incidentally from both organic and mineral sources that they do not reach shortage status. Chlorine, taken up by roots as chloride anions, is an essential nutrient. It is naturally plentiful and thus rarely deficient but it can reach excess in sodic soils when salinity will present problems. However, it does not convert in soils into chlorine gas nor into hypochlorite and thus there is no adverse effect recorded from routine use at recommended rates of muriate of potash (potassium chloride) as the main straight form of potash applied to soils for more than a century.

It is not necessary in most situations to test for more than a few of these elements. As long as pH is maintained at an adequate level (ideally between 6 and 7) then the nutrients most likely to be limiting are nitrogen, phosphorus, potassium, and sometimes magnesium and sulphur (Johnston & Salter, 2001). While nitrogen is needed in the highest quantities of all these to sustain optimum cereal yields on most soils, it is not possible accurately to measure directly its soil content in any meaningful way to allow quick chemical testing for required fertiliser predictions. Other factors must be computed into the assessment of N need.

4.5. Soil fertility

Soil fertility is a comprehensive concept referring to the soil's ability to produce and go on producing useful crop yields. It is not just about nutrient levels in soils or the proportion of these readily available to the crop at any one time. In order to achieve sustainably adequate fertility, the soil must provide:

- Space (porosity for suitable air/water balance and depth/volume)
- Water
- Air
- Anchorage
- Balanced supply of all essential mineral nutrients
- Favourable pH (around 6.5-7.0)
- Warmth
- Absence of toxins and restrictions
- Suitable OM level and decomposition rate (3-5% in mineral soils)

The first four of these requirements are clearly closely related to soil structure, which determines the air/water balance and suitability of soils conditions for roots and other beneficial biological activity. To assess whether this is good or not, a spit of soil can be dug when cereal roots are well established and bumped on the ground just enough to see whether fissures (cracks) develop vertically as desired, or else horizontally indicating compaction. It is also possible to over-loosen soil. *Colour* is principally an indicator of the drainage status of the soil. Mottled soil colouring with a mixture of yellows, ochres, greys and often blueish-green tinges is due to gleying (the production of ferrous iron compounds in anaerobic conditions) and is a common indication of some degree of impedance of drainage.

It is vital that residues should decompose rapidly. This process not only releases elements which can be used again by the next crop (mineralisation) but also removes a potential reservoir for trash-borne diseases and pests. The end result of decomposition is the much more slowly dissipated *humus* which has twice the capacity of the best montmorillonite clay and twenty times of the poorest kaolinite clay to hold onto nutrients, apart from its role in aggregating sands and aiding retention of plant-available water. There is a close correlation between the soil's ability to support a large and diverse soil population and its suitability as a root environment. Thus the nature of its OM is some evidence of its suitability for cropping. Earthworm populations are perhaps the easiest to observe and measure. Their population size depends greatly on the degree of soil disturbance as well as these other factors.

The detrimental consequences of excess water in the soil arise largely from its displacement of oxygen (which diffuses some 10,000 times slower through water than through soil air). The results are poor establishment of the crop and reduced rooting depth, volume and activity. All biological activity is impaired in anaerobic conditions but some microorganisms continue to thrive and produce toxins such as ethene (ethylene), hydrogen sulphide and excess ions of aluminium and manganese, all of which can inhibit roots. The slower, festering decomposition of OM from previous crop residues also means that seedlings of the next crop are hindered and more likely to contract diseases from the still-lingering trash.

Johnston & Hollies (2003) express very well the aspiration of soil fertility management: 'The productive capacity of a soil depends on often complex and sometimes little understood interactions between the biological, chemical and physical properties of soil. Nevertheless, good farm practice aims to manage the various factors that make up each of these three properties so that yield is optimised in environmentally friendly ways.' Every effort must be made to increase understanding of beneficial microbiological processes in soils which themselves depend on having conditions suitable for optimal crop root development, notably good soil structure and ample replenishment of OM (Russell, 1957; Alexander, 1961; Wibberley, 1987; Davet, 2004; Gobat *et al.*, 2004). There have always been advocates of small additions to soil as 'microbial amendments' but these cannot be sustained in soils, except where they have specific niches to colonise. This is the case with rhizobia able to nodulate their own specific legume (but these are usually applied to seed rather than to soil for more reliable effect). The reason is that the soil is an intensely competitive environment with rich microbial populations exceeding the over 6500 million human population of the world within a level teaspoonful of fertile soil. The particular mix of organisms is the result of the soil environment provided naturally and by management. Therefore, it is this environment which needs to be improved in order to stimulate beneficial biological activity within a vigorous nutrient cycle. This can be done by judicious, ample and regular amendment with OM and attention to maintaining all those conditions for its rapid decomposition that arise from good soil structure to achieve air/water balance and correct pH. Even a soil of low OM – say 2%, will contain almost half a tonne of biomass carbon per hectare; a few grams of expensive 'microbial amendment' will not have a lasting impact on this contextual scale. It is the aim of good soil management to encourage the beneficial activities of which farmed soil populations are naturally capable, viz.:

- Decomposition of OM, accompanied by a healthy smell due to some actinomycetes.
- Mineralisation of nutrient reserves.
- Special chemical changes such as nitrification.
- Assisting aggregation of soil particles through gum secretions.
- Antibiotic production, which deters pathogens.
- Nitrogen fixation (*Azotobacter*, Blue-green algae, *Rhizobia* with legumes).
- Breakdown of toxins arising as natural or synthetic pollutants.

Of course, soil microbial activity can also be detrimental:

- Competing for limited nutrients with crop roots (usually more aggressively).
- Denitrification in poorly aerated soils leading to loss of N as gases.
- Toxin production in anaerobic soils (e.g. hydrogen sulphide, butyric acid).
- Some are pathogens or pests in their own right.

However, all of the above detrimental effects of soil microorganisms are associated with mismanagement of soil rather than being inevitable consequences of an active soil population. On the contrary, it is an active beneficial soil population which is the best means of counteracting detrimental effects. This is best sustained by an ample nutrient supply, including as diverse sources of OM as possible, into a well-structured soil at the correct pH.

4.6. Soil nutrient supply systems

Nutrients are held in soils in three main phases (Fig. 4.2 after Wibberley, 1979). These are reserves of either sparingly soluble rock minerals or else within OM (anything previously living but now dead and in varying stages of decomposition) and exchangeable reserves of varying availabilities which effectively buffer supplies to the soil solution by two-way transfers both to it and from it. These three phases are analogous to food store (larder), table and plate for human nutrition, or else analogous to deposit account, current account and money in purse in financial supply terms. Obviously, materials vary in their rates of decay and release of available nutrients into the soil system. Nutrients also interact with each other in continually dynamic ways (Russell, 1973).

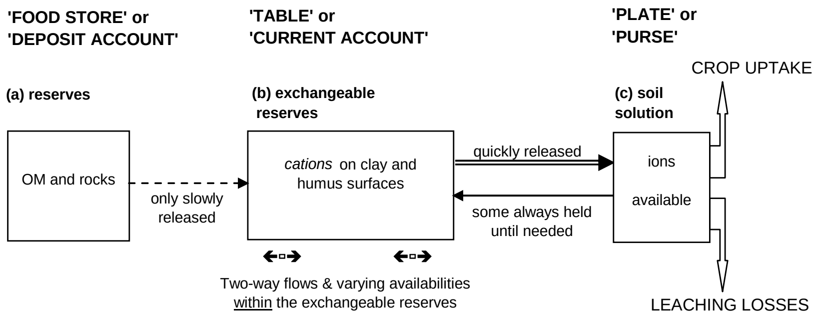


Fig. 4.2. Nutrient phases in soils (after Wibberley, 1979).

Note: Ions are produced when a substance dissolves in water, e.g. muriate of potash fertiliser (potassium chloride):

KCl	➔	K^+	+	Cl
Potassium chloride		Potassium cations		Chloride anions

4.7. Soil sampling for soil testing

The wise cereal farmer will 'know' the soil farmed by doing the following:

- Handling it to feel its type (textural proportions of sand, silt, clay in mineral soils).
- Examining its profile (vertical section to one metre; wheat roots up to 2m).
- Working it to gain experience of soil variability, especially depth and stoniness.
- Classifying it as to land capability, soil series, the farmer's own criteria.
- Testing it (or, more usually, having it analysed).

For soil testing, it is possible to purchase colorimetric kits to assess the chemical constituents of the soil. Rapidly registering probes for pH and moisture status are also obtainable. Commercial firms and advisory services offer laboratory analytical services for soil nutrient testing. Some farmers have obtained computerised, detailed analyses for all essential elements, both major and minor (trace), from sophisticated laboratories. Whatever the degree of sophistication of the testing, it remains axiomatic that the usefulness of the results depends on how sensibly the sample was taken. There are four commonsense considerations of good sampling (which apply in principle to any bulky commodity, including the grain harvested):

Representative: The sample should truly represent what is to be treated and managed as a result of the analysis. Areas of obviously contrasting soil type within a field should be dealt with as separate blocks. Headlands, gateways and any obviously atypical spots should be excluded from the sampling or dealt with separately. As fields have become larger in many farming systems worldwide, the statistical probability of variations in soil conditions within them is increased and in practice this means parts of fields may need to be fertilised and otherwise treated differently from other parts of the same field (Dampney *et al.*, 1997). These need to be sampled as if they were separate fields. The soil sampler needs to walk in a '**W**' fashion taking core samples across the piece of land to be managed as a unit on the basis of the results that will accrue from the aggregated soil sample tested. This is also the case when large fields even of fairly uniform soil type are subdivided into blocks with rotated crops in order to take account of the differing prior manuring used on the various crops and thus affecting soil residual nutrient supplies.

Randomised: Samples should be taken without bias from scattered spots throughout the whole area to be treated. Fields may be walked in a W or in an X fashion taking core samples as one goes. The scatter of samples should be taken evenly throughout the field or block of land to 15 cm depth for routine topsoil analysis purposes.

Replicated: The accuracy of the sampling or at least its correlation with reality is increased by the number of samples taken, which should never be less than 16 and preferably 25. It is statistically better to have many small samples than a few large ones. Normally the individual samples are bulked, mixed, sieved through a 2 mm sieve and then subsampled for analysis. Although analysis may be conducted on several replicate subsamples, each of these is often a very small amount of soil. When one considers that the top 15 cm of 1 hectare of topsoil weighs around 2,500 tonnes (1,000 tons per acre) and analysis is conducted on a few grams, it is clear how vital it is to sample sensibly.

Regular/Routine: repeated frequently enough to monitor changes in nutrient status so that land can be managed accordingly. In practice, many serious farmers have one-third of their fields tested each year. Heavier soils, which tend to lose nutrients more slowly, may only require testing every four years.

Digital printouts to numerous decimal places are routinely possible nowadays with the sensitivity of equipment (which can detect literally millionths of one millionth of a gram of chemicals). However all this is futile unless the original sampling fulfils the above four Rs of good procedure.

4.8. Soil analysis and its interpretation for nutrient management

Alternative approaches to soil analysis for advisory purposes are available. In particular, there is debate (Johnston & Hollies, 2003) between conventional soil analysis to derive soil indices (e.g. MAFF/ADAS, 2000 – 7th revised edn; 1st edn. 1971) for key nutrients and the Base Cation Saturation Ratio (BCSR) and 'soil audit' approaches advocated in America (Kinsey & Walters, 1993) and applied elsewhere (Scamell, 2000). Of course, any analytical information must be interpreted in the light of the many factors that may affect overall soil fertility and potential in any particular field, especially previous cropping, previous manuring and climate.

Much advisory work on fertiliser recommendations around the world derives from extensive databases from trials and field monitoring, some of it dating back well over 100 years. It has long been established that determining the total soil content of nutrients such as P, K and Mg has little meaning since this correlates poorly with yield. Fortunately, proven methods of assessing the readily available amounts of P, K and Mg (in mg/l or ppm) are established and this does correlate well enough with crop yields (Fig. 4.3). In intensive cereal systems, soils are tested every 4 to 5 years to monitor changes in nutrient levels due to cropping and fertiliser practice. Soil extractable P can be assessed by the Olsen method (Olsen *et al.*, 1954) using sodium bicarbonate solution at pH 8.5 and then producing varying intensities of blue colour by using acidified ammonium molybdate. Extractable K is determined using molar ammonium nitrate solution and then assessing K intensity using a flame photometer. Mg is also extracted with molar ammonium nitrate solution and the extract submitted to an atomic absorption spectrophotometer. Accordingly, soils can be described on scales (converted to indices, 9 down to 0 in the UK) from 'very rich' to 'very deficient' with corresponding fertiliser responsiveness ratings for crops from 'not responsive' to 'highly responsive'.

The correlation between soil analysis and fertiliser recommendations can only be legitimately derived from properly repeated field trials. These are usually done by testing the same crop in several soil types, sites and seasons under similar conditions except for the particular nutrient under test. This is supplied at varied rates to all but the control plot and yields recorded to compile crop response graphs which show the optimal rate of addition at their asymptotes (Fig. 4.4).

An alternative approach is to test plots of differing soil index for a particular nutrient (but otherwise treated similarly). These can be established and then crop yields plotted against soil index to determine the critical index required.

After attaining the ideal index, crop uptake in a particular season can then be replaced by fertiliser additions to that field to maintain the index. For P, K and Mg, maintaining an index of 2 for cereal crops (revised to 2^{-} for K or 120-180mg/l) ensures that they are not limiting to yield (Tables 4.1 & 4.2).

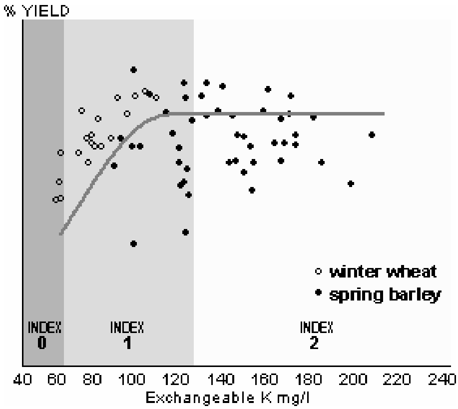


Fig. 4.3. Response of winter wheat and spring barley to soil exchangeable K (*Adapted from*: PDA).

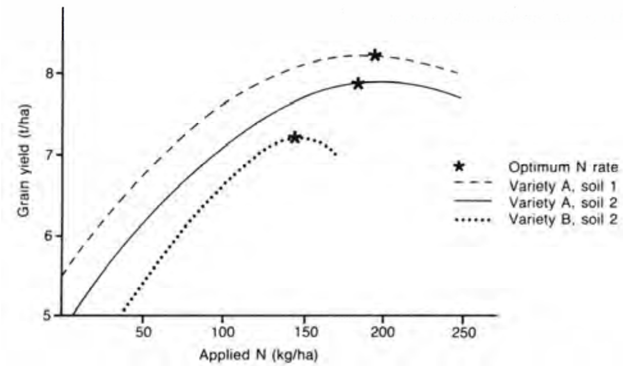


Fig. 4.4. Nitrogen response curves of winter barleys (after Wibberley, 1989).

Table 4.1. UK soil P and K index with matching levels of available P and K (mg/l).

Soil P index	0	1	2	-	3	4	5
mg/l P_2O_5	0-9	10-15	16-25	-	26-45	46-70	71-100
Soil K index	0	1	2-	2+	3	4	5
mg/l K_2O	0-60	61-120	121-180	181-240	241-400	401-600	601-900

Adapted from: MAFF/ADAS, 2000.

Table 4.2. Phosphorus and potassium recommendations for various cereal yields.

	P or K index				
	O[a]	1	2	3	Over3
			kg/ha		
Straw chopped in or burnt					
Yield level 5.0 t/ha					
Phosphate (P_2O_5)	90	40	40M	40M	Nil
Potash (K_2O	80	30	30M[b]	Nil	Nil
Yield level 7.5 t/ha					
Phosphate (P_2O_5)	110	60	60M	60M	Nil
Potash (K_2O)	95	45	45M[b]	Nil	Nil
Yield level 10.5 t/ha					
Phosphate (P_2O_5)	130	80	80M	80M	Nil
Potash (K_2O)	110	60	60M[b]	Nil	Nil
Straw removed					
Yield level 5.0 t/ha					
Phosphate (P_2O_5)	90	40	40M	40M	Nil
Potash (K_2O	110	60	60M[b]	Nil	Nil
Yield level 7.5 t/ha					
Phosphate (P_2O_5)	110	60	60M	60M	Nil
Potash (K_2O)	140	90	90M[c]	Nil	Nil
Yield level 10.5 t/ha					
Phosphate (P_2O_5)	130	80	80M	80M	Nil
Potash (K_2O)	170	120	120M[c]	Nil	Nil

[a] At index O large phosphorus and potassium input is recommended to raise soil index over several years.
[b] Not needed on most clay soils.
[c] A lesser amount may be used on most clay soils.
M = Maintenance dressing to prevent depletion of soil reserves rather than to give a yield response.

Adapted from: MAFF/ADAS, 2000.

Failure to replace the P and K removed by crops during times of economic pressure for the farmer may not result in measurable changes in soil indices for several years but this policy will deplete soil reserves. While in extreme circumstances it is legitimate to omit P and K for a year or two, efforts to counteract this deficit of investment should be rectified once the economic crisis has past. Clearly, on those soils of already low P and K index there will be a yield penalty detectable sooner unless adequate nutrient inputs are maintained. It is important to bear in mind that after additions of extra P and K to compensate for earlier limited inputs, the indices may not necessarily rise immediately. This is because the extra P and K – especially K – will enter the slowly available pool of nutrients whereas index analysis methods only measure that in the readily available pool of nutrients. For maintenance (M) of soil nutrient status and to move slowly towards the desired index of 2, adjustments to applications of P and K are advocated by guidelines for British farmers (MAFF/ADAS, 2000) according to present soil index as in Table 4.3.

Table 4.3. Guideline fertiliser rates (kg/ha) to attain P_2O_5 index 2 and K_2O index 2.

Soil index	0	1	2	2-	2+	3
P_2O_5	M + 50	M + 25	M	---	---	M - 50
K_2O	M + 50	M + 25	---	M	M - 25	M - 70

Adapted from: MAFF/ADAS, 2000.

Note: Some 500 kg/ha of P_2O_5 and 400 kg/ha of K_2O are needed to change an index by 1 band.

The BCSR system of soil analysis advocated by Kinsey & Walters (1993) measures, as the name suggests, the ratio of base cations Ca, K, Mg, Na, and their relationship to total cation exchange capacity (CEC). CEC includes all other cations present, notably aluminium, hydrogen and ammonium plus copper and zinc. However, BCSR is also usually extended by analyses for other essential nutrients in order to present a Soil Audit. This approach claims to be more ecologically appropriate but it appears to ignore the oft-repeated caveat with standard soil analysis data that they are only a guide to be used in the context of a comprehensive approach to soil fertility management by feeding the soil and its diverse microbiological population. Furthermore, a Soil Audit can become very expensive and the meaning of its results somewhat obscure for farmers. Where there are soils with a very specific known deficiency of, say, a trace element, then it is usual practice to monitor and target this specific need rather than expensively testing for every nutrient, apart from the major nutrients.

These merit regular monitoring in the most straightforward and well-tested way possible which has been linked to widespread field results for decades now. Independent assessment of the BCSR system has not so far supported any correlation between it and yield (Johnston & Hollies, 2003). There are problems in assessing the base cations together anyway since Ca results are exaggerated as soils become more calcareous in origin and it is not a limiting nutrient for cereals anyway since liming supplies it. In the BCSR system, cations are expressed as milli-equivalents per 100 grams of soil (cmolc/kg) and so not directly comparable with familiar index systems. Kinsey & Walters (1993) propose that ideal cation ratios (% of CEC) should be:- Ca 60-70; Mg 10-20; K 3-5; Na 1; H 10-15; Others 2-4. In practice, any soils above pH 7 will have very little hydrogen within their CEC. There appears to be no proven correlation between BCSR and yield for winter wheat. Despite variation in Ca:Mg ratios from 37:1 to 9:1, yields of winter wheat were 8.5 and 8.0 t/ha respectively. In another test, BCSR varied but the index system indicated adequacy (over 2) for both K and Mg cations and pH was suitable, yet yields were similar (Table 4.4).

Table 4.4. Winter wheat yields on soils of contrasting BCSR but ample K and Mg.

Soil	pH	Ca	Mg	K	Na	Yield	Ca	Mg	K	Na
		%				t/ha	mg/kg	mg/kg (index)	mg/kg (index)	mg/kg
No. 1	7.2	76	4	4	0.2	9.6	2380	66(2)	247(3)	10
No. 2	7.0	69	19	8	1	9.8	1460	243(4)	66(2)	32

Adapted from: Johnston & Hollies, 2003.

A further complication of BCSR is that some advocates suggest contriving local acidification of soil to counteract excessive Ca by using ammonium sulphate. Farmers well know that ammonium sulphate not only acidifies soils but its use on calcareous soils under warm conditions leads to volatilisation and thus waste of N as ammonia. However, root activity in a healthy soil generates its own local H+ secretion at the rhizoplane (rootlet surface) which assists naturally in mobilising nutrients. Other proposed manipulations of the soil population sometimes linked with soil audit advice are questionable (see Soil Fertility section above).

Assuming common sense in taking all due care of soil fertility, the straightforward determination of readily available soil P and K does correlate well enough with cereal yield for practical usefulness (Fig. 4.5).

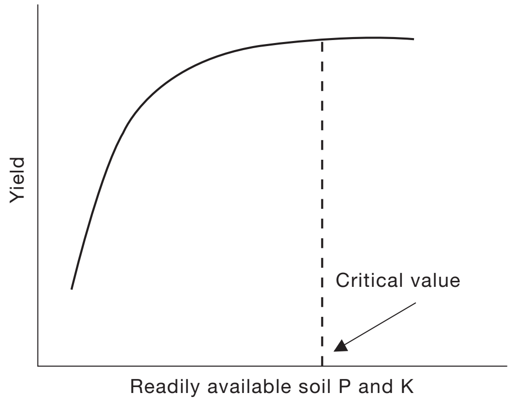


Fig. 4.5. Correlation of readily available soil P and soil K with cereal yield (Johnston & Salter, 2001).

4.9. Soil organic matter

Soil OM consists of everything in soil which was previously living and is now in varying stages of decay or decomposition. Total OM content of soil determined by burning a sample means very little since it does not tell the investigator anything about the quality nor rate of decay of it; there is plenty of OM in a stagnant pond but that is an unhealthy environment. The fully decomposed highly chemically complex end product of OM decomposition is the relatively stable, amorphous dark substance known as humus. This too continues to decompose but at much slower rates than freshly dead OM such as cereal straw or dead earthworms and microbes. Humus content in soil is not measurable directly but is taken to be soil carbon content (%) multiplied by a factor of 1.72 to represent the typical carbon proportion in humus. Both the absolute content and the rate of replenishment of humus are vital for soil fertility because humus is associated with:

- Assisting soil aggregation to form stable soil structure.
- Improving the soil's plant-available water holding capacity.
- Providing a reserve of nutrients, especially N, P, S and trace elements.
- Ensuring undesirable microbial activity is suppressed by rapid humus formation.

There are few places where humus has been long monitored but an example is Broadbalk field at Rothamsted, England – a silty clay loam under wheat – where it has stabilised at approximately 2% for more than a century.[1] In warmer and especially tropical climates, humus depletion can be damagingly rapid rendering dryland soils infertile and thus more prone to erosion. Managing OM status is absolutely critical to the long-term sustenance of paddy rice that has been achieved in the Far East. For cereal cultivation in temperate regions it is desirable to maintain humus at 3-4%. Above this level in cool temperate mineral soils and in soils with much higher (>25%) humus contents such as the 'muck' soils of the USA and Canada, nutrient management for cereals may present additional challenges. Such soils can render copper and manganese immobile and they can oversupply nitrogen in an uncontrollable way making crops weaker and slower to mature than is desirable. Rich black organic soils are generally better suited to higher value crops than cereals such as vegetables, with cereals as an occasional break crop.

4.10. Nitrogen (N)

Although nitrogen constitutes over 80% of the air, there is very little within the rocks of earth's crust. Therefore, N arrives in soil either by biological nitrogen fixation or in a more limited way by chemical fixation during thunderstorms or chiefly by additions of organic manures and accumulations of OM from previous cropping. More than 90% of soil N is thus in the soil OM. Nitrogen is the key nutrient for all cereal crops. Most, but not all, higher yielding cereal crops will require nitrogen fertiliser. Where N is applied, the farmer has a very useful agronomic tool for managing growth, yield and quality according to how much total N is given and by judicious timing of split doses.

It is possible to analyse quite accurately the total nitrogen present in:

- *Soil*: Chiefly in the OM fraction. This varies depending on soil type, previous cropping and manuring from 0.1 to 0.7% of the topsoil (top 15 cm). This soil can be taken to weigh 2,500 tonnes/ha; thus, from 2,500 – 17,500 kg/ha N is present. However, only as much as one-fiftieth of this is likely to be available during the life of any one cereal crop, i.e. as little as 50 kg/ha or less.
- *Fertilisers*: For example, ammonium nitrate 34% N; urea 46% N.
- *Plant tissue*: Simple test papers for the sap are a rough guide to current N status and laboratory equipment is very discerning. Although showing

[1] Broadbalk field, Rothamsted, England also has approximately 25-30 t/ha of potash in its topsoil (to 23 cm). Only around 200 kg/ha of this is in the readily available K pool and only some 20 kg/ha extra K is released per year into this pool from soil mineral reserves.

promise, correlations between nutrient storage pool concentrations and yield maximising fertiliser requirements are imprecise (Barraclough, 1993). However, Barraclough (1997) also reports useful correlation between leaf %N for winter wheat and maximum yield. The critical %N lies between 3.5-4.6% and this is a better predictor than basal stem nitrate (BSN). BSN has been more used internationally but it varies with site and its critical value for maximum yield declines anyway during crop development.

However, two vital questions remain:

- What proportion of this total nitrogen is going to become available in a form which the crop can extract to coincide with its demand?
- What recovery of the available nitrogen can the root system achieve?

Availability depends on solubility and the preferred form is nitrate (NO_3) which is actively taken up, with a limited intake as ammonium (NH_4^+) which can enter roots passively. Thus the pool of available soil N depends firstly on soil microbiological activity, both decomposers and nitrifiers (their activity is related to moisture, warmth up to 40°C, aeration and pH; it is often greater after dry spells once moisture arrives). Secondly, it depends on how much of the total is added as available nitrate, and ammonium, as fertiliser. NH_4^+ becomes toxic at much lower concentrations than NO_3.

Recovery depends on the volume and depth of the root system that in turn depends on date and density of planting and quality of soil conditions for root development. In addition, recovery may be jeopardised by the premature loss of available N from the rooting zone principally by leaching but also by volatilisation losses from concentrated ammonium sources and denitrification losses in poorly drained conditions. Table 4.5 shows variation in N recovery and off-take by a range of winter wheat crops.

It is evident that determining the nitrogen requirement of a cereal crop is not a straightforward matter. There is not a simple linear relationship between crop growth and N fertiliser need. This varies not only with Soil Nitrogen Supply (SNS) but also with DM accumulation rate of the crop which in turn depends on the season and other growth factors. Crops which achieve high DM accumulation rates also tend to produce extensive, more efficient root systems. Put conversely, it is not possible to have a good crop without a good root system. It follows that if there is a higher percentage recovery of added nitrogen then such a crop may be satisfied by a lower rate per tonne of expected yield. On the other hand, crops with root diseases such as Take-All (*Gaeumannomyces graminis*) may need extra N to try to compensate for their poor root systems yet still achieve low yields. Since the visible response to added N fertiliser on cereals is frequently so noticeable, there is a danger that some farmers or advisers may tend to use it as a ‘cure-all’ treatment when attention to other underlying causes of poor growth, especially root restriction, is actually needed.

Table 4.5. Fertiliser nitrogen recovery in nine winter wheat crops.

Location	Fertiliser N kg/ha	Yield t/ha	Fertiliser N % harvested	Nitrogen off-take kg/t grain
Wheat after wheat – direct drilled				
Bounty	213	7.39	44.6	27.4
Huntsman	178	5.57	52.6	25.0
Armada	175	7.71	60.5	23.4
Wheat after wheat – cultivated				
Flanders	140	7.11	47.9	22.2
Hobbit	152	8.87	70.4	20.7
Armada	131	6.72	55.5	21.7
First wheat after a break crop				
Hobbit	143	9.84	49.0	17.2
Armada	182	8.60	64.5	26.0
Huntsman	110	6.74	40.4	22.9

Adapted from: Sylvester-Bradley *et al.*, 1987.

Soil Nitrogen Supply (SNS) is difficult to estimate but easy to define as ‘the amount of nitrogen in the soil that becomes available for uptake by the crop from establishment to the end of the growing season, taking account of nitrogen losses’ (MAFF/ADAS, 2000). The principles upon which this approach is based are internationally applicable. SNS can be estimated by growing a crop without N fertiliser and determining its uptake. However, soil nitrogen recovery can be greater when N fertiliser is applied owing to its effect on root activity. Alternatively, SNS can be estimated from measuring soil mineral N content (soil mineral nitrogen, SMN = nitrate plus ammonium N) in the soil profile to rooting depth of the crop. To do this, soil cores to 90 cm are taken monthly. N already in the crop is included and the calculation adjusted by adding an amount estimated to be mineralised between sampling date and the time of maximum crop uptake minus estimated N losses. Other ways of estimating SNS use the expected gains from the mineralisation of N in soil OM, crop residues, manure residues and aerial deposition, minus the losses from leaching, volatilisation and denitrification.

Factors which increase SNS are:

- Soils high in OM.
- Soils with a long history of manure application.
- Soils with N-rich residues of previous crops e.g. legumes, vegetables given much N.
- Soils where mineralisation of N is encouraged by deep, thorough cultivations.

Factors which decrease SNS are:

- Soils low in OM.
- Succession of previous crops leaving low N residues e.g. cereals, low N grassland.
- Wet, dense soils with deleterious microbial activity: immobilisation, denitrification.
- Leaching through free-draining soils.
- Volatilisation as ammonia – especially from warm, alkaline soils.

MAFF/ADAS (2000) introduced a seven level SNS index system (kg N/ha):

- 0 = <60
- 1 = 61-80
- 2 = 81-100
- 3 = 101-120
- 4 = 121-160
- 5 = 161-240
- 6 = >240

For cereals, the amount of N in growing crops during the stem extension phase is proportional to the number of shoots per square metre. Crops with 500 shoots have 5-15 kg N/ha, those with 1,000 shoots have 15-30 kg N/ha, while those at 1,500 shoots can be reckoned to have 25-50 kg N/ha.

Cereals are usually more responsive to the addition of this nutrient than any other element. N uptake roughly parallels rate of DM production. Nitrogen occupies 1.5 to 2.0 % of total yield. It is a constituent occupying some 16 % of every protein molecule. Proteins are regular components of protoplasm, the ground substance of every living cell. They include enzymes and the additional protein deposits stored in the aleurone layer of the grain.

Applied nitrogen is analogous in the cereal's life to glucose tablets in that of athletes in so far as it is a readily available source accelerating the current activity of the plant at the time of uptake. It is renowned for increasing the leaf area of cereals and it also prolongs green leaf life, also known LAD. It can encourage tiller survival, particularly in adverse conditions, during the normal period of tiller deaths. It promotes stem extension if applied when the crop is physiologically concentrating on this process. It can increase the number of grains surviving per ear and late N can boost grain protein content (see Chapter 6). Overall, N is associated with greater DM production and higher grain yields. However, it accelerates water uptake and crops demand more water in order to take up the N.

Excessive N produces surplus vegetative growth including too much dark blue-green leaf of low DM percentage which is soft and more susceptible to foliar diseases. It can encourage too many tillers and generally lush, weak vegetative growth. In a wet season it further encourages too tall a plant with soft stems liable to lodge. Later applications can delay ripening. In a dry time, on the other hand, later applications can interfere with grain filling and produce a pinched sample.

Whilst grain may contain up to 2% N at a crude CP level of 12.5%, straw remains low in CP - around 1.75 to 2.0% CP for wheat and rye straw, with 2.75-3.0% CP for barley and oat straw. This gives a nitrogen uptake of 20 kg/tonne of grain and, allowing for the highest CP level, about 5 kg/tonne of straw. On these figures, assuming a harvest index (grain as percentage of total DM) of 55%, this gives, for example:

- 5 t/ha grain + 4 t/ha straw, roots, etc. removing 100 kg N + 20 kg N/ha
- 10 t/ha grain + 8 t/ha straw, roots, etc. removing 200 kg N ± 40 kg N/ha

Where straw and cereal residues are retained on the field and incorporated rather than removed or burned, the SNS system is depleted then by about 20 kg N off-take per tonne of yield harvested whereas this figure rises to some 25 kg per tonne when straw is removed or burned.

4.11. Phosphate (P_2O_5)

Some 90% of global phosphorus consumption is as fertiliser, one quarter of it produced by the USA, with China and Morocco also major producers. Morocco has around 50% of world land-based reserves and South Africa also has a useful reserve. Huge reserves of phosphate have been identified on the continental shelves and seamounts of both Pacific and Atlantic oceans.

Phosphorus is the least mobile nutrient in soils as it is only sparingly soluble. This fact has three practical consequences:

- It does not leach, as release of available forms just matches demand providing soil conditions favour release (correct pH, structure, and microbial activity).

- Reserves (analogous to a bank deposit account) can be built up in the soil; on the other hand an insidious run-down of deposits can occur over the years.
- Timing of application is unimportant. Indeed, if conditions are difficult either practically or financially, a particular season's phosphate dose can be omitted without detriment, provided an adequate soil supply has been previously attained. Varying the dose from year to year will not usually give yield responses.

The available phosphate in a soil can be quite accurately determined from analysis (Tables 4.2 & 4.3). It is sensible for the serious cereal grower to ensure that the P index is not a limiting factor in securing yield targets. An index of at least 2 is desirable. Most soils have substantial phosphate reserves, but removal is proportional to crop yields harvested.

Low phosphate supply is associated with:

- Acidic soils (or some very alkaline soils).
- Wet or compacted soil conditions (restricting rooting with purplish pink leaves).
- Coming out of long-term grassland into cereals.
- Deep cultivation systems can disperse P to depth.
- Previous crops inadequately supplied with P, especially on heavy land.

Where index 0 to 1 occurs, combine drilling or other means of fertiliser placement is generally advisable or else an extra 30 kg/ha of phosphate. Indeed, phosphate is generally applied to the seedbed just before, during or soon after sowing cereals. When straw is ploughed in, it is sensible to apply the P to this, provided it is going into a soil of index 2+.

A sensible guideline for all cereals is to give phosphate at the rate of 10 kg/tonne of expected grain yield**.** This will replace P off-take in the crop and maintain soil reserves. Thus a 7.5 t/ha crop would receive 75 kg P_2O_5/ha. Up to 25 kg/ha may be deducted from this calculated requirement if a soil index of 3 is maintained. Burning rather than baling and removing straw makes no significant difference to soil phosphate supply. However, a consortium of UK agencies has agreed the crop removal data presented in Table 4.6.

4.12. Potash (K_2O)

Potash is abundant in nature, especially as muriate (potassium chloride) which occurs in association with common salt (NaCl) from which it is separated and ground as fertiliser. This is mined, often at a few hundred metres depth, as well as being extracted from evaporation ponds in the Middle East. Some 85% of global K consumption is as fertiliser, with Canada producing around one-third of the world total, with a further third contributed by Russia and Belarus together.

Potash is absorbed as potassium ions (K). These may be held on the surface of clay and humus in the soil or more tightly between clay plates within soil aggregates (see Appendix 2). This helps K to resist leaching, though it is not so resistant to loss as is phosphate. On micaceous clays, especially at near neutral pH levels, potassium can become fixed between the layers of clay plates (micelles) which constitute clay particles. They may thus trap other ions. However, they tend to be erratically released into the available soil pool of K so adding a variable to the difficulty of predicting K behaviour in some clay soils. In more acidic soils, especially in warmer climates, aluminium behaves rather similarly to K and can interfere with other nutrient behaviour (Russell, 1973). However, non-exchangeable K can act as a strategic part of the soil K reserves at low K concentrations in the soil solution, especially in clay soils rich in vermiculite, illite or smectite which are well-buffered in this respect. The problem is that on many soil types, the lowest yields arise when the crop has to rely on non-exchangeable K (Grimme, 1974; Fig. 4.6).

Potassium is likely to be short on sandy soils, other light soils and black puffy humose soils. Low status may prevail after cut grass crops unless slurry is given (dairy cow slurry is a particularly rich source). Some clays, such as chalky boulder clay, tend to be rich in potassium while kaolinite clays tend to be short of K. Soil can be analysed to give a good indication of its potassium-supplying power (Tables 4.2 & 4.3).

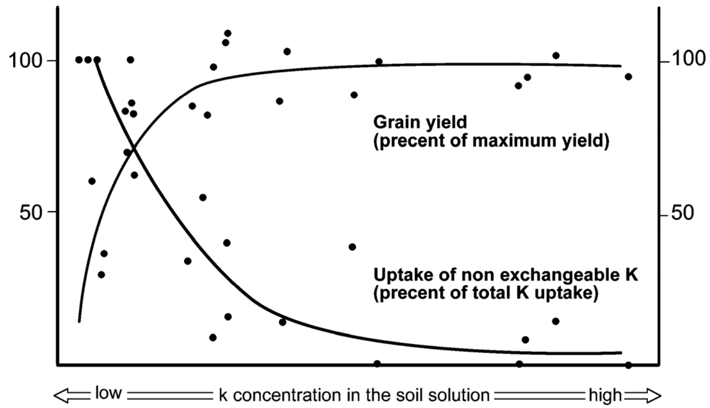


Fig. 4.6. Yield and uptake of initially non-exchangeable potassium. (*Adapted from:* Grimme, 1974).

Crops can indulge in luxury uptake of K, i.e. may they absorb far more K than is needed to maximise yield. Some of this is returned to the soil during growth. This borrowing of surplus K could be important for the plants' general health and ability to withstand stress (climatic or disease).

Combine drilling or other means of placement of potash fertiliser is worthwhile if the soil index is 0, or else gives an extra 30 kg of K_2O. Most cereal growers apply K just before, during or soon after sowing. However, some like to give a little K top dressing to actively growing crops. There is a suggestion that in moist conditions which give a late N response there may be a boost to TGW from a little K also.

When straw is burned or ploughed in rather than baled and removed, there is a return of just over half the K taken up by the cereal crop. Where this procedure is repeated, K doses can be reduced accordingly. Deep cultivations may disperse K to depth. Although the K requirement for cereals is a little higher than for P, many growers use a compound fertiliser supplying equal amounts of each once they have ample indices for both. An index of 2- for potash is desirable and 3+ preferable for highest yield systems.

A sensible rule-of-thumb to achieve adequate supplies and maintain soil reserves is 10 kg/tonne of expected grain yield, i.e. 100 kg K_2O for a 10 tonne crop. However, a consortium of UK agencies has agreed the refined crop removal data presented in Table 4.6 which show this needs adjusting for the different cereal species.

Table 4.6. Cereal requirements (kg/tonne fresh crop) for phosphorus and potassium.

		P_2O_5	K_2O
		kg/tonne fresh crop	
Grain only	All cereals	7.8	5.6
Grain + straw	Winter wheat & winter barley	8.6	11.8
Grain + straw	Spring wheat & spring barley	8.8	13.7
Grain + straw	Oats, rye, triticale: winter or spring	8.8	17.3

Source: Author's collation of data from the UK.

4.13. Magnesium (Mg)

Cereals are only likely to respond to Mg fertiliser at soil index 0. However, with increasing yields and rates of potash fertiliser use in particular, available Mg may become depleted. It is wise to monitor the Mg index and maintain an index of 2+ using either kieserite or, where liming is also needed, magnesian limestone. Organic manures are a useful source of Mg also. As a guide, some 20 kg/ha per year of Mg (given perhaps every third year) should maintain reserves at average cereal yields. Both high potassium and high calcium availability can be a threat to adequate magnesium uptake by the plant.

4.14. Sulphur (S)

Organic manures can supply most if not all the sulphur needed by most cereal crops, which is around 2.5 kg/tonne of grain yield. However, shortages are becoming more frequent where cereal yields are increasing and air pollution is controlled (McGrath, 2001). Incidental addition of sulphur has often occurred in the sulphate form in fertilisers. Most compound fertilisers are now becoming more concentrated and as a result are depleted or devoid of their sulphur content. Sulphur foliar sprays may give a little incidental contact fungicidal activity also. Cereals may benefit in some circumstances such as where the air is pure, far from industrialised areas.

4.15. Micronutrients (trace elements)

Manganese (Mn) analysis of soil is not reliable. Most cereal growers rely on a sound OM cycle and natural reserves in the soil to ensure supplies. This usually works except for certain well-known districts where preventive treatment of crops is routine. Mn may be routinely needed on some sandy land and certain calcareous soils at about 10 kg/ha of manganese sulphate. Mn can be in temporary deficiency, especially during a slow growing period due to cold or other stress, including dry weather. Where used for crop protection purposes, a useful bonus of *maneb* fungicide is its incidental supply of Mn.

Copper (Cu) may be deficient for cereals, especially on certain peaty soils, and soil analysis can help to predict likelihood of deficiency. However, its actual occurrence is very much a seasonal thing. Copper sulphate may be soil applied for prevention at around 10 kg/ha or, for immediate effect, a foliar spray of copper oxychloride at 2.5 kg/ha is given during tillering. In addition, Cu has fungicidal activity that can prove strategic. Cu deficiency can lead to crop failure; barleys and durum wheat appear to be particularly sensitive, especially on humose soils over chalk. High soil phosphate index can marginalise Cu.

Zinc (Zn) shortages are very common. Sillanpãã (1982) found that about 30% of the agricultural soils of the world are Zn deficient. Zn deficiency is commonest on calcareous soils, especially those with high P index. Boron can be lacking and is reported to be quite common in parts of Asia (Gooding & Davies, 1997) where it is associated with sterility in wheat.

Trace element mixtures are on the market, chiefly for later application to assist ear filling in cereal crops**.** Evidence of the need for these is not consistent. However, at the highest yield levels it is logical that crops endeavouring to balance the much greater major element levels made readily available to them may benefit from an extra, readily available supply of trace elements. Seaweed extracts can act as a physical barrier to fungal pathogens as well as introducing diverse trace elements, including iodine, into soil systems. Where trace elements need to be applied to correct a specific deficiency, common sources and rates are suggested in Table 8.4 (see page 157).

4.16. Seedbed and seedling nutrition

Nutrient requirements at this stage are critical when the seed has used up its own reserve supplies for germination and the radicle and shoot have emerged and begun to develop. Suitable moisture and warmth for this phase to pass quickly is paramount but the soil's pH and its readily available nutrient supply will soon impact the seedlings. On soils of low inherent fertility (such as coarser sandy soils, those with a history of exhaustive cropping, those with little previous manuring) there will be a response to seedbed nitrogen addition (up to 20 kg N/ha) and to placement of phosphate, potash and any magnesium fertiliser supplied. The ideal seedbed is one that is not only well structured but also previously well-supplied with nutrients (such as well-incorporated manures and crop residues) and having these actively mobilised through a healthy microbial population by their enzyme action (such as phosphatases and urease). In this case, fertiliser application of N to the seedbed is unnecessary and may in many situations be undesirable since the seedling lacks root capacity to pick up available N that thus becomes vulnerable to loss from the soil. Also any P, K or Mg fertiliser added for later use by the crop may be conveniently applied to the seedbed but is not required by the crop at that stage and is not likely to show any timing response if compared with later application of the same amounts. However, on lighter soils of low fertility when higher rates of seedbed potash in particular are proposed, some of this should be deferred until later in the crop's life in order to avoid seedling scorch. This deferred K can be given with later N top dressing(s) to advantage since it will then help balance the N:K availability to the faster growing crop.

4.17. Nutrition during the exponential vegetative growth phase

This is the time when the soil's capacity to release ample available nutrients will come under pressure from the crop. In particular, there will be response to nitrogen rate and timing during this phase (see chapters 6 & 8). Trace elements, where only marginally available, may begin to produce deficiency symptoms in the vegetative crop.

4.18. Nutrition during the reproductive phase of the crop

It is important that nitrogen is not excessive during this phase since it will delay ripening and impede balanced uptake of potassium and other elements. The grain is concentrating phosphate and sulphur at this time and a balanced deposition of these elements, along with adequate nitrogen is likely to boost grain protein. During this phase for durum wheat on black clay soils, a balanced K:P ratio is important for yield, while N:P ratio is closely related to yield at all stages of growth (Kuzmina, 1997).

Farmers have to synthesise soil data and experience with crop behaviour under their own agro-climatic, site-specific conditions. Chapter 5 attempts to indicate, inevitably somewhat eclectically, how this varies for the major cereal growing regions.

Chapter 5: Small-Grain Cereal Nutrient Management and Agro-Ecology

5.1. Diversity of cereal adaptation

Each of the small-grain cereal crops is encountered in surprisingly diverse soil and climatic zones. None is so widely distributed as wheat (from 60°N to 60°S, including the highland tropics from 1,500m to 3,500m altitude). Wheat can mature on less than 500 mm of rainfall – even as low as 350 mm in Libya, according to Rowland (1993) while rye is principally a locally important cereal of Northern Europe.

Wheat is found growing from South Australia to tropical Kenya and Southern Africa, to the steppes of Russia, to Western Canada, to Midwest USA, to China and Japan, to the Punjab of India and Pakistan, to Argentina, Chile, Southern Brazil, Mexico, the Middle East, Europe and many other places too. Clearly, although there are valid universal principles, there needs to be some adjustment in the nutrient management policy and practice to suit these wide agro-ecological variations. Sowing dates in the Northern Hemisphere vary from August to December for winter varieties, from late January to May for spring varieties, with harvest dates ranging from February to September. In the Southern Hemisphere – Australia, South Africa, South America – sowing is from March to August and harvesting from September to December. Of course, farmers choose species and varieties as well as sowing dates to adapt their cropping to suit their agro-climatic situation. For instance, in North America, the top quality hard red spring wheats are especially found in Manitoba, Minnesota and western provinces. Hard red winter wheats are predominant in Central USA and soft red winter varieties in the Eastern USA and Eastern Canada, along with some soft white varieties. Durum wheat is chiefly a species for the central prairies.

5.2. Agro-climatic zones

After excluding deserts and mountains, other terrain can be broadly classified into six agro-climatic zones, and their distribution is outlined below. It must be noted that global warming – now widely agreed as a man-induced phenomenon (Houghton, 2004) – is also associated with greater unpredictability of weather patterns in many areas, together with more violent winds and more extreme rainfall regimes. In general, rainfall seems to be shifting both northwards from the subtropical areas, and southwards from the southern subtropics, possibly through a stronger clash of the opposing winds which meet within the Inter-Tropical Convergence Zone. Worldwide, in any one district, and even within a single farm, actual agro-climates can vary immensely. Thus, there is no substitute for local monitoring of rainfall, temperature and site characteristics (altitude, aspect and soil conditions). The more elaborate systems of applied climatological classification are deemed beyond the scope of usefulness for this book. Growers of cereals in each country should become aware of their national classification used as a guide to agro-ecological zones with their particular parameters.

Cool humid temperate agro-climates suit small-grain cereals and these predominate in much of Europe, parts of Siberia and in much of Eastern and Central North America. In New Zealand, cereals are mainly grown on the Canterbury Plains of South Island which have light, often stony soils. Similar climates feature very importantly in South Australia and Tasmania, Southern Chile, parts of South Africa, North-East China and Northern Japan. Here, the principal constraints are growing season length owing to low winter temperatures, sometimes poor working weather and sometimes short-term droughts. Yield potential is generally good and relates to inherent soil fertility and management.

Cool dry temperate agro-climates characterise the continental interior in Western Canada and North-Western USA, Ukraine and the Russian Steppes, the Hungarian Plains and parts of Argentina. The unreliability of rainfall is a constraint to attaining high average yields but this is somewhat compensated by special quality potential such as of hard red spring wheats in Manitoba.

Warm humid temperate agro-climates are relatively reliable and are found in South-East USA, much of Argentina and Uruguay, Eastern South Africa, Eastern Australia, much of China, North-East India, and Southern Japan. The potential for China to develop its cereal output from these areas is considerable, though traditional very mixed farming systems there are typically highly energy-efficient, high-yielding and diversified and have proven sustainable over centuries (King, 1911).

Warm dry temperate agro-climates have hot, dry summers but some may also have notably wet winters. However, they are typically overall semi-arid (sometimes arid). They are found around the Mediterranean and Southern Europe - where they can sustain useful yields of specialist cereals such as durum wheat. Other important regions featuring this agro-climate include Southern Africa, much of Australia, Central and Western Asia – including the major bread-wheat producing area of the Punjab of India and parts of Pakistan – Central and Southern South America, Northern Mexico and California.

Wet tropical agro-climates are used to grow perennial crops as well as supporting intensive annual cropping and mixed cropping systems. These are found in much of Brazil, Indonesia, Malaysia, the Philippines, and equatorial Central and West Africa. These are not areas for the temperate small-grain cereals under consideration in this book, though wheat may be found in some well-drained upland districts that are thus cool enough.

Dry tropical agro-climates are typically seasonally dry – sometimes with a bi-modal rainfall pattern giving two cropping periods, one often less watered than the other. In some areas, such as parts of the Kenyan and Tanzanian highlands and in upland tropical South America, altitude renders the climate equivalent to warm dry temperate and wheat cultivation is locally important. Also in the drier tropics and subtropics of Southern Africa, including Zimbabwe and the Transvaal area of South Africa, wheat production during the dry, winter season with irrigation (often centre-pivot sprinkler systems) has become important; at this time, cereal disease pressure is low owing to the dry atmosphere.

Location-specific management is required in relation to eco-geographic factors. Key issues here are climatic and edaphic (soil and site) factors. Klages (1942) was a pioneer in developing this subject, linking agronomy to geography and ecology. He sites Ball (1925) for his excellent definition of agronomy as ‘the art and science of field crop culture’. Duckham & Masefield (1970) developed the subject in relation to whole farming systems and many others have followed in their steps.

5.3. Climate and cereal cropping

Climate affects cereal cultivation in several ways both long term and short term (weather variations):

- Restricts species and, indeed, cultivars of cereal which can be chosen.
- Directly influences their establishment, e.g. a wet, closed autumn limits the planting of the target winter wheat area on heavier land in the Northern Hemisphere and necessitates some alternatives including spring wheat.
- Determines their development and subsequent performance in both yield and quality aspects e.g. barley is especially susceptible to premature ripening with tiny grains if drought occurs and must be grown in areas of reliable rainfall in dry regions such as above 2,000m in East Africa.
- Affects the incidence and severity of problems - weeds, pests, diseases. Also, the microclimate within areas of a crop can provide a focal zone for disease development being particularly favourable to many foliar diseases where the crop is densest.
- May directly damage crops, e.g. hail, drought, blind grains through wetness at flowering, lodging by wind and rain.

- Alters the responsiveness of crops to applied treatments both to promote growth (such as fertilisers and PGRs) and to protect from problems (the biocides).

Historically, the seasonal climate has greatly influenced cereal prices, and national prosperity has fluctuated with the wheat price of the previous harvest (Baker, 1883). For instance, in Britain, the wheat price at Exeter in 1608 was 50 per cent above the average for the decade 1600-1609 owing to a bad season. Now, with such mechanisms as EU surplus stock and pricing policies and the USA Farm Bill provisions, the average person is insulated from the realities of seasonal weather fluctuations to considerable disadvantage as far as an understanding of farming is concerned. On the other hand, citizens of many poorer countries are unduly exposed to cereal harvest and grain trading fluctuations.

While climate is generally agreed to be changing significantly (Houghton, 2004) its influence on crop yield and quality has long been studied. Fuller (2002) reviews frost sensitivity in crops and categorises cereals according to their frost hardiness:

- Very frost hardy (< -15°C) = winter rye
- Good frost hardiness (-10°C to -15°C) = winter wheat
- Reasonable frost hardiness (-7°C to -10°C) = winter barley
- Moderate frost hardiness (-4°C to -7°C) = winter oats; spring cereals

Of course, there is considerable difference between varieties in their frost tolerance. There is also evidence that acclimatisation occurs when cereals are gradually exposed to lowered temperatures as can occur with winter cereals in Canada (Gusta & Fowler, 1977). Data from Russia show the effects of fertiliser on overwinter survival of wheat. Whereas with no fertiliser 51% of plants died, this was decreased to 37% by applying muriate of potash alone and to 22% by NPK. These effects were explained as due to encouragement of a well-nourished, deeper root system (Kemmler, 1983). Rye produces antifreeze proteins endogenously and these confer resistance in the leaves (Griffiths *et al.*, 1992) and there may be scope to breed this capacity into other cereals. Frost damage to cereals over winter is not only by direct impact on leaves and above-ground parts but also alternating freeze/thaw, especially in heavy soils, can break roots or else soil cracking and heaving can expose them to cold. Cereal roots are more cold-sensitive than tops. In addition, persistent frost induces physiological drought. Snow cover confers protection in continental interior climates such as in Russia and Canada. However, it can - especially in milder climates - cause disease problems of snow rot (*Typhula incarnata*) and snow mould (*Fusarium nivale*).

The effects of extreme heat on cereals can also be marked. Not only is there direct heat stress but also associated drought. Farmers in different countries of Europe and North America have observed that potash fertiliser can apparently help to alleviate mild drought, probably by enabling the cereal plants to close their stomata more swiftly in reaction to falling humidity thus limiting transpiration losses (Skogley, 1976; Fig. 5.1). Yield is often depressed by reduced grain numbers as well as by poor grain filling, as shown in Australia (Nicolas *et al.*, 1994). Barleys are particularly prone to have very thin grains. In Kansas USA, hard red winter wheat growing at approximately 30°C during the reproductive phase achieved yields between 2-3 t/ha whereas in cooler regions it attained 7 t/ha (Gibson & Paulsen, 1999). In this case, yield decline was calculated at the rate of 3-5% for every 1°C temperature rise above 15°C. Quality decline is also noted at high temperatures, as in Australia where above 30°C the proportion of glutenins in flour protein declined while gliadins increased (Panozzo & Eagles, 2000). However, within the moderate climate of England over 17 years of study, a positive interaction was found between summer temperature and CP content of winter wheat grain (Benzian & Lane, 1986); this was also the case for hard red spring wheat in Western Canada (Hopkins, 1968). CIMMYT has led studies to seek better management of wheat as its cultivation spreads into warmer areas (Saunders, 1991; Wall *et al.*, 1991).

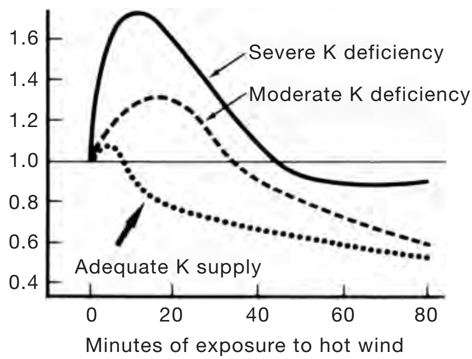


Fig. 5.1. Effect of K supply on the ability of barley to limit transpiration losses (relative to 1.0 under non-stress; Skogley, 1976).

Strategies to combat weather problems include:

- Choice of appropriate species and variety; barleys generally require a climate to enable maturity within 90-120 growing days according to variety, whereas wheat varieties may mature over a longer period if necessary – up to >200 days – though high-yielders tend to be shorter-term varieties. Awned cereals (those possessing bristled heads) tend to tolerate drought (as well as bird pests) better than non-awned ones and taller varieties often have a correspondingly deeper root system.

- Timely crop establishment and timely application of all treatments.
- Adequate drainage and subsoil management to maximise rooting potential.
- Irrigation: This is especially vital on light sandy land. Moisture supply can critically affect establishment of cereals on such land and profoundly limit the growth rate, particularly from GS 30-59. Strategic use later can prolong green leaf area that is vital to maximise grain filling. Wheat can be irrigated at lower altitudes in the Tropics provided that the air is relatively dry as in Sudan, parts of India and Northern Nigeria. It is grown during the cooler dry season (winter) in South Africa, Zimbabwe, Pakistan and India (*rabi* season – except in the hills such as in South India where *kharif* crops may be taken too). In the Punjab, India's 'bread-basket', irrigated wheat in the *rabi* season is alternated with rainfed cotton and maize during *kharif* (summer).
- Use of alternating moisture-conserving fallows e.g. on the slopes of Mount Kilimanjaro in Tanzania, rainfed wheat is grown at under 600mm of rainfall by conserving moisture with a following fallow, as done in parts of the Prairies in Canada. In the Sind of Pakistan, *kharif* cropping with sugarcane on part of land to conserve moisture, alternates with a reduced proportion of fallow alongside wheat during *rabi*.

Increasing latitude limits the length of the growing season, though it is compensated by higher summer light intensity. For example, the Gulf Stream (originating in the Tropics) protects the west of Britain from late frost, while easterly winds (from Siberia) in the winter can be bitter along the eastern side of the country and on exposed land, especially when cereal crops are not protected by snow cover. Eastern European wheat growers, such as in Ukraine, look for at least 10 cm of snow cover before their winter air temperatures of -15°C or below set in.

Altitude has a profound effect on the growing season, shortening it in Britain by about two weeks for every 100 metres up. Local undulations of the land creating winter frost pockets or humid zones in summer can be influential. Aspect of slopes is also important; a southerly one obviously favouring greater growth in the Northern Hemisphere, while a northerly one is favourable in such countries as New Zealand.

As a minimum, the diligent cereal farmer now monitors rainfall and soil temperature at 10 cm as guides to expectations when inspecting crops and to the timing of treatments.

Of global concern is the ‘greenhouse effect’ leading to global warming (Houghton, 2004), due especially to carbon dioxide accumulation following combustion of fossil fuels and net loss of forest cover, plus gases such as chloro-fluoro-carbons (CFCs) from aerosol propellants (CFCs are now largely regulated and reduced). During the past century, the result is a rise in mean global temperature of around 0.5°C with concomitant increase in mean sea levels and more erratic weather. Some zones, notably those nearer the tropics, are suffering more frequent droughts while others, such as in Northern Europe, may find conditions more conducive to crop production. The intensity of winds has increased and thus the speed of changes in weather and the potential severity of rainfall and hail impact on crops as well as the overall level and seasonality of precipitation received.

5.4. Soil conditions and cereal cropping

In general, wheat suits heavier, richer soils; barley suits lighter, somewhat more alkaline sites and requires good drainage; oats tolerate marginal acidity on loamy land; rye copes on poorer, light, relatively acidic sites – as does its hybrid with Durum wheat and Triticale. Durum wheat itself is the most demanding of rich land and a warm growing season to succeed.

Soil is indeed the farmer’s basic asset, and any civilisation loses it at its peril. Long-term land care is at the heart of true husbandry. Some farmers say ‘Land should be treated like a new-born baby - kept in its place, its face kept clean and its bottom dry!’

It is of fundamental importance for any farmer to *know* the soil, including the often considerable variation within fields. Most problems in husbandry have underlying causes in the soil, and failure to investigate such causes can lead to a ‘cure symptoms’ approach to cropping which is unsatisfactory and never-ending. There are three vital points anyone should check when new to farming a block of land – its boundaries, drainage status and pH (cereals need an optimum of around 6.5 to 7.0). There is no substitute for knowing each local situation. Some regions are now well mapped according to soil series classification and land-use potential, with indications of such practical matters as ‘typical number of suitable working days for machinery’ (e.g. Findlay *et al.*, 1984) and broad indications are given for zones and crops (e.g. Landon, 1991 & Table 5.1).

Of the great soil groups, the chernozems or ‘black earths’ of Russian steppes and Ukraine are among the most naturally fertile and have huge potential for improved performance, especially of wheat under good management; they are only limited in some places by climatic constraints. The associated kastanozems (chestnut-brown soils) are similar though usually more restricted in depth. The vertisols or black montmorillonite clays found in parts of India and Africa are generally of high nutrient content with especially high reserves of potassium but their performance for wheat is limited by difficulties of managing structure when wet and the fact that they often occur in semi-arid climates. Loess soils (generally of high silt content) in Europe and in China have high availability of potassium and with good fertiliser input and protection from wind erosion in places can give useful cereal yields. The arenosols, such as the sands of Central India lack OM and so are often deficient in sulphur as well as being short of available nutrient-holding capacity; their performance is thus reliant on regular OM replenishment and greatly boosted where irrigation is possible.

Table 5.1. Required/tolerated soil conditions for cereals.

	Wheat	Barley	Oats	Rye
Requirement (Low/medium/high)				
Water	L/M	L/M	M	L
Clayey texture of soil	H	L	L	L
Good soil structure	H	L to H[1]	L	L
Calcium	H	L	L	L
Acid conditions	L	L	L	L
Tolerance (Low/medium/high)				
Waterlogging	L	L	H	L
Drought	M	M/H	L	L/M
Clayey texture	M/H	M	H	H
Acid conditions	L	M	H	H
Salinity	M	H	L	M

[1] Varieties within species differ in their responses.

Adapted from: Landon, 1991.

In Pakistan, wheat is grown in the four principal arable cropping systems, viz. rainfed wheat/fallow; wheat/rice, wheat/cotton and wheat/maize. Not only soil type but also cropping sequence and irrigation régime has a significant impact on nutrient responses. Irrigated sandy soils are liable to huge fluctuations in water content and thus in nutrient availability; they are also susceptible to developing salinity. Irrigated clays can fix potassium as well as being susceptible to soil structural damage that may restrict root development, especially the ‘black cotton’ montmorillonite clays.

Soil Erosion is of huge importance. The agents of soil erosion are heavy rainfall and/or high winds. Predisposing field factors for soil erosion to occur, include the following:

- Sloping land which really needs tree or grass cover at least in periodic belts across it.
- Sandier soils.
- Declining OM status.
- Large fields and exposed sites without windbreaks and wash-stops.
- Cultivations and tramlines up and down slopes, rather than following the contours.
- Fine, loose tilths.
- Intensive arable cropping, especially with some monocultures.

Vulnerable sites exist throughout the cereal growing regions of all continents – and on long-exposed wheatlands of Australia, North and South America, Asia and Africa. Though typically less widely vulnerable, annual topsoil loss rates in Europe may be around some 2 t/ha on clays, 15 t/ha on silts and over 45 t/ha on some sands, whilst the rate of formation of new topsoil approximates to only 1 t/ha/year. Long before gullies develop, early signs of sheet erosion are declining soil fertility, especially through loss of phosphate in eroded topsoil.

Soil Fertility management is integral and comprehensive status of soil is vital for cereal success. It is central to the theme of this book, as covered in Chapter 4 above.

5.5. Field drainage

The single most yield-influencing change that can be made to a soil is to improve field drainage where necessary. The benefits of improved field drainage for cereal growing are:

- Better soil structure can be achieved.
- Rooting is thereby encouraged.
- Nutrient uptake is consequently more efficient.
- Decomposition of crop residues is accelerated and so conditions are healthier.

- Cultivating periods are increased by some 3.5 weeks extra on average in both autumn and spring for all appropriate soil series in the UK. This allows greater probability of drilling cereals at the target time in nearer optimum conditions followed by more rapid passage through the vulnerable seedling phase of the crop.
- Yield potential from the land is therefore substantially improved.
- Land value is increased in real usefulness terms and better financial value is soon likely to offset the gross drainage costs.
- There is greater flexibility in day-to-day management options and in possible cropping choice for the field.

An appropriate piped underdrainage scheme for cereals will include considering consequences and legal wayleaves through lower neighbouring land, determining outfalls into ditches and marking these by coloured posts when installed to ease later location for maintenance. Next, will be checking positions for main drains (often now 80-160 mm perforated plastic pipes, though clay pipes are still made). These are laid along lines of least fall (often 1 in 100 to 1 in 400) followed by lateral pipes (usually 50-60 mm perforated plastic, unless the run is so long that some 80 mm pipe may be needed to link into the main). Lateral falls are greater than the mains, usually between 1 in 50 and 1 in 200. The main variables in scheme design are then:

- Lateral Pipe spacing - typically 20 m for cereals.
- Pipe depth - typically 75-90 cm, and not less than 60 cm.
- Pipe diameter (possibly also filter-wrapped on very fine sandy soils).
- Use of stones as permeable backfill over pipes to within at least 37 cm of the soil surface. These can almost double scheme costs. Some schemes now use close-spaced (3.5-5 m) plastic pipes at normal depths but without backfill to achieve greater effects at similar cost, it is claimed. Backfill is generally needed where poor permeability is the problem.
- Use of secondary treatments. Moling is the preferred one usually done at intervals of about 2.5-3 m and depths of 52 cm. A mole-plough has an adjustable metal plate with a ‘bullet’ mounted on its base which is drawn uphill through the soil to create a temporary channel across and above the line of the drainpipes and connecting with the backfill. A mole channel may last from 2 to 5 years (longer on heavier soils). Alternatively, subsoiling is used on stony sites at shallower depths (30-35 cm) and closer spaced (1.5 m). Sometimes subsoiling is justified in addition to moling on very dense clays.

With existing drainage schemes, it is vital to ensure regular maintenance of ditches, outfalls and renewal of moling and/or subsoiling as conditions may dictate. This will usually be within five years for moling and often within three years for subsoiling.

5.6. Irrigation

Irrigation may be needed as well as drainage on the same field at different seasons. Adequate soil moisture supplies in the active growing season are vital in laying adequate foundations for a good harvest. Later on, moisture availability is often the limiting factor in securing adequate grain filling and thus both TGW and HLW. Best responses to irrigation of cereals are associated with:

- Sandy soils.
- Application during late stem extension, especially just before ear emergence.
- Ensuring that soil moisture deficit (SMD) does not drop below 25 to 50 mm. Normally total water use of up to 50 mm is strategic except in a real drought; 25 mm per dose is sensible.
- N supplies being correspondingly good.
- Late disease protection for the consequent susceptibility to colonisation by ear diseases after irrigation.
- Use of straw shortening and/or stiffening treatments.

Mobile irrigators have made irrigation more practically feasible for cereals, though lodging is highly likely in some situations despite use of PGRs. Farming systems with higher value crops may have irrigation facilities and justify the extra capacity which will allow cereal irrigation when necessary. In Southern Africa, North Africa, the Middle East and elsewhere, wheat is successfully grown under centre-pivot or line-sprinkler irrigation during the dry ‘winter’ season when disease pressure is low owing to generally low air humidities.

5.7. Cultivations

Cultivations include all soil tillage processes carried out before, during and after the growing of a cereal crop and can significantly influence its performance. They can be considered longer term (directed to the *soil,* e.g. subsoiling, subsoil mixing) and shorter term (directed to the *crop,* i.e. its tilth requirements). They provide the critical context for the proper nutrient management of cereals which is the main theme of this book.

The variable factors which determine the choice of an appropriate cultivation system for cereals include its objectives, cereal species, soil types, sites, seasonality, weed problems, power sources and equipment available.

The possible *objectives* of a cultivation treatment for a cereal crop may be:

- *Soil structural adjustment,* i.e. aggregate size control.
- *Seedbed preparation* - to ensure maximum contact between seed and soil for moisture imbibition and rootlet development and to provide ample consolidation to ensure good control over drilling depth crucial for correct seed placement.
- *Root bed preparation* - adequate depth for unhindered root system establishment.
- *Soil structural improvement,* i.e. air/water balance optimised; removal of caps and crusts; pan busting; increasing permeability (reducing bulk density by aerating).
- *Soil conservation* - erosion control by contour cultivations and use of bunds and benches where appropriate. Water conservation often goes with good erosion control and excessive cultivating loses moisture, which is critical on light soils in semi-arid zones and in drier spring seasons elsewhere.
- *Incorporation of fertilisers* - bulky organic manures (BOM) need ploughing in. Certain inorganics, e.g. urea, ammonia and lime; placement of phosphates, especially for maize.
- *Disposal of crop residues* - disposal is important if residues are diseased, but often it is done for convenience and appearance (complete burial unmixed is often undesirable). For straw incorporation, chopping on the combine and then ploughing is currently the most used method and usually avoids yield depression.
- *Weed control* - creation of a false seedbed - that is, soil disturbance leading to annuals germinating; burial of existing growth; repeated fragmentation to starve perennials after stimulating growth, especially rhizomatous grass weeds such as temperate couch (*Elymus repens*) and tropical swordgrass (*Imperata cylindrica*) but glyphosate is now used, often pre-harvest; removal for burning of couch, ground elder, wild oats before seeding.
- *Pest control* - exposure of grubs for birds; consolidation to suppress wireworms; avoidance of clods to reduce shelter for slugs.

Seedbed preparation clearly requires the operation of agronomy as both art and science for it to be successful. It is sound discipline to check soil conditions from depths upwards (wheat roots to 2 m) i.e. drainage, subsoil management and then topsoil condition.

A good cereal seedbed needs to be *clean, rich, moist, fine enough* and *deep enough.* The traditional method of achieving a seedbed is by progressively breaking down the soil: e.g. plough, disc or rotavate, harrow, then possibly ring-roll before drilling. This is in order to prepare land with as uniform a resistance to seed drill penetration as possible so that sowing depth is well controlled at 2.5 to 4 cm.

Appearance can be deceptive, and zeal to make land look clean may:

- Excessively dilute nutrients and organic material from surface layers.
- Deplete moisture.
- Damage structure, causing compaction and/or panning because so many treatments were gone through.

The choice of seedbed preparation method depends on:

- Soil type.
- Tilth needed for a particular cereal.
- Time available: shorter time may necessitate larger equipment pulled by a more powerful tractor. There is a trend towards 'multiple' implements to give fewer passes, e.g. two passes - plough plus power harrow with a bridge-link to a drill with a light tine bar behind, especially to sow compaction-sensitive silts on the right day. The same can suit other soils except clays, on which plough, disc (set straight) followed by self-cleaning wide rollers may well be the best system.

Traditionally the procedure was to treat topsoil (invert and burst), mix and then firm and make fine enough. General rules are:

- Fine for spring cereals.
- Cloddy but firm for autumn cereals; though fine enough for residual herbicides to work.
- Level for precision seeders.
- Fine, firm, flat for very small-seeded minor species.
- Deep for maize and relatively deep for sorghum.

5.8. Conservation farming (CF)

CF is the simultaneous practice of minimal soil disturbance, permanent soil cover and crop rotations/associations. Zero tillage was first tried in USA in the 1930s, in the UK during the 1960s and in Zimbabwe during the early 1970s. Many Brazilian farmers are keenly practicing it.

Reduced cultivations and direct drilling (minimal or zero-tillage) have been widely popularised for sites where moisture conservation is at a premium. However, pure direct drilling allowing intensive monoculture, especially of wheats and barleys, has produced problems of carbon build-up and associated failure of grass weed control chemicals, especially for blackgrass, *Alopecurus myosuroides*. There is a discernible trend towards more subsoiling and/or rotational ploughing, i.e. part of the farm each year, often one-third to one-fifth of the cereal area to overcome this problem. However, to do so interrupts the sequence of years of non-disturbance and potentially loses some of its long-term benefits in stabilising soil structure.

Under tropical conditions, non-disturbance of soil plus the mulching effect of previous crop residues on the surface can protect from soil erosion, from moisture loss and from easy weed colonisation. Such CF has been popularised in Brazil, and in Zimbabwe (Oldreive, 1993, 2004). The Indo-Gangetic Plain covers 13.5 Mha and is the world's most intensively farmed area producing 45% of South Asia's food. Between 1999 and 2002, more than 0.5 Mha were zero-tilled for wheat and upland rice. Wheat yields were up 10-17% at cost savings of US$ 65-180 per hectare (DFID, 2002). In all, more than ten million hectares of wheat are produced in India.

It was developed by Brian Oldreive from 1982 at Hinton Estates, Bindura, Zimbabwe, and grew to cover 3840 hectares of annual crops by 1994 when he had already set up 50 trial plots on small farms nation-wide and at the Agricultural Research Trust (Oldreive, 1993). While maize was the main cereal involved, Oldreive (2004) is now convinced of the validity of CF for all areas of Zimbabwe, except the very sandiest soils of the Kalahari fringes. He was asked by the World Bank to share his findings in Zambia in 1995 where development of CF has accelerated from that start. There, the CF Unit (Haggblade & Tembo, 2003) sets out the following principles:- 'no burning of residues; correctly spaced permanent planting basins established before the rains; early planting of all crops; early weeding; rotation with a minimum of 30% legumes in the system.' As to fine tuning these principles, best practice in farming is always location-specific, especially with regard to soil and climatic conditions. Tropical farmers, especially those marginalised in the most vulnerable areas, are risk-averse in order to be survival-oriented. The problem is that fatalism with defeatism can ensue. CF can offer a way out of this vicious circle of poverty. Where HIV/AIDS weakens the farmers, moving only 15% of the soil with CF rather than full cultivations can help considerably. A central philosophy of CF is to 'feed soil' so building fertility over time.

5.9. Choice of a cereal cultivation system

Plough if drainage is poor, if surface structure is damaged, if crop trash is excessive, or if cereals are to be drilled late in autumn/winter.

Shallow cultivate if land needs leveling, if a false seed-bed needs to be created to encourage volunteer cereals to grow, or if burnt ash needs a surface scratch cultivation to clear it.

Direct drill (No-till) if soil type is suitable (notably stable soils such as calcareous and clay loams), if soil structure is reasonably good, if a good burn is obtained of straw and stubble (in regions where this is still allowed), or if the site is more or less free of perennial weeds.

Cultivations after drilling have a number of purposes:

- To control weeds - by hoe (e.g. inter-row, especially for maize and sorghum but also in some areas on wide-spaced wheat or other small-grained cereals), by long-tined light weeders (especially in organic systems) and/or by sprays – both pre and post-emergence of the crop.
- To keep surface loose - to aid infiltration of water, to break a soil cap for aeration, to reduce run-off damage, to create a ‘dust mulch’ to restrict evaporation.
- To firm soil around plants, e.g. after heaving overwinter, to reduce lodging later.
- To level the surface and push in stones (to protect harvesting machines later).
- To earth up, e.g. ridged crops.
- To thin crops by tine-harrowing across the lines of seedlings.

The trend is away from rolling/harrowing after emergence of most cereals, though this was once the prevalent practice in many systems. Most farmers prefer to start with a good tilth and promote rapid crop cover by timely sowing whenever possible to obviate the need for after-cultivations.

Possible adverse effects of cultivations include the following:

- ‘Powdering’ of soil if too dry.
- Loss of pores within aggregates and smearing if too wet.
- Loss of moisture by over-aeration.
- General compaction by heavy implements, creating local pans.
- Loss of uniformity - physically (stones and lumps dug up) and biochemically (infertile subsoil lifted).
- Dilution of OM - warm, moist conditions accelerate breakdown and deep cultivations will mix limited OM to depth.
- Decline of earthworms - arable soil under the plough typically has one-third of the earthworm population of equivalent soils under direct drilling or under grassland.

5.10. Fertilisers and agro-ecological zones

There is considerable variation in the usage of added fertiliser nutrients between zones. Of course, fertiliser statistics do not include the diversity of other nutrient sources locally arriving in soils through various organic materials. However, the overall use of these is far from the levels required to sustain the long-term yields of which soils are capable. Table 5.2 gives total fertiliser nutrient application rates for arable land in a range of countries. The fullest possible conservation of locally available sources of nutrients is recommended for sustainable cereal production everywhere. In addition, supplementation where possible with fertilisers boosts yields and gives a management tool to affect quality to some extent also, avoiding excessive use of soluble materials especially in leachable sites and where there is a premium for avoiding such products as for organic grain markets.

Within the overall use of fertiliser, there is considerable variance in the ratio of key nutrients. For instance, it is important that cereals should access adequate potassium in relation to nitrogen. In Western Europe and North America, the N:K ratio in fertilisers applied averages approximately 2:1 (which is too skewed towards N) whereas, even more extremely, in Asia the N:K ratio in fertilisers applied can exceed 10:1 and averages around 6:1. It is ironic that although K is more absorbed by cereals than other nutrients, it is applied at significantly lower rates than nitrogen and phosphates. Nevertheless, FAO data for Israel suggest N:K ratios applied overall of around 1.7:1 and K rates around 250 kg/ha on feedwheat.

Table 5.2. Fertiliser nutrients added to arable land in selected countries (kg/ha).

	Kg/ha	
Nigeria	7	*
S. Africa	51	*****
India	103	*********
USA	105	*********
Brazil	140	**************
France	225	******************
China	279	**********************
UK	288	*************************
Japan	325	****************************
Vietnam	365	********************************

Adapted from: FAOSTAT data, accessed 2002.

Where low doses of fertiliser are used, it is usual to apply them to the seedbed for rainfed crops while irrigated wheat, for example, may receive a split dose – some in the seedbed and the rest top-dressed with the first irrigation. Fertiliser incorporation with irrigation water (fertigation) has expanded to over 1 million hectares in the USA, more than 0.5 Mha in Spain, and is fast increasing in China and India. It is relatively common in South Africa and the Middle East (Hagin *et al.*, 2002). Of course, much of it is applied to non-cereal crops.

The yield and quality responses of cereals to the various nutrients are now the subject of chapter 6, with linkage to the agro-ecological contextual influences discussed above.

Chapter 6: Effects of Fertiliser Use on Yield and Quality of Small-Grain Cereals

6.1. Cereal nutrition and ultimate crop performance

Fertiliser type, timing and dose can all have significant effects on cereal yield and quality. Yield responses tend to be incremental with dose and then to display diminishing returns, with excessive dosages even depressing yields. The quality effects of fertiliser applications can also be considerable. Not only dose but timing and in some cases type of fertiliser can also show marked effects. The quality response also depends upon the overall yield attained by the treated crop. In general terms, the higher the yield the more 'diluted' some specific components may become, particularly if yield was pushed up yet DM percentage decreased by high nitrogen without concomitant supplies of other essential nutrients being available.

Yield is the product of several factors which can be influenced by crop management, though capacity to affect the crop in this way decreases as it matures and grain filling is very weather-dependent except in rare cases where irrigation is possible. The components (see Chapter 3) are:

Yield = plants/hectare x tillers/plant x % ear-bearing tillers x grains/ear x weight/grain (mg).

Harvest index (the proportion of total DM in the grain) has been improved in cereal varieties with the reduced height (Rht) gene, derived in wheats especially from the Japanese variety Norin 10. Such wheat crops are now 70 cm or less in height whereas they formerly attained 125 cm or more. Harvest indices in many wheats and barleys are now around 50-55%, even up to 60% in some wheat crops. Of course, some small-grain cereals may be grown for their long straw value (e.g. for thatching in Europe) which may be at least as important as the grain value per hectare and so tall varieties may be sought. Although what usually finally counts may be the overall yield of grain (often expressed at 14% mc), the size of the grains making that up and their other quality characteristics can have a significant effect on crop value, even disqualifying it from some markets.

The maximum biological yield technically possible with superior-performing varieties and optimal support inputs, including nutrients, is not the same as economic yield. If the cost of inputs exceeds the incremental yield return, which tends to diminish at higher yield levels, then it pays the farmer to settle for less than the technically highest achievable yield. Furthermore, the quest to attain the highest yields entails greater risk because it requires greater investment in inputs and so more is at stake should dramatic weather, pest or disease damage intervene, or the market prices drop. More importantly still, economic yield in the short term may not be the same as sustainable yield long term which must simultaneously conserve the means of production – soil and environmental quality. Much experimental data concerning cereal yields measure the technical optima and often, for simplicity of interpretation, in relation to a single input under test. Yield stability from year to year is important for farm as well as for national and international planning (Cherfas, 1994). Aiming for the highest sustainable yield requires a change in thinking by farmers, as well as advisers and researchers. Central to this is an integrated approach towards soil fertility as well as to weed, pest and disease problem prophylaxis by farming system change rather than their elimination with biocides after they become established. It requires whole farm thinking and costing 'for the rotation' within the whole system, not simply for a single crop. The aim is to maintain good agricultural and environmental condition.

6.2. Quality requirements of different cereals for particular uses

It must be noted that standards can be changed (usually tightened but sometimes relaxed) and may vary with market supply and from country to country so what follows is a general guide to standards that are widely accepted as good.

Wheat (Triticum aestivum): The typical wheat grain consists of some 82% endosperm, 3% germ and 15% 'skins'. It must be noted that a good milling wheat is one which is hard, i.e. separates clearly into a sizeable flour fraction (70-75%); the remainder is bran or outer skins (some 6%), weatings (inner skins, inseparable starch grains and nutrient-rich aleurone layer) and germ. For breadmaking purposes, wheat may need many additional features and these will depend on the particular end product sought e.g. chapatis in India, steamed rolls in Northern China (see Gedye *et al.*, 1981; Stoskopf, 1985; Gooding & Davies, 1997). Milling varieties as first wheats are usually grown after a break crop in order to maximise the chance of attaining the required quality features. The most important features are briefly considered here:

- *Protein content*: CP (i.e. all nitrogenous compounds including non-proteins) is taken as percentage of N x 6.25 (on the basis that proteins contain an average of 16% N). True protein is taken as N x 5.7 to take account of the proportion of the total nitrogenous compounds that are actually proteins. High protein content is indicative of a good extensible grain gluten level which is essential to make good breadmaking dough as opposed to biscuit dough. Millers seek 11% protein or more at 14% mc; much of the EU expresses protein on a percentage of DM basis. Premia are usually payable to the grower. Protein content is largely dependent on variety. Spring cultivars generally outdo winter ones. Extra nitrogen just before ear emergence can boost grain protein, as can urea given just before green leaf disappears.

- *Hagberg falling number* (HFN): This test indicates the *alpha*-amylase enzyme content of the grain. This enzyme breaks down starch to sugar in the grain, thus reducing the strength of the crumb structure in bread that is also sweeter and darker-crusted. The test involves heating a suspension of ground wheat for 60 seconds and then dropping in a plunger and recording the number of seconds it takes to reach the bottom of the mixture. Results vary from just over 60 to above 400; 240 plus arw desirable. Low HFNs are related to particular varieties and delayed harvesting, declining especially in wet conditions when α-amylase enzymes are mobilised pre-sprouting. In a wet harvest, sprouting in the ear will actually occur and the crop is useless.
- *Dough machinability*: This relates to the stickiness of the dough, since those varieties which produce doughs that adhere to processing machinery are clearly uneconomic to use. The test simulates commercial dough-mixing equipment.
- *Dough rheology* (shape behaviour): This means the extensibility of the dough coupled with its elasticity; it can be depicted on an alveograph (Fig. 6.1). Some doughs are strong owing to high protein content with a good proportion of high molecular weight glutenins i.e. they resist extension and tend to spring back towards their original shape on release. This correlates well with good bread-making characteristics. Weak doughs offer little resistance to extension and are non-elastic but often tend to suit biscuit-making.
- *Zeleny score*: This test assesses baking quality of the flour. It measures the sedimentation rate of a flour suspended in a lactic acid solution. This further indicates high gluten level and high gluten quality. Thus it distinguishes a strong (high gluten) flour from a weak one (suitable for biscuits). Values can range from less than 10 to above 75. Above 35 is desirable and 20 is minimal. Variety chosen is crucial; so is avoidance of overheating during drying.

Durum wheat (Triticum durum or pasta wheat)

- It must have 70% plus of vitreous (hard, flinty, amber, translucent) grains, *not* mitadine (soft opaque) grains; early harvesting and careful, slow drying produce this vitreous grain.
- HFNs are sought above 240 (some contracts specify higher), specific weight above 78 kg/hl, protein levels above 12.5%.
- Premia of 50-60% is obtainable over prices for common (*T.aestivum*) milling wheats but only if the grain meets the above specifications and is

neither heat-damaged nor sprouted (yields of durum wheat are likely to be about 60-70% of common wheats in comparable conditions in cool temperate climates).

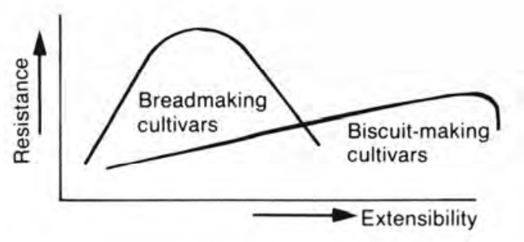


Fig. 6.1. Dough Rheology: Resistance and extensibility tests of wheatflour doughs.

Barley (Hordeum sativum)

Feed barley does not have any specific criteria attached to it although high protein content is desirable. For *malting,* barley must meet certain criteria. Maltsters like pale yellow, well-filled grains in addition to the following:

- High *germination* percentage, because the malting process involves steeping grain to 45% mc and sprouting it to allow enzymes to convert starches to malt sugar. As near 100% as possible is therefore needed.
- Low *nitrogen* content. High levels slow down the malting process, trouble both brewing and distilling processes and can cause cloudiness and poor keeping-quality in beer. A content of 1.5% N is sought but higher levels are tolerated when supplies of ample quality are short.
- High *starch* content. This is the converse of high protein; it ensures a high extractable malt yield, which should be 20-24% of the grain weight submitted for malting. The residual brewers' grains are a most useful feed, typically selling wet for some 20% of the price of whole grain feed barley.
- High *activity* of precisely the same enzymes which impair breadwheat quality.

There is a useful export market for British malting barley, especially to West Germany. Rye is also malted and distilled to make whisky, especially in Canada and the United States, gin in the Netherlands and beer in Russia.

Achievement of high malting quality rests on:

- Choice of variety.
- Avoiding lodging, and harvesting the crop in a ripe state.
- Avoiding a late N dosage, i.e. not after GS 30-31 in any quantity.

- Avoiding a total N level above the yield, site and seasonal potential.
- Careful drying (basically treat as for seed corn and dry slowly at low temperatures).

The best soils are light to medium land and in the UK, the east of England is favoured over the western climate in likelihood of securing malting samples. Premiums for malting over feed barley prices have been around 20-25% for the best samples down to 10% for inferior but acceptable ones. For this reason, many farmers are opportunist growers of malting barley.

Oats (Avena sativa)

- Oats are used for human consumption in porridge, muesli and other oatmeal products. Thin-skinned varieties are preferred for oatmeal production, giving 55% plus of groat, i.e. kernel, extraction rate rather than only 40% for high husk types. Naked spring oats enjoy premia up to 40% over common oats and are concentrated sources of nutrients. However, handlers and processors of naked oat grain need to wear dust masks.
- Millers like to contract to take oats at harvest and store at around 10% mc.
- Oats once suffered from the action of lipase, an enzyme that degrades its rather high content of fats and oils, so turning it rancid – a notoriety for which it once suffered but which is now controlled.
- At least 50 kg/hl is the expected specific weight.
- There has been no EU intervention buying arrangement so prices fluctuate.
- There is sometimes a lucrative market in sales to horse owners.
- Growing oats risks making or hiding a wild oat (*Avena fatua*) problem.

Rye (Secale cereale)

- Rye can command milling wheat prices, especially under contract for crispbread biscuits; it typically has a weak flour and is liable to sprout in the ear.
- It is second only to wheat as a bread grain in the north temperate zone. The bread stays moist and is often deliberately soured as in the black bread (*smörbröd*) of Scandinavia or the *Schwarzbrot* of Germany.
- Rye can be malted and it can be distilled.
- Requirements for these markets parallel those for milling wheats (more like biscuit-making varieties) and malting barleys, respectively.
- Above all, rye must be protected from the toxic, grain-infecting fungus ergot (*Claviceps purpurea*); and ergoted grains must be separated from

any grain for consumption either by passing through indented cylinders or by flotation.

Triticale

- This product of a wheat (usually *Triticum durum*) mother crossed with a rye (*Secale cereale*) father is of local importance in highland Africa (e.g. Ethiopia, Kenya highlands) but especially in Eastern Europe, notably Poland, and in North America as well as in parts of Western Europe, including the UK.
- It offers not only useful livestock feed potential at a cost-saving per tonne of 3-5% over other feed grain for compounding, but also milling potential - both of these markets owing to its higher content of certain essential amino acids (especially lysine) than other cereals. In view of this, there is also some market interest from the health-food trade.

In processing cereals for human consumption, food manufacturers often blend cereals of different species, cultivars or field lots in order to obtain their desired qualities. This blending is also practised to an extent by export shippers to satisfy such criteria as minimum specific weight expectations of buyers.

6.3. Economic fertiliser responses

At current relative prices, 1 kg of N costs as 6 kg of grain, approximately, but produces on average 15 kg of grain. Thus the cost/benefit ratio is 1:2.5. Obviously, relative costs need to be monitored per hectare and per tonne of grain produced (Fig. 6.2).

Relative costs of fertiliser and cereal end-products vary considerably with:

- Nation
- Time
- Particular fertiliser source used
- Bulk quantity and timing of purchase (cash-flow is crucial in running a farm)
- Species and quality of cereal grain and method of marketing it

It can be argued that the relative cost of N has been too low, causing some farmers to apply unnecessarily high ‘insurance’ doses. The argument is twofold: (1) the energy cost of producing N fertiliser is about 5 tonnes of oil (or natural gas equivalent) per tonne of N produced, thus it should be used very carefully, and (2) there have been cases where leached nitrates have caused harm, e.g. eutrophication in waterways and nitrate levels in drinking water supplies above the safety limit. Indeed, Gooding & Davies (1997, p.170) note that for wheat 'the encouragement of high nitrogen inputs to [seek to] combine high yields with high quality increases the risk of nitrate leaching, N volatilisation and support energy requirements, without necessarily giving a consistent benefit to the user.' The energy cost per kg of N fertiliser produced is 9.5 times that for potassium and some 6 times that for phosphorus, yet the purchase cost per kg of potash (K_2O) given as muriate is roughly half that of N given as ammonium nitrate. Phosphate is approximately 10% cheaper than N. Steadily maintaining the soil indices of both P and K close to index 2 as described in Chapter 4 does not carry the same risks as overdosing with N.

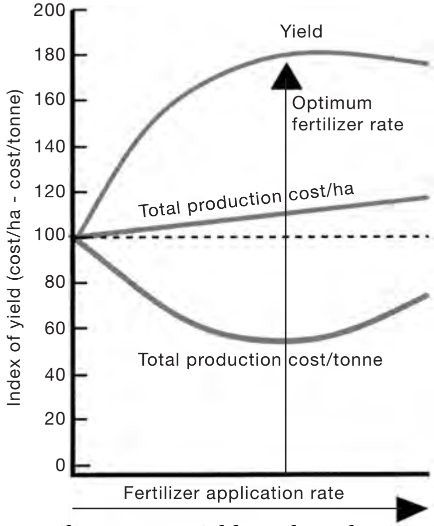


Fig. 6.2. Optimum Fertiliser rates, yields and production costs per t and per ha (PDA).

Clearly, the changing cost per kg of nutrient must be monitored against kg grain produced per kg nutrient applied and the fluctuating value of that grain. When comparing organic manure applications as nutrient sources, account must be taken of the extra cost of storing, carting, spreading and incorporating such bulky materials into the soil.

Impacts of individual nutrients on yield and quality are considered below.

6.4. Nitrogen (N)

Nitrogen has the greatest impact on yield and quality of small-grain cereals and offers the most scope for management by the amount and timing of applications. The particular form of N used makes little difference unless it is misapplied (see chapter 8) or else it contains another nutrient of which the crop is short, such as sulphur. The cereal plant is more efficient in partitioning N than overall DM into its grain, which accumulates some three-quarters or more of the total N removed by the crop. Daily uptakes can be around 2.5 to 4 kg/ha during peak growth.

N given at tillering tends to increase shoot number but then the crop sets up a greater biomass which requires subsequent sustenance with further N, other nutrients and water if this early 'platform for yield' is to fulfil its promise. N at ear emergence stage can boost yield by increasing the number of grains per ear retained and filled. In France, Jeuffroy & Bouchard (1999) found levels below 40 kg/ha of N applied depressed grain numbers in HYVs winter wheat Soissons. N at flowering stage tends to boost quality, particularly in terms of grain protein content – and sometimes also in the gluten % of this which correlates with good dough characteristics for bread-making in wheat. Of course, extra N at flowering is exactly the reverse of what is required for malting barley quality, though it is welcome in feed barleys and other feed grains to boost their CP contents. It is generally found in practice that, for higher yielding crops, it is inadvisable to hold back the N that would have generated a higher yield platform if given earlier. Rather, it seems advisable to regard late N as a bonus to use when conditions of crop structure and weather allow its use. If the crop and climate are not promoting active growth then, it may not be beneficial. Adjustments can be made to subsequent N manuring of the field after the late N fed cereal has been harvested (Chaney, 1990). However, up to 50% of grain N is taken up after ear emergence. In Germany, giving 70 kg N/ha to wheat after ear emergence prolonged active uptake of K until milk-ripe stage of the grain, and of P, Ca and Mg until crop maturity.

In the semi-arid climate of Turkey, the FAO fertiliser programme recorded good responses to 40 kg/ha N in the presence of similar or larger amounts of P_2O_5. Responses on non-irrigated wheat were 8-9 kg grain per kg N given, and 5.8 kg/kg K_2O, but these were not so high in other countries (Ethiopia, Guatemala, Lebanon and Syria). There, overall responses (kg wheat/kg nutrient) showed the following ranges: N = 3.6 - 9.5; P_2O_5 = 2.4 - 10.2; K_2O = 0.7 - 5.8. Results reported by Kanwar (1972) for dryland India in 2,235 trials of HYV wheat showed responses (kg grain/kg nutrient) to NPK fertilisers as follows: N = 9.68; P_2O_5 = 11.30; K_2O = 3.25. He also found that placement was the best fertiliser application method to ensure responses. Placement is found to maximise fertiliser responses for other crops, including maize, in dryland circumstances (Oldreive 1993, 2004; Urvoy, 2004; ICRISAT work). In Israel, under semi-arid conditions, non-irrigated wheat - which is sometimes rotated with cotton - gave best responses to N (8 - 9 kg grain/kg N) when this was split as 47 kg N at tillering and then 47 kg N at ear initiation. In dryland India, when soil is too dry to enable late N transfer to the crop, a foliar application of urea is the only means of entry to the plant and can increase both yield and grain N content (Swaminathan, 1971). It must be noted that in drought conditions, late N must be used with care, not automatically, since it can depress yields and both the TGW and specific weight of grains (Gallagher *et al.*, 1987). In Ireland, Conry (1997) recorded over 3 seasons significant reductions in yield of spring malting barley in most of his experiments by using urea.

Evidence from India using HYVs suggests that the use of irrigation in dry climates interacts very positively with N such that responses per kg N applied can double or even increase by a factor of 2.5. In practice, this means that where a dose of 180 kg N per hectare might be recommended under irrigation, 90 kg N might be the maximum for a rainfed HYV crop. In the Punjab, irrigated wheat may get 40-50% of its N at sowing and the rest split with the first and third irrigation periods.

Responses of intensively grown winter barleys to nitrogen were studied over 8 years on calcareous silty clay loams in the west of England (Jenkinson & Wibberley, 1986). Optimal N rate was 140 kg/ha ± 40 kg/ha, the lower rate after a dry winter and the higher after a wet spring. There was some adjustment for soil type and season but clear management and yield advantage was shown from giving 50 kg N/ha in mid-February followed by the remaining 90 kg in mid April. If applied in mid-March, N induced 60% disease on the flag leaf and leaf 2 as against around 30% from April application (Fig. 6.3). A major foliar disease of yield-reducing concern is powdery mildew (*Erysiphe graminis*).

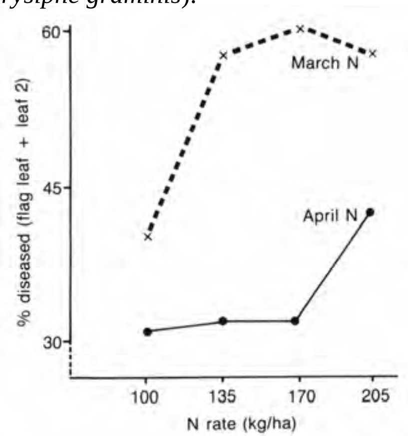


Fig. 6.3. Influence of N rate and timing on severity and onset of barley foliar diseases (Jordan & Stinchcombe, 1986).

Grain N% increased with N rate, reaching on average 1.6% at the optimal N rate for yield, though varying with season and variety (Fig. 6.4). TGW was depressed at high N rates, especially beyond the optimum for yield (see chapter 3 & Fig. 3.5). This work was done in conjunction with a Farmers' Study Group (Wibberley, 1984a, 1988, 1997) constantly relating research data to practical constraints and realities.

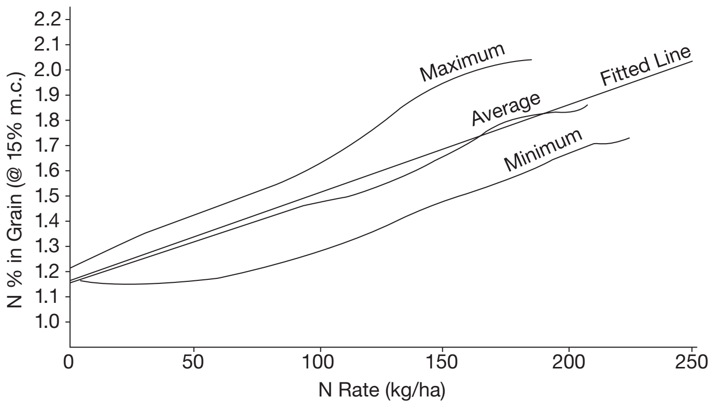


Fig. 6.4. Effect of N rate on grain N% in Winter Barley over 7 seasons (Fitted line, average and extreme years shown; from Jenkinson & Wibberley, 1986).

For wheat in the UK, grain protein normally rose in linear fashion with rising N rate (Benzian & Lane, 1986). However, Sylvester-Bradley (2003) noted that although yields have risen by 2 t/ha in the twenty years since 1984, there has been no increase in applied N fertiliser that remains on average at around 190 kg N/ha/year. Grain protein % is now often low since it declines with rising yield in wheat in the absence of enough N. It could possibly be boosted by 1% with 50 kg/ha extra N at the flag leaf stage. However, excess N in a wet season can depress HFN, especially if it induces lodging but varietal responses on this are inconsistent (Gooding & Davies, 1997).

Breadwheats of high quality (vitreous grains of high protein content and high % gluten) can be obtained very well with organic manures such as farmyard manure (FYM, e.g. Lebidinskaya *et al.*, 1988) as many farmers know, especially organic growers.

6.5. Phosphorus (P_2O_5)

Phosphorus applications to cereal crops tend to lead to stronger root development, earlier flowering, earlier grain set and earlier ripening. All of these are especially crucial in dry climates and phosphorus was the first fertiliser nutrient used to increase yields, especially of wheat, under semi-arid conditions. Australia pioneered in this using superphosphate while the FAO programme starting in the 1960s targeted similar land in Turkey and elsewhere. In North-West Syria, no benefit from split dressing of phosphate was found; a single application to wheat (at 52.5 kg/ha of P_2O_5) before lentils could reduce the cost of lentil production without significantly reducing lentil yield (Harmsen *et al.*, 2001).

In India, in 2,844 trials during the 1960s referred to by Kemmler (1983), each kg of P_2O_5 applied to rainfed wheat gave an average of 4.1 kg grain, and under irrigation it gave 8.7 kg grain. Optimum P rates, reckoned at some 70 kg/ha of P_2O_5, applied to HYVs under irrigation gave up to 15 kg grain per kg P_2O_5. In India responses to added P_2O_5 have been as high as 30 kg grain per kg fertiliser on low P soils which require fertiliser applications over 100 kg/ha for HYVs under irrigation (Kemmler, 1983). Grain protein contents have also been improved (Sen & Misra, 1987). However, this is not always the case but instead there may be improvement in TGW and specific weight of grain with increasing phosphorus availability (Hagras, 1985, cited by Gooding & Davies, 1997). Other quality effects of P include its capacity to increase the vitamin B1 content of grain and of that the reduced levels of essential amino acids (lysine, methionine, and tryptophan) associated with low P.

6.6. Potassium (K_2O)

Potassium often seems the neglected element when fertiliser supplementation is considered, being overshadowed by both N and P for cereals. However, as yields and stress factors in cereal cropping systems increase, attention to K supplies becomes more imperative. It is the most environmentally benign of the major fertiliser nutrients.

Suboptimal K supplies during early growth stages of the cereal crop reduce ear numbers and so pose the greatest threat to yield. However, shortage after flowering tends to depress TGW, sometimes below the marketable standard required. Dry spells of weather can induce marginal K uptake that needs to be around 4 kg/ha of K_2O per day at ear emergence. CIMMYT work found that wheat plants between 36-95 days old absorbed 240 kg/ha of K_2O. Peak uptake occurs just after heading (see Chapter 3 & Fig. 3.2). Overall K usage can be 50-100% higher than the ultimate K removal in the crop owing to exudation from roots as the crop reaches maturity (see Chapter 4, Fig. 4.1). Kemmler (1983) reported data from India where the wheat yield response (kg grain/kg K_2O) was 5.3 under irrigation and 3.8 for rainfed crops. Regarding quality, also for breadmaking wheat, K increased both CP and % gluten in Germany while it improved TGW in Russia.

HYVs given high rates of N and longer runs of cereals do deplete soil K with consequently rising responses to applied K from 2.75 kg grain/kg K_2O initially to 7.6 kg grain/kg K_2O after three years (Polish data cited by Kemmler, 1983). Light sandy and organic soils need K little and often while certain heavy black clays can be very deceptive in their K responses owing to high K fixation. Responses to K also tend to be far more variable in dryland conditions than in the deep brown forest loams of Europe.

6.7. Magnesium (Mg)

Cereals only tend to respond to Mg when it is at very low availability in soils, which is often induced by over-use of potassium fertilisers. Balanced treatment to avert acidity with materials containing both magnesium and calcium usually ensures adequate supply in high-yielding situations. However, there can be significant within field variations in magnesium (Dampney *et al.*, 1997). In barley, improved Mg content of the grain has been associated in Germany with increased TGW (Beringer & Forster, 1981; Fig. 6.5). In warmer climates, Mg can alleviate the aluminium toxicity associated with acid soils.

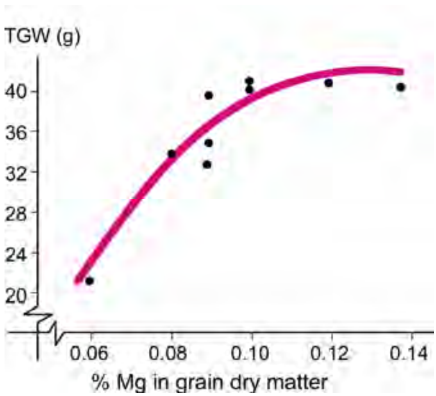


Fig. 6.5. Relationship between the Mg content in the grain of barley and grain size (Beringer & Forster, 1981).

6.8. Sulphur (S)

In UK experiments from 1993-1996, Withers *et al.* (1997) reported susceptibility to sulphur deficiency in cereal crops on light sandy and/or shallow soils away from industrial areas where incidental addition from air pollution is slight. Application of sulphate fertilisers just before stem extension gave yield responses averaging 21% more grain and 34% more straw, with optimal S rates of 10-20 kg/ha. Late foliar S applications during grain filling showed no benefit. Grain N:S ratio should be kept below 16:1 for breadmaking wheats (McGrath, 2001). An imbalance of excess N reduces yield and quality, such as loaf volume in breadmaking wheats (Zhao *et al.*, 1999); increasing grain sulphur content appears to increase glutenins which strengthen dough. McGrath (1985) found that increasing N rates were associated with greater uptake of sulphur into the grain, with corresponding improvements in the sulphur-containing amino acids such as methionine.

For spring malting barley in Ireland, Conry (1997) found that sulphur containing nitrogenous fertilisers (‘Super Net’ = 27.5% N, 5% S; and ammonium sulphate nitrate = 14% S) were superior to calcium ammonium nitrate for yield responses on light soils but gave no yield responses on medium and heavier land.

6.9. Micronutrients

Responses tend to be soil specific though increasing cereal yield potential puts supplies under pressure on more sites. Zinc shortage is relatively common on cereals in India where around 50 kg/ha of zinc sulphate is used to correct it. The application of Zn as broadcast onto soil, or as seed coating or as foliar applied, all proved equally effective in the grain yield and level of Zn in grain (Cakmak, 2004). Farmers sharing experience of difficulties in a district can help raise each other’s awareness of trace element issues. However, in most soils, one should beware expensive testing for micronutrients and prioritise recycling of varied organic manures and well-made composts. In industrialised, urbanised countries tests may be needed to avoid trace element toxicity from some such sources.

6.10. Yield, quality, location and nutrient responses of cereals worldwide

Much of the reported data sources in world literature refer to wheat, particularly regarding quality, with much less for barley, oats, rye and triticale. This is in part due to the substantially greater importance of wheat in area, production and trade but especially owing to its substantial use for direct human consumption. Wheat is made into bread, *chapatis* (flatbread) in India, steamed bread in North China, noodles in the Far East, *pan blanco* in

Central America or the many biscuit and doughnut products of North America and Europe.

The introduction of HYVs based, among other genetic sources, on Japanese varieties for cooler climates and Mexican ones for warmer zones, has led to significant yield improvements. Corresponding increases in nutrient supplies have not everywhere kept pace with the potential of new cereal varieties. It is certain that, irrespective of the particular causes of higher yield potential – genetic and/or environmental management through cultivations, irrigation, crop protection from weeds, pests and diseases – nutrient supplying power of the soil-plant system must be improved to match, and long-term soil conservation must be ensured.

India has managed to keep pace in food supply – notably wheat and rice – despite its burgeoning population such that, whereas during the 1950s and 1960s famines arose, since then India feeds herself. Awareness of synergistic effects of management components for cereals is long established (Swaminathan, 1971). There is extensive advice and field experimental data available to farmers. Kemmler (1983) reports yields of wheat in India varying from 2 to 6 t/ha with average nutrient removal (kg/t grain yield) for local varieties of 28:11:20 of, respectively, N:P_2O_5:K_2O; HYVs removed similar amounts, 25-28 N:8-12 P_2O_5:21-29 K_2O. In some areas, soil and plant mobile clinics are used to good effect in order to avoid over-use of fertilisers as well as to encourage adequate dosage or proper stewardship of other nutrient sources. There is an established village tradition of biogas production with residues providing useful fertiliser material. Indian farmers have led the world in drawing attention to the negative impacts of excessive world trade on farmers' livelihoods and the problems of intellectual property rights associated with patenting of farmer-selected genotypes by TNCs. So far, Indian farmers have increased production of wheat to some 6 billion tonnes per year selling most of it directly to consumers at the local corner shop or via the local flour mill, with by-products such as bran available for local animal feed and consequent local nutrient recycling. In N. India, wheat is referred to as *kanak* (gold) and the wheat economy is decentralised with small-scale local production, processing and distribution within integrated farm-household systems. Shiva (2000) warns that if India's wheat economy is industrialised with loss of control of inputs and sale of outputs to TNCs then the livelihoods of at least 100 million people will be destroyed. Instead of fresh food, local supply, low cost, low environmental impact and high nutrition, they will get long distance supply, staleness, higher cost, high environmental impact and lower nutrition due to over-processing – meanwhile losing their livelihoods and independence. In this context, Sharma (2003) articulates concern over the real links between GM foods – with TNC control thereof – and hunger. Food security and nutrient cycle management must be as locally controlled as possible in order to be sustainable.

In Pakistan, HYVs show superior response to balanced fertiliser use rather than N alone or NP fertiliser on cereals. However, recommendations under irrigation are to increase both N and P inputs by around 50% compared with rainfed soils of similar potential.

China is radically restructuring its agriculture and gearing up its inputs to cereals, including its fertiliser rates to levels almost equivalent to the UK (see Chapter 1). Historically, it has been famed for the high energy-efficiency and resourcefulness of its farming systems (King, 1911) which proved their sustainability over 4,000 years. It is to be hoped that this heritage will not be squandered since it exemplified diversified nutrient cycling and all the environmental management imperatives which are now being urged upon the already industrialised countries (Addiscott *et al.*, 1991; Powlson, 1997; Simmelsgaard, 1998; van Donkersgoed, 2002; DEFRA/HGCA, 2002). Already, Dai & Xu (1995) have reported progressive depletion of K in soils of Jiangsu region of China. They calculate depletion rate at 2.3 mg/kg/year and recommend replenishment. In Japan, high fertiliser rates are used on HYVs. High phosphate fertilisers are used on volcanic ash soils. The small-scale farmers grow wheat as a winter crop, often alternating with rice and sometimes inter-cropped with Chinese cabbage or other vegetables.

In North Africa, especially Algeria, Morocco and Tunisia, wheat and barley cultivation is chiefly concentrated in the coastal regions. Barley bread is made and the majority of the wheat is durum. HYVs together with balanced NPK fertiliser use have produced good responses with rates recommended according to increasing rainfall above 400 mm/year, or at greater rates with irrigation. Nitrogen top dressing tends to be given only if October to January rainfall is sufficient. Some wheat is grown under planned, usually irrigated schemes in N. Nigeria, Sudan and Egypt.

In Southern Africa, yield responses are most closely correlated with moisture supply. Rainfed crops are fertilised stepwise according to rising rainfall probability with banding levels of 300 mm; 300-500 mm; >500 mm. In South Africa and Zimbabwe, the growing of dry season wheat with irrigation – often centre-pivot systems – has greatly boosted potential grain supplies during recent decades (notwithstanding disruptive upheavals) benefiting from the low disease pressure with the low relative humidity of the season. Recommended fertiliser rates for wheat in these circumstances are currently up to 125 kg/ha N and typically 40-60 kg/ha each of P_2O_5 and K_2O, according to previous cropping and yield potential. At least the N should be split on sandy soils and it may be advisable to split the K fertiliser too. In East Africa, especially in the Kenya highlands above 2,000 m, but also in higher land in Tanzania, wheat and some other small-grain cereals are grown successfully. Responses are greatest to added phosphate fertilisers and it is common to use a high P compound fertiliser. Some cases of copper response have been reported and treated with copper sulphate at around 10 kg/ha. Triticale is doing well in Kenya and in the Ethiopian highlands being thriftier in the absence of soluble fertiliser supplies than is wheat. Smallholder cultivation of wheat is found in Africa with seeds from this self-pollinated crop being retained through many generations. The author was recently in a crop in Zimbabwe of bearded wheat – which offers some bird pest resistance – for which the seed had been retained by the farmer for 18 years and was given to him by his grandmother who previously kept it for an unknown number of years. Such crops provide household food security since they are clearly adapted to the situation and the seed is already with the farmer for optimum sowing date whereas bought-in seed supply is all too frequently delayed. Of course, this is not an argument against introducing new, superior yielding varieties so long as they do not displace all of the proven ones whose particular management has been learned by farmers over generations.

In Latin America, Argentina has been a longstanding wheat-growing nation though recent economic disruption has weakened cereal prices relative to input costs, including fertilisers. Brazil has expanded its wheat cultivation in particular, especially using zero-tillage or CF methods and mainly in the south of the country especially on *terra roxa* soils (volcanic, reddish soils). These are subject to degradation unless conserved carefully and may tend to be high in aluminium sequioxides that sometimes induce aluminium toxicity. This can be countered using lime. There are also good responses to fertilisers, especially those rich in phosphates – sometimes as high as 90-100 kg/ha basal P_2O_5 is recommended for intensive cereal land. Mexico has been the source of many of the HYVs which have benefited the warmer climates of the world, starting with the 1943 Rockefeller Wheat Breeding Programme. This led to the formation of the International Centre for Improvement of Maize and Wheat (*Centro Internacional de Mejoramiento de Maíz Y Trigo* – CIMMYT) which is part of the CGIAR network of international agricultural research centres. CIMMYT is a source of much relevant and current data. Between the 1940s and 1980s, wheat yields in Mexico increased from around 0.75 t/ha average to some 4 t/ha and are now commonly over 6 t/ha. Borlaug (1969) recommended 120-140 kg/ha N and 40 kg/ha P_2O_5 for HYV wheats, rather neglecting potash; current recommendations are of course, higher. However, Mexican farmers now face a tide of cheap imported cereals since they entered NAFTA (North American Free Trade Association) with USA and Canada, threatening the sustainability of their whole farms. In the Andes slopes of Venezuela, wheat is grown up to around 2,000 m while barley is found up to some 3,200 m, both necessitating soil conservation measures to combat erosion. Maintaining soil OM and simultaneously supplying the majority of the nutrient requirement for both yield and quality assists this. In Chile and Uruguay, small-grain cereals are of some importance. In Chile, there has been adoption of higher input cereal management, aided no doubt by the ready access to Chilean nitrate fertiliser, and the deep alluvial loams of the Central Valley where cereals are found alongside higher value fruit crops.

In North America, cereals tend to be grown in relatively low cost, low input systems and many farmers have left farming in recent years. Canada likewise has relatively low average yields but in both countries this is compensated by the ability to grow high quality, especially wheats. Of these, hard red winter wheats (HRWW) are the most important (see Chapter 1). HRWW is grown mainly in the Central and Southern Great Plains (Kansas, Nebraska, Oklahoma, Colorado, New Mexico and Texas). Fertiliser recommendations tend to be closely related to expected yields and close monitoring to achieve least-cost production per tonne of grain, adjusted for soil status of nutrients. Semi-arid areas such as in the Northern Great Plains of the USA achieve yields little above 2 t/ha for winter wheat. Yields are depressed below 300 mm of rain but foliar diseases can set in above 400 mm! Optimum yields are attained with around 100 kg N/ha in no-till systems (Halvorson *et al.*, 1999). Better adapted to the shorter growing season, hard red spring wheats (HRSW) are common in the Northern Great Plains of the USA (North and South Dakota, Montana and Minnesota) and in the Prairie Provinces of Canada (Manitoba, Alberta and Saskatchewan). HRSW yields are low but quality is of the highest order in terms of protein content and protein quality (gluten % especially), good flour separation during milling and good bread-making characteristics. In the Prairies provinces too, the main malting barley production is concentrated – again with low yields but high quality, in this case low (aiming <1.5%) in N so as to avoid cloudiness in the beer made from it. White wheats are grown in the Pacific north-west and south-west states where they can respond to N applications of over 135 kg/ha provided that rainfall exceeds around 400 mm. Eastern USA and Eastern Canadian farmers tend to grow softer wheats and feed barleys, as well as some oats and triticale in mixed farming systems. At higher yield levels, these crops are given split dressings of N and some may benefit from extra K on coarse-textured and organic soils. Spring feed barleys are not usually given more than 70 kg/ha N for fear of inducing lodging and both P and K dressings are according to measured soil status. Since spring barleys and oats often appear within mixed livestock systems and follow a wide range of previous cropping and sowing dates, manures may be used to supply most of their nutrients, taking care not to overdose them with these and so induce lodging. Growing triticale in such mixed systems can also lead to lodging – even without any fertiliser applied - when it follows grazed forage legumes.

In Europe, there is considerable scope following the demise of communism to increase cereal yields on the good soils of the eastern countries, such as Poland, Hungary, Rumania, Russia, Lithuania, Ukraine and Kazakhstan. Many good, deep soils exist, some of them with histories of very uneven fertiliser treatments in some State collective farming systems. Wheat is the most important cereal, though barley, oats and then rye become more significant further northwards. Triticale is increasing in importance in Poland where it can appear in rotations with potatoes and thus not receive much if any fertiliser nutrients directly. In the continental interior, spring wheat is as important as winter varieties, if not more so in some districts. These hard red grain crops can respond to late N in terms of improved grain yield, grain protein content and % gluten. Kemmler (1983) reports data for both spring and winter wheat fertiliser trial responses, and commercial yields of over 7 t/ha from HYVs. It should be possible now for a wheat producer in Ukraine for example to achieve 8 - 10 t/ha as a farm average consistently, monitoring and correcting nutrient status as described in chapter 4 above.

In Western Europe, high cereal yields are attained, particularly in France, Germany and the UK. In certain regions, such as Schleswig-Holstein in North-West Germany, and in Eastern England, farm yields can average 9-10 t/ha consistently where nutrient cycles are maximised and farmers pay close attention to detail in crop management. In Southern Europe, more durum wheat is grown – in Italy and Greece - and soil depth and consequent moisture shortage can limit yields. Much effort has been made to increase cereal production in Turkey, with a large FAO programme there from the 1960s/1970s. Wheat in Anatolia is grown under semi-arid conditions and so fertiliser usage has to be sensibly matched to rainfall, fallowing is used plus legumes and FYM (Tosun *et al.*, 1996). Where irrigation is used, FAO reported responses to potash at 20 kg/ha while soil supplies might have sustained a rainfed crop on similar land.

Australia and New Zealand are important cereal growers, Australia in part for export and NZ largely for self-sufficiency. The main ‘bread-basket’ of NZ is the Canterbury Plain of South Island where cereals – principally wheats and barleys - are grown with similar management to that given in the opposite season in England, sometimes even similar varieties performing as well in both hemispheres. Some of the crops, especially of barleys, are grazed by sheep during their vegetative phase requiring the art of management to avoid unduly jeopardising future grain yield by leaving the sheep in too long! Most of Australia’s wheat is grown in extensive systems in the south, though some is found in Queensland and elsewhere. Silsbury (1990) tested legumes (peas, vetch and medick) in rotation with such wheats. All these gave similar grain N in following wheats when allowed to mature but this and wheat yield was greatly boosted when the legumes were ploughed in as green manures. In the south-east and south-west of Australia, the May to October (growing season) rainfall is only around 200 – 400 mm, sometimes less. In this situation, it is vital for the farmer to assess potential responsiveness to N fertiliser according to the moisture reserves detected in the soil profile, and to time sowing well. Particularly on these extensively grown, low yielding crops ensuring adequate phosphate has proven crucial over the years. As higher yields are achieved, or with irrigation, nutrient inputs from some source have to rise accordingly. Certain areas of Australia have also experienced shortages of particular elements, including molybdenum.

Chapter 7 now considers the greater complexities of cereal rotations more fully, especially in relation to nutrient management.

Chapter 7: Small-Grain Cereals in Rotations - Integrated Nutrition and Protection

7.1. Brief history of cereal rotations

Crop rotations are cropping sequences where a particular crop follows another on a field in a more or less repeated cycle. Mixed cropping is also very important in many farming systems, especially within the Tropics. This includes both inter-cropping and intra-cropping (where one crop is sown after the main crop and harvested before it). Mixed cereals are sometimes grown and frequently include oats and barley in varying ratios, often 50:50, the aim being to stabilise yields by spreading risk and reducing susceptibility to specific diseases. A useful overview on rotations and cropping systems is edited by Clarke *et al.* (1996).

In Mediterranean climates, a three-course rotation works well starting with winter sown cereals (barley, oats or wheat) followed by summer crops such as sunflowers or chick peas and then a legume hay crop such as short-term red clover.

Historically, before Roman times in Britain, (2,000 years ago) a common rotation was as follows:

Year 1: Autumn-sown cereal (usually wheat).
Year 2: Spring-sown cereal (often barley).
Year 3: Fallow.

The Romans introduced a better fallow/wheat/beans rotation.

In 1730, Viscount Townshend of Raynham, Norfolk, England introduced his famous four-course rotation: - Roots, usually turnips; Barley - spring sown; 'Seeds' - usually red clover; wheat - winter sown. This remains in spirit if not in rigidity the basis of many rotations today. It was designed for light and medium soils. The system contained 50% of the land in cereals, the two cereal species being suitably separated by crops of other families (Wibberley, 1996).

7.2. Cropping policy

The consequences of any particular Cropping Policy must be considered in relation to five factors:

- *Soil* conservation against erosion and sustenance of soil fertility are paramount.
- *Crop* effects on each another - beneficial or detrimental - must be considered.

- *Staff* morale and required team size depend on techniques and cropping sequence.
- *Nation*: The national interest is affected in four main ways by cropping policy:
  - *Environment*: Cereals occupy a significant proportion of the land area. Landscape quality in terms of appearance and biodiversity are determined by the pattern and methods of cereal cultivation to a significant extent.
  - *Energy*: Adoption of energy-efficient cropping policies is clearly a matter of international concern. The richer countries have an alarmingly bad record by contrast with the poorer nations. Bray (1994) reports a 3:1 ratio for inputs to food outputs in industrialised intensive farming while traditional polycultures use only 0.05:1.
  - *Social*: Rural depopulation and farmer loss should be a matter of great political concern. Vibrant, agriculturally employed rural communities are desirable.
  - *Cost*: The cost of taxpayer support is now very high in the EU, Japan and USA.
- *Profits* As well as being beneficial to soil and society, cropping must be profitable. Three levels limit the cereal system adopted:
  - *International*: WTO policy favouring non-discrimination against imports leads to least-cost production, excessive export energy costs and consequent huge damage to the environment and to farm livelihoods.
  - *Regional*: For example, The Common Agricultural Policy of the EU with its centralised decisions tends to limit the choice of economically feasible cereal systems. The economic and political climate of member countries tends to limit severely the numbers of people employed in cereal cultivation and hence enforce mechanised, low-labour techniques.
  - *Local*: Individual farm circumstances determine what other enterprises are technically and economically feasible. For instance, a large rental or overdraft charge usually enforces a higher output, higher pressure, higher risk system.

7.3. Principles underlying crop rotation

Early rotations attempted to be more rigid in respect of precise crops, their order and the number of years to complete full-circle than is common today. However, the principles are:

- *Substitution* of alternative crops for the fallow (uncropped) period to give fuller use of land. Setaside of land from cropping is used as a policy instrument to regulate cereal output and it also can reduce weed, pest and disease pressures.

- *Balance* between exhaustive and restorative crops. Exhaustive crops are those that deplete soil nutrients and tolerate declining humus quantity and quality without sudden failure. Cereals, other than paddy rice, are exhaustive and so benefit from integration with restorative crops in rotation. Restorative crops are those which enrich the soil or require ample nutrient replenishment of the soil if they are not to perform miserably. A period under a ley or other longer-term crop allowing soil structure stabilisation or restoring OM is considered restorative. Root crops needing enriched soil conditions can be restorative. Whilst legumes can have a restorative role by adding nitrogen compounds to the soil, their continuous cultivation has proved very exhaustive where practiced overseas, such as with groundnuts in Senegal.
- *Breakage* of the life cycles and population build-up of soil-borne pests (e.g. cyst nematodes); diseases, especially soil- and trash-borne ones (e.g. eyespot); and weeds, especially those cereal relatives, the grass weeds, which are expensive to control.
- *Cover*: The object is to maintain continuous soil cover, so minimising exposure of bare earth to weed colonisation and soil erosion.
- *Diversity*: Growing them in blocks within the same farm, not necessarily by rotating them all within each field can attain some of the advantages of producing a range of different crops. However, individual field rotation where possible secures all benefits simultaneously.

Diversity of cropping results in:

- Less economic risk if the season or market is bad. It is unlikely that all will be equally affected. Undue dependence on one product can make one politically vulnerable too. The advantage of keeping to a definite rotation is that the farm may carry more or less the same proportion of each crop every year (depending on variability of field size or block size grown), with generally steadier returns.
- Less biological risk. A diverse range of residues replenishing soil is more likely to preserve the size and diversity of the soil microbial population. Furthermore the likelihood of many weed, pest or disease infestations is reduced.
- Greater variety of diet and crop by-products available locally, thus reducing import dependence and costs of transport in the overall economy.

- Greater variety of work, therefore improved job interest. The opportunity for specific tasks such as subsoiling, organic manuring or liming may logically fit before the more responsive crops in the sequence.
- Better spread over the year of work and hence of labour demand.
- Less waste because different enterprises can interact positively.
- Somewhat higher yields for lower inputs of energy-consuming biocides and fertilisers. Standards of crop quality can be higher e.g. less grass weed contamination is likely in cereals from mixed arable sequences. However, labour requirements and certainly management skills are likely to be higher though better spread: this may mean less pressure for staff and increased challenge and interest for management.

The greatest aggregate of the above advantages of rotations could be expected to accrue from the widest contrast between crops included, thus suggesting a rotation with as many different plant families represented as sensible for the particular farm.

7.4. Why are rotations now followed less rigidly?

Fertilisers: Ever since the early work of Lawes and Gilbert at Rothamsted UK during the 1840s, the use of fertilisers has increased. It has escalated during the past sixty years and especially since 1970 on cereals in Western Europe. When one can replenish nutrients in a particular ratio, the need to balance soil supplies using an assortment of crops and carefully returning all residues is lessened. Undoubtedly, fertilisers support the high average cereal yields in modern rotational systems but they especially sustain continuous cereal systems.

Biocides: Crop protection chemicals against weeds, pests and diseases of cereals have provided powerful alternatives to cultural means of control. However, biocides should not be a substitute but rather a supplement to good general husbandry. Biocides and fertilisers together have made continuous corn technically feasible longer than they are truly sustainable.

Plant breeding: Resistant varieties reduce dependence on diversity of cropping to lessen disease pressure. Furthermore, the disadvantage of monocropping is lessened owing to the existence of a greater selection of cereal varieties with somewhat different required dates of sowing and harvesting.

Machines: Relatively larger areas of cereals or any single crop enterprise are needed to justify possession of specialised, increasingly large equipment. Crops of lesser importance have in some cases proved more technically difficult to mechanise than cereals.

Management: Specialisation in fewer or even single crops allows the concentration of skills. Furthermore, the simplification of cropping to just cereals affords greater leisure and, perhaps, easier management.

Labour: Decline in the agricultural labour force has been rapid and continuous. Cereals by contrast with other crops have rather lower labour requirements per hectare anyway. Specialists are being trained and roles even within cereal enterprises are often quite demarcated e.g. sprayer operator, combine driver.

Tenancy agreements: Tenant farmers are usually now allowed more freedom of cropping by landlords.

Economies of scale: Running a larger cereal enterprise can enhance bargaining power in purchasing inputs and selling outputs.

Targets: Economic performance and market objectives are more imperative. Fixed resources can be focused on a single enterprise, whereas an assortment of different crops may compete leading to a clash of priorities. Furthermore, mixed cropping can lead to muddled management, and ‘passenger’ (uneconomic) enterprises may be tolerated because financial analysis is not incisive enough to detect them. Of course, a mix of crops can be properly costed but a specialist cereal farm is clearly more straightforward to evaluate.

Government policies: Governments can alter the balance of species cropped by price-fixing arrangements, subsidies and other production incentives or protective measures. Above all, cereals are the mainstays of most agricultural economies and crops have become commoditised. Collapse in the cereal market would be disastrous for agriculture as a whole. Therefore, market support for cereal production has had to be consistently encouraging, significantly reducing the economic risk of cereal monoculture.

7.5. The place of different small-grain cereals in rotations

Wheat

Common wheat *(Triticum aestivum)* is the chief world wheat. Wheat is the normal first crop after a restorative break crop. This would usually be winter wheat and the intrinsically lower-yielding milling varieties may well be sown as first wheats after the break, high-yielding feed wheats as second wheats and, if a third wheat is being grown, a more disease-resistant and thrifty variety as a third wheat. Spring wheats rather than spring barleys logically follow late-harvested vegetables or root crops on heavier land, or can be sown to cheapen weed and disease control in a run of winter wheat crops. Quality is generally high and autumn sowing satisfactory for many varieties.

Durum wheat *(Triticum durum)* is a distinct species really adapted to

Mediterranean climates and requiring the better cereal soils. Major world producers include the USA, Canada, the USSR, Central and South America. In Europe, production is mainly in Spain and Italy, followed by Greece and France. Durum has been sown in the autumn but overwinter survival has sometimes been poor and spring sowing is an option since no vernalisation is required, and sowing durum wheat as a first cereal after a break crop is desirable.

Barley (Hordeum sativum)

Barley crops are reckoned thriftier than wheats, though they are less tolerant of heavier, structurally inferior land. Spring barley is a very flexible crop, allowing a wide range of sowing dates and thus fitting into a wide range of cropping sequences and has been grown continuously on light land. The chief advantage of winter barley in a cropping sequence arises from the earliness of its harvest at a time when staff and equipment are not tied up with other crops except perhaps winter oilseed rape.

Oats (Avena sativa)

Any oat crop is a camouflaging hazard on a cereal farm which is attempting to control wild oats or where considerable sums have been spent for years to reduce the weed. As a minor combinable alternative crop to wheat and barley, it is more straightforward to handle than some of the non-cereal breaks used. In long runs of either barley or wheat, it can yield well as a break and may form part of a successful rotation of combinable crops, e.g. winter oilseed rape/winter wheat/winter oats/winter barley. It is less at risk from eyespot or take-all but cyst nematode susceptibility could be a problem, especially with spring oats. Germany is the leading EU producer, while Russia produces over one-third of the world oat crop.

Rye (Secale cereale)

Rye's reputation for moderate resistance to such common problems as drought, acidity and rabbit-grazing does not mean a lack of response to better conditions. Like oats, rye should be considered by the wheat and barley grower seeking an alternative combinable crop before turning to some of the more exotic minor crops which may be difficult to manage and sell.

Triticale

Tetraploid (4x) durum wheat is the usual mother of this hybrid, whilst diploid (2x) rye is the father. Artificial doubling of the chromosome number of the resulting sterile hybrid using colchicine gives hexaploid (6x) triticale. The crop has been developed at the University of Manitoba, Canada, and at the CIMMYT in Mexico. In Ethiopia, it has shown suitability for poor, sandy and acidic soils whilst its superior resistance to leaf stripe and stem rust has given it double the yield expectation of established wheat varieties in Kenya. The use of triticale flour as a substitute for wheat in doughnuts was undetectable in a consumer survey by Egerton University in Kenya. Polish varieties have spearheaded its adoption in Europe. It is often sown on poorer land where it can only respond to lower N rates. It resists mildew and gets less take-all but can succumb to eyespot and ergot. It should need only a single fungicide treatment and so is a cheaper cereal to grow than wheat.

7.6. Criteria determining practical cereal cropping policy

- *Objectives* = short and long-term expected outcomes regarding produce, soil or farm improvement and maintenance.
- *Environmental constraints* = limitations of soil, site and climate.
- *Economic factors* = profitability, reliability, demand. It may be better to have cropping of lower *potential* seasonal profitability if yield is more reliable from year to year and demand more consistent.
- *Technical options* = varieties, mechanisation, chemicals, and their costs.
- *Human issues* = preferences, supply of labour, skills.
- *Husbandry aspects* = rotational possibilities, crop interactions, by-products. Crucially, how will the cropping sequence work - how will it fit the fields as they are, when will the peaks of work occur? Will the crops complement each other either biologically or economically, especially in terms of shared use of fixed resources?
- *History* = experience, cropping records. What local experience exists about the proposed crops? It is good practice to consult an obviously tidy and successful farmer when new to a district: his or her wisdom is likely to be worth a thousand printed documents. If farm records exist, they should be consulted for past performance of proposed crops. There is a case, of course, for pioneering novel crops or techniques. If that had not occurred, cereals would not have spread from the Fertile Crescent of the Middle East!
- *Legal constraints* = laws, contracts, quotas. The frequency of cropping or juxtaposition of some crops (e.g. cereals for seed) is restricted as to variety. It is always possible for governments to introduce new quotas for categories of cereal. In some countries, there are restrictions on nitrate usage and other soluble fertilisers on soils where leaching is likely, such as certain sands near watercourses supplying reservoirs. The UK designates such land as NVZ = Nitrate Vulnerable Zone. Here the total N and its timing are moderated.

- In Denmark, nitrate leaching was monitored for twenty years under different cropping régimes on soils varying from coarse sands to sandy clay loams (Simmelsgaard, 1998). Barley undersown with grass gave the lowest leaching rate (17-24 kg/ha/year of NO_3). Winter cereal after winter cereal with an autumn-sown catch crop was moderate (36-46 kg/ha/year of NO_3). High rates were recorded from either winter cereal after oilseed rape/peas, or from bare soil, or after autumn application of FYM/slurry (71-78 kg/ha/year of NO_3). Average leaching during the whole study was 68 kg/ha/year on land with 5% clay and 26 kg/ha/year at 20% clay in soil.

7.7. Examples of cereal-containing rotations

There are many recipes but their effective management is paramount. Some possibilities, especially found in Europe, are given below (Wibberley, 1989):

- Alternate husbandry or ley farming consisting of, for example, *three-year ley/two winter wheats/winter barley*. This rotation allows soil stabilisation and OM accumulation under the ley phase, particularly if it is grazed. Once livestock parasites and grassland weeds have accumulated, the ley is ploughed and fertility cashed in for one or two wheat or other cereal crops. The ley must be released by the livestock enterprises of the farm in adequate time to allow preparation without high pest risk and for timely sowing of the next wheat crop. Grass weeds may build up, particularly meadow grasses affecting cereal yields and quality. The cereal sequence is ended before arable problems can accumulate seriously and the winter barley allows early direct sowing of the ley to follow. The sequence could be extended by having a catch crop such as stubble turnips after the winter barley and following these with a spring barley crop undersown with seeds for the next ley. The system provides for a balanced, safe cropping policy. On deeper, lighter land a root crop or potatoes may also be interposed.
- *Two or three winter wheats/winter beans* - a traditional heavier land rotation, often now appearing as a longer run of wheat with winter oilseed rape as an alternative as well as beans.
- *Sugar beet/spring malting barley/peas/winter wheat* - a good, balanced lighter loam sequence emulating the famous Norfolk four-course rotation.
- *Winter wheat/potatoes/sugar beet* - a traditional Fenland (deep fertile peats) sequence where the wheat is really the poor relation. Celery, onions and other vegetables may often be found now, with wheat as an infrequent break.

- *Potatoes/winter wheat/brussels sprouts/spring wheat* - a balanced sequence found suitable on deeper sandy clay loam land.
- *Two or three winter wheat/winter barley/winter oilseed rape* - this is a typical sequence to allow a combinable alternative crop into an otherwise all-cereal sequence. Sometimes on lighter land only winter barley may appear, perhaps with spring barleys or triticale and the intermittent break crop of oilseed rape, linseed or pulses every fifth year.

A double break from cereals allows a cereal seed crop to follow afterwards if other conditions of field hygiene are met.

In tropical and subtropical areas where wheat is the principal temperate cereal found, it appears in many systems including:

- Wheat - rice
- Wheat - maize - soyabeans
- Wheat - cotton
- Wheat - legumes, such as chickpeas in the Middle East and West Asia

7.8. Continuous cereals

Wetland or paddy rice has been successfully grown continuously for several thousand years because it involves carefully managing the swampy ecosystem. However, this has not been the case with dryland rice or with other cereals.

Arguments and counter-arguments about attempts to continuously grow small-grain cereals include the following:

- It is *biologically narrow,* leading to the accumulation of specific pests, diseases and grass weeds coupled with a relative microbial stagnation due to the lack of variety and quantity of raw OM arriving in the soil. Soil structural stability may thus be weakened. Reducing cultivations, with therefore less soil aeration so that decomposition is slower, can conserve the amount of OM present. However, long-term reduced cultivation for continuous winter cereals is dependent upon burning straw, at least more often when direct drilling is to be practiced, thus depriving the land of a source of OM. Burning is also prohibited in many European countries now. Opportunity to add external sources of OM to the system is offered by the periodic insertion of a spring cereal into the sequence. This also relieves pressure of grass weed build-up and allows a cheaper control possibility. In addition, the interchange of different cereal species in the sequence can relieve specific disease and pest pressure relative to continually cultivating only one species of cereal. Proponents of continuous cereals would claim technical sustainability in the medium term (decades, not millennia!) using the range of available crop protection chemicals (biocides) and fertilisers now available in some parts of the world. They may add that the Take-All fungus (*Gaeumannomyces graminis*) declines after a few years but recovers again once a break crop is introduced.

- It is argued that it is *economically narrow,* with dependence on inputs from outside the farm and on direct sales of grain off the farm. These drawbacks can be offset if the cereals are grown continuously not over the whole farm but only within a block of land on the farm whilst other parts of it grow different crops - perhaps grass in a grazing block and a cutting block. Alternatively, even the all-cereal farm could diversify markets by feeding at least some of the grain via non-land-using enterprises such as pigs, poultry or feedlot beef, at the same time adding substantially to the value of that grain. However, on individual fields cropped continuously there will tend to be an inevitable increase in variable costs for both sprays and fertilisers per tonne of yield, generally resulting in a less energy-efficient system. Nevertheless, proponents would argue the benefit of economies of scale in fixed costs per tonne by specialising in a larger area of cereals. It must be remembered, though, that if the scale is too large - i.e. beyond the managerial capacity of the farm team - financial benefits may be lost.
- Another argument is that it is *managerially narrow,* producing a simple cropping system which is less flexible, though it is easier to manage in several ways (specialised knowledge and skills are more attainable if only cereals are grown). It is easier to expand into alternative crops if there is already some prior experience of growing them in rotation on the farm. A diverse range of crops adds interest and challenge to work and offers the chance of a better spread of work or labour profile over the year. However, continuous cereals enable the farmer to reduce labour used per tonne produced, i.e. fewer staff to control and to pay. On the other hand, this trend can be seen as detrimental to rural employment prospects.
- Undoubtedly those farmers who have succeeded in continuous cereal production over several decades have done so by exploiting the simplicity, specialisation and scale advantages of the system and by sustaining crops by detailed attention to soil management, fertiliser application and crop protection. The long-term sustainability of such systems is clearly open to question, as is the desirability of such systems. Some soils and regions are particularly vulnerable to damage by continuous cereal cropping but a rotation of crops generally reduces such risks. In any case, yields of first winter wheat crops after a break are

generally 10 – 15% higher than second and third wheats although this may often be used in practice to justify planting a lower-yielding but higher-quality variety as a first wheat. Some UK experience in trying to measure rotational effects on cereal performance was summarised by Bowerman and Jarvis (1982).

7.9. Break crops for cereal rotations

A break crop is any change of crop from the one customarily planted on a particular field. It may even be so described if a spring cereal is planted in a winter sequence of the same species, or when another cereal species is interposed for a season.

The following is a checklist on the purposes of break crops:

- *Weed control*: A major cost, hindrance and yield detractor of intensive cereals can be weeds, especially grass weeds. A break crop may allow a cultural and/or a herbicidal opportunity to deal with the offending weeds.
- *Pest control*: A change of crop can starve out a soil pest relatively cheaply.
- *Disease control*: Soil- and trash-borne diseases can be dealt with during growth of a non-host crop under which the infective cereal trash can thoroughly decompose.
- *Restorative effect*: Is a change of diet due for the soil organisms - or an improvement in soil conditions?
- *Economic diversity*: If the market looks less promising for some of the cereals and/or has been boosted for another crop, then it may be time to include it.
- *Human value*: Is a break crop needed to interest the staff?

The following characteristics are those sought for a suitable break crop from cereals:

- *Growth habits*: Preferably a different botanical family with another growth pattern.
- *Value*: Profitable in its own right or at least offering reliable, acceptable returns.
- *Fixed costs*: Produced with cereal equipment, notably the combine harvester.
- *Compatibility*: Providing a good preceding crop for a cereal, usually winter wheat.

- Data from a decade of yield records on calcareous soil in Southern England (1965-1975 recorded at Bridgets Experimental Husbandry Farm, Hampshire) show the relative impacts of different break crops on the yield of the following first wheat; the actual mean wheat yield was 4.55 t/ha (Table 7.1).

The superior effect of winter oilseed rape may be explained by:

- Its requirement for soil structure to be well-managed to depth before planting it.
- The fact that it is harvested early enough for the following wheat to go into a good seedbed.
- Its need for good nutrition (see Orlovius, 2003).

Table 7.1. Effect of preceding crop on relative yield of the next winter wheat.

Preceding crop	Relative winter wheat yield
Continuous winter wheat	100
Barley after wheat run	100
Continuous barley	103
Second wheat after grass ley	109
Oats	112
Oats and faba beans	117
First wheat after grass ley	117
Forage maize (cow slurry given)	122
Faba beans	125
Potatoes	126
Oilseed rape	137

Source: Farm data collated by E.John Wibberley.

7.10. Catch crops

These are so called because they ‘catch’ short periods of opportunity for cropping between main crops and they ‘catch’ nutrients which may otherwise leach or be lost from the soil system in other ways. Furthermore, depending on how they are utilised, they may introduce fresh nutrients into the soil system. Examples include stubble turnips, forage rape, short-term red clover, forage rye. Thus the case in favour of catch crops in the cereal rotation can be summarised thus:

- Make *fuller use* of land.
- Maintain *soil cover,* thus helping to smother weed flushes and keeping soluble nutrients cycling through catch crop plants within the upper horizon of soil.
- Maintain *soil OM* status and relieve the monotony of cereal root and stubble diet for soil organisms. They may be specifically grown as green manure: this effect can be a stimulus to the organic activity in sandy soils, though a single such crop will not produce a lasting effect.
- Allow *stock* into the arable rotation without reducing the cereal hectarage.
- Fill *fodder gaps* for livestock enterprises.
- May replace a *failed crop.* A wise farmer can always think of something at virtually any time of year to occupy redundant land beneficially. Catch crops are often still cheap to grow (broadcast on, cheap seed, perhaps some nitrogen fertiliser to boost yield, e.g. 75-100 kg of N per hectare for stubble turnips).

7.11. Crop rotations and nutrient balances

Crop rotation has a huge impact on nutrient availability to cereals. The aim of assessing nutrient balances is to monitor trends for better nutrient management planning and practice. In the UK context, Table 7.2 reports P and K balances for the main cereals and the principal alternative crops which appear on different land types. It specifies deeper land rotations (where potatoes and sugar beet grow well) and land of more limited capability (where combinable crops pre-dominate with oilseed rape being the chief break from cereal growing). These data indicate the potential compensating effect of rotational applications of fertiliser rates exceeding off-takes for some crops. However, there is a tendency for potash shortfalls for winter wheat and spring barley. Maincrop potato, a crop traditionally expected to leave a positive balance of K, may also be given significantly less than it removes. One key reason is that farmers are seeking to economise on fertilisers, which frequently account for over 40% of the variable cost of growing cereal crops in high input systems. Importantly also, the data do not take account of organic manuring additions.

There is a special benefit to the whole nitrogen economy of the system when cereals are preceded by legumes, particularly when these are ploughed in as green manure or else fed *in situ* to livestock whose dung and urine returns directly to the field. Huge yield and quality responses to legume inclusion have impacted the largely extensive cereal rotations of much of Australia. In more intensive arable rotations of Europe, even a grain legume crop such as *faba* beans can leave a residue of 35-50 kg/ha extra N compared with a preceding cereal crop, thus saving on applied N fertiliser. Non-legume, non-cereal crops such as oilseeds (e.g. oilseed rape, sunflower) can have an unexpectedly high benefit to nitrogen – and other nutrient availability - by requiring that soil structure is improved so that they can send their tap roots to depth. This opens up the soil for better exploration by the root system of the following cereal, which is usually wheat – though maize-sunflower systems have the same effects. In the UK, Sylvester Bradley *et al.* (1987) compared yield and efficiency of N recovery by wheat after cereals and after non-cereal break crops showing an average 7% yield improvement with a saving of 47 kg/ha of N fertiliser (Table 7.3).

Table 7.2. Average P and K balances for principal arable crops in the UK in 2002.

Crop	WW	WW	WB	WB	SB	SB
Yield t/ha	8.1	8.1	6.3	6.3	5.2	5.2
Nutrient	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
Off-take kg/ha	70	96	54	74	46	71
Applied kg/ha	70	80	63	79	45	61
Balance kg/ha	0	-16	+9	+5	-1	-10
Crop	**OSR**	**OSR**	**MCP**	**MCP**	**SBT**	**SBT**
Yield t/ha	3.6	3.6	49.2	49.2	51.3	51.3
Nutrient	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
Off-take kg/ha	50	40	49	285	41	87
Applied kg/ha	72	77	148	246	82	128
Balance kg/ha	+22	+37	+99	-39	+41	+41

Key to crops: WW = Winter wheat; WB = Winter barley; SB = Spring barley; OSR = Oilseed rape; MCP = Maincrop potatoes; SBT = Sugar beet (yield given as 'clean roots').

Adapted from: Armstrong, 2004.

Note: Cereal data assume that cereal straw is removed whereas it may be incorporated into soil.

Table 7.3. Previous crop effect on yield and efficiency of N recovery in wheat.

Previous crop	Cereal	Break	Difference
Grain yield (t/ha) at optimum N rate	8.4	9.0	0.6
Optimum N rate (kg/ha)	210.0	163.0	47.0
Crop N with no N fertiliser (kg/ha)	71.0	99.0	28.0
Crop N @ optimum N rate (kg/ha)	192.0	195.0	3.0

Adapted from: Sylvester Bradley *et al.*, 1987; data from 36 UK field experiments.

When the previous crop is grassland (particularly if it contains legumes and is grazed) or green forage, especially a legume such as alfalfa (lucerne or *Medicago sativa*), there is a huge benefit to following cereals, usually led by wheat. Alfalfa is particularly useful since it roots deeply and may persist for up to five years or so during which time soil structure and OM level can build up to be 'cashed in' somewhat during the cereal phase of the rotation. In the USA, maize - wheat - alfalfa rotations are strip cropped along contours to reduce soil erosion and they provide a sustainable, lower nitrogen input system. It must be noted that the sloughed off nodules of legume roots which decompose to release available nitrogen may boost the soil system with a flush of N as large as from nitrate fertiliser applied. An alfalfa crop can fix some 300 kg/ha/year of N. In Canada, spring wheat grown on chernozem soil in Saskatchewan in rotations with legume/grass hay crops had higher yield and protein content than when the wheat was alternated with fallow (Zentner *et al*., 1990).

After 28 years of trials on sandy loam pH 7 to 8 in dryland Anatolia, Turkey, Tosun *et al.* (1996) reported the superiority of a 3 year sainfoin (*Onobrychis viciifolia*) crop followed by fallow/wheat, fallow/wheat to attain the highest yields of 1.75 t/ha. However, to provide more wheat from the rotation, the wheat grain yield was only marginally lower in the fallow + 20 t/ha farmyard manure/wheat system at 1.64 t/ha. Despite it being a legume, the use of vetch (which is harvested in July depleting soil moisture) gave the worst yields of wheat alternated with it in these long-term trials.

It must not be assumed that a break crop is always beneficial to the following cereal, even if both are sown and harvested as near to optimal dates as possible. In Kansas in the Great Plains of the USA, Norwood (2000) studied rotational effects over 7 years alternating winter wheat with one of four different break crops – sorghum, maize, soyabean or sunflower. Here moisture is the critical factor, limiting wheat yields to around 2 t/ha. After soyabean and sunflower, soil water at planting was reduced by 9.3-19.9% by comparison with the situation after maize and sorghum. As a result, wheat after sunflowers had fewer ears/m^2, less grains/ear and 0.85 t/ha lower yield.

In India, chickpeas (*Cicer arietinum*) have been successfully intercropped with rainfed wheat and within irrigated rice-wheat systems (Ali, 1993). In the UK, Clements (1996) has reported research on the use of a permanent perennial understorey crop of white clover (*Trifolium repens*) into which companion cereal crops are direct drilled each year to create a sustainable, low input, low erosion system. The cereal is taken as whole crop wheat silage with the clover included or else the wheat can be left to mature and the grain harvested separately. It is interesting that a hundred years ago a farmer (Mr. Chamberlain) in Oxfordshire, England developed a means of sustaining barley and wheat crops on calcareous soil using an understorey of *Trifolium*.

7.12. Towards an integrated approach

A new orientation towards ‘alternative agriculture’ was proposed in the USA following a five-year review for the USDA (Pesek, 1989). The Report defined alternative agriculture as any system of food or fibre production that systematically pursues the following goals:

- More thorough incorporation of natural processes such as nutrient cycles, nitrogen fixation, and pest-predator relationships into the agricultural process.
- Reduction in the use of off-farm inputs with the greatest potential to harm the environment or the health of farmers and consumers.
- Greater productive use of the biological and genetic potential of plant and animal species [but see the GM discussion in Chapter 1].
- Improvement of the match between cropping patterns and the productive potential and physical limitations of agricultural lands to ensure long-term sustainability of current production levels.
- Profitable and efficient production with emphasis on improved farm management and conservation of soil, water, energy and biological resources.

Agricultural efficiency is most usefully defined as the ratio between total energy invested per hectare starting with soil preparation compared with the total energy available from that hectare as food on the plate (Wibberley, 1989 – pp. 214-216). Thus it takes account of the total energy cost of field operations and of producing and delivering all inputs, of processing, packaging and transporting all outputs. Efficiency defined in these real terms increases with localisation of farming system (see Pretty, 1995; Hines, 2000) and decreases with greater intensification and commoditisation into world trade and food processing of the products. In a salutary calculation, Gooding & Alliston (1993) estimate the energy cost per kg of $N:P_2O_5:K_2O$ = 75:14:8 MJ (Megajoules)/kg.

Integrated systems of arable production have been redeveloped in recent years (El Titi *et al.*, 1993; Jordan & Hutcheon, 1993 & 1996; Wibberley, 1995; Davies *et al.*, 1997; Gooding & Davies, 1997). Experimental work on them is more difficult to interpret with the many possible interacting variables and yet these are the same variables that the farmer must synthesise into a practical management strategy to implement.

Broadly, all attempts seek to take a systems approach (FAO, 1989) and to follow the principles listed above (Pesek, 1989) adapting them to the particular circumstances of each nation and ultimately each farm. Leake (1996) has usefully compared cropping management in 'conventional', 'integrated' and 'organic' systems.

7.13. Organic farming of cereals

'To the maximum extent feasible, organic farming systems rely on crop rotations, crop residues, animal manures, green manures, off-farm organic wastes, mechanical cultivation, mineral-bearing rocks, and aspects of biological pest control to maintain soil productivity and tilth, to supply plant nutrients and to control insects, weeds, and other pests' (USDA). Such methods have been stimulated by concern over pollution by agrochemicals as well as by analyses of the declining energy efficiency (gross output of energy against support energy used) of conventional agriculture, in spite of dramatic yield increases. Pimentel *et al.* (1984) reckoned organic wheat in the US to yield 4% below conventionally grown crops with 35-47% better energy efficiency but 26-49 per cent lower labour efficiency (i.e. more man-hours needed per tonne).

In Britain, the Soil Association was founded in 1946 as a charity 'to promote a fuller understanding of the vital relationship between soil, plant, animal and man' since 'life on earth depends on the soil. To respect and nurture the soil is essential if the quality of life and life itself are to be maintained' (Balfour, 1943); see also Conford (2001). It operates a scheme of agreed standards required for organically grown produce to claim the premium available on the market with a symbol to indicate its acceptability. It must be emphasised that organic produce must also satisfy normal market requirements on cereal quality, such as Hagbergs and protein standards for milling wheats.

In Europe, organic farming has long been promoted in Switzerland and Germany (Vogtmann *et al.*, 1989). In 1977, the International Federation of

Organic Agriculture Movements (IFOAM) held its first international symposium. The British government has a UK register of organic food standards (UKROFS). National movements also exist worldwide, though in many countries the market does not require the sophistication of an 'organic' label and production is encouraged along 'sustainable agriculture' or 'environmentally friendly farming' lines without strict regulations.

Procedures of organic farming have to be followed in order to secure market premia accorded in some countries to produce so grown. Lampkin (1990) provides a full treatment of organic farming, while Lampkin & Padel (1994) discuss its economics.

Organic cereals must usually:

- Come from a field which has not received agrochemical-grown crops for at least two previous seasons.
- Have no soluble fertilisers given except up to 250 kg/ha of Chilean nitrate of soda (which gives 37 kg N and 65 kg Na/ha). This product is justified as being a totally natural salt deposit.
- Have no seed dressing or synthetic agrochemicals applied to it.

On the positive side, such a crop may receive:

- Additional N from livestock manures and slurries, previous legume crop, composts, sewage sludge and various bacterial/organic preparations.
- Additional phosphate as micro-ground reactive rock phosphate, basic slag and bone meal.
- Potash from slurry, wood-ash and Highland potash (Adularia shale feldspar).
- Lime as ground chalk or limestone, including magnesian limestone (dolomite).
- Seaweed preparations as foliar feeds or otherwise. These provide trace elements and can also give a protective effect against pests and diseases.
- Derris or pyrethrum as insecticides.
- Sulphur or copper as simple contact fungicides. (Wettable sulphur powder is moderately effective against cereal mildew).

Establishment can be very difficult in wet, slug-infested seedbeds: 25 - 30 % only is not uncommon, often with the need to re-sow. Effective weed control is perhaps the most difficult aspect for the purist organic farmer in a low-labour economy. Control is attempted by crop rotation, cultivations including shallow (10 - 15 cm) ploughing and the use of fine-tined weeders, bastard fallows, smothering with undersown green manures such as trefoil, and roguing. Overzealous cultivations before sowing can critically deplete moisture. Post-emergence harrowing can damage an advanced crop, whilst the use of minimal cultivations can encourage persistent grass weeds. The use of a suitable weeder can be quite effective. Both grass weeds and disease pressure are eased by delayed sowing of winter cereals - say late October instead of late September in Britain or France - but this is likely to incur a marked yield penalty, especially on droughtier and difficult soils. Sowing in earlier October at conventional densities to get a good competitive crop established, followed by grazing with sheep later on to remove diseased foliage as well as weeds, can be a workable compromise.

On the positive side, the need for rotations and the avoidance of high doses of soluble N sources reduce the incidence of grass weeds markedly by contrast with intensive winter cereal cropping. It is also noticeable that the less lush foliage of organic cereals may be host to a wide spectrum of diseases but at tolerable levels. Organically grown cereals at IACR, Rothamsted, England have been found to have fewer aphids and more predators - notably rove beetles, springtails and mites, which comminute the added crop residues and manures, sewage sludge being especially favourable for this. An example rotation might be a three-year ley, winter wheat, spring oats, spring beans undersown with the ley again.

Under English conditions, cereal yields are likely to be approximately 65-75% of conventionally grown crops with considerable savings on variable costs (say 20-25% of normal since they amount to seed only in some cases, there being no fertilisers and no sprays). Leake (1999) reported seven years of results showing that winter wheat averaged 68% of conventional yields and winter oats 81%. Prices per tonne of grain fluctuate but have been typically at least 25% and may be 50% above conventional crops.

7.14. Prognosis on sustainable farming and its interactions

Management is said by opponents of integrated farming and especially of organic farming to be too complex. Many fear that weeds, pests and diseases will eventually take over. Others point to its environmental benefits. Sir John Russell (1957) reported a 25% reduction in nitrate leaching into drainage water from Broadbalk field at Rothamsted, England when N was given as FYM at 35 t/ha rather than the equivalent 96 kg/ha nitrate-N fertiliser. Furthermore, data over the 150 years of work growing wheat on this silty clay loam field with and without rotation and with differing nutrient supply régimes gave the results shown in Fig. 7.1, which also chronicles principle agronomic changes which share the credit for yield improvements.

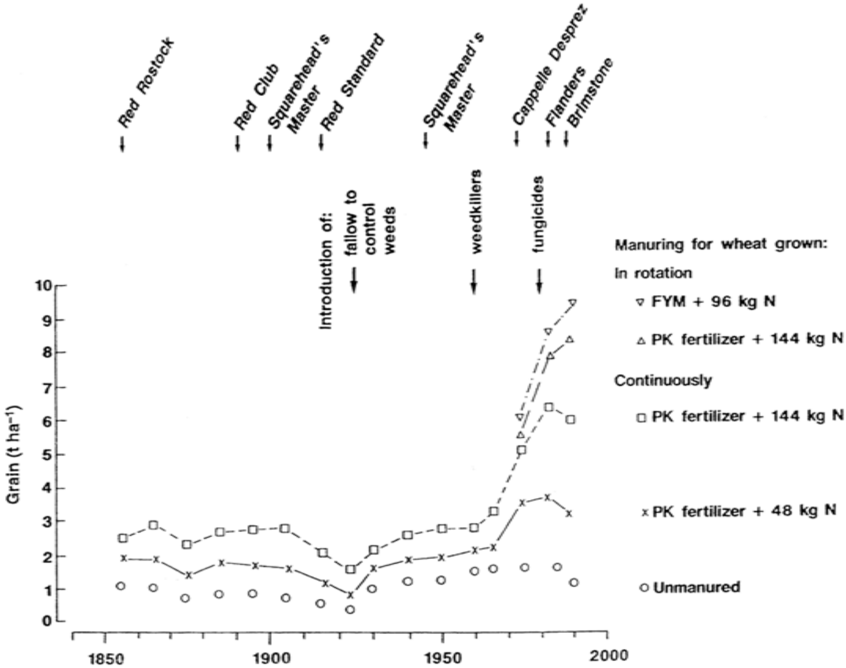


Fig. 7.1. Wheat yields as affected by nutrition, rotation and other agronomic factors (Johnston, 1997).

Nutrient management interacts with other aspects of cereal agronomy as indicated already in this book. Soil conditions and rotations offer positive contributions; so do the selection, timing and efficiency of all operations that lie at the heart of husbandry. There may be advantage in use of growth regulators, as briefly discussed in chapter 3. There must be due prevention or control of the negative aspects – weeds, pests and diseases. In this regard, nutrient management can both exacerbate or alleviate according to circumstances:

- *Weeds*: A competitive, well-established crop, sown at the optimum seed rate for the situation and growing vigourously can outgrow many weeds. However, cereals do not present a particularly competitive canopy. Furthermore, the most troublesome weeds of any crop are closely related species – grass weeds in the case of cereals, such as wild oats (*Avena spp.*) in oat crops – or those which can scramble within the crop, such as cleavers in Europe (*Galium aparine*). The very soil conditions, especially of ample N supply which favour cereal growth also favour many grasses. Nevertheless, by a combination of cultural, rotational and chemical means, weeds can be managed. The weed spectrum reflects and may offer indicator species which can help identify soil nutrient status, an important facet of local knowledge. For instance, in England, spurrey grows in acidic soils, brome grasses in soils of low fertility, cleavers in soils of high fertility, couch in heavier calcareous soils and mayweeds in light sandy soils. The two greatest rules for maintaining soil productivity are: get the nutrients in, and keep the weeds out. Cultivation systems have a huge potential impact on the weed bank in a soil and in either facilitating or denying its activity. Reduced cultivations limit the resurrection of buried weed seeds as well as potentially co-existing with some mulch with previous crop residues (providing that these do not harbour too many pests or else carry over diseases!). On the other hand, zero tillage combined with intensive runs of cereals can develop intractable grass weed problems, such as with blackgrass (*Alopecurus myosuroides*) in many climates – from Europe to N. America, Western Asia and in New Zealand; Bermuda grass (*Cynodon dactylon*) in tropical and subtropical arable land. Some pernicious weeds of cereals perennate by rhizome pieces or other parts and can be spread by soil cultivations and encouraged by nutrient enrichment of cropland e.g. couch (*Elymus repens*) in cooler climates and, in warmer climates, swordgrass or alang-alang (*Imperata cylindrica*) and nutrias (actually a sedge, *Cyperus rotundus*).

- *Pests*: A strategy that deters pests is to establish crops so that they grow through the seedling phase quickly with unimpeded nutrition. However, yield and quality improving strategies including early sowing and diverse rotational cropping may favour pest survival by providing no interruption to their food supply on the field, or else by introducing newly interesting crop residues. Slugs are much more likely to trouble a cereal crop after a legume or oilseed crop than after another cereal. Certain cereals have obvious morphological adaptations which help, such as awns of barley or bearded wheat cultivars which deter bird pests. Early sown, well-fed crops are more susceptible to aphid colonisation, as are those managed for prolonged green leaf area with late N. On the other hand, crops growing poorly may be more readily colonised by comminuting leaf beetles and will be more easily demolished by invasive pest swarms, though any crop is likely to succumb to many such attacks. By making the crop more lush and soft-tissued, there will be a more suitable microclimate for some pests to thrive and such crops need monitoring, though co-existence with most pests rather than attempted chemical annihilation is now deemed the best approach in most situations. It is significant that the return towards integrated approaches to cereal growing was pioneered for pests especially on rice.

Integrated Pest Management (IPM) relies on the use of crop monitoring and cultural field management to:

- Maintain pest populations below the economic threshold of damage.
- Avoid unnecessary use of pesticides.
- Protect natural enemies of the pest such as beneficial insects.
- Protect the environment from habitat and wildlife chain pollution.
- Avoid development of pesticide resistance within pest populations.

- *Diseases*: There is perhaps more specific correlation between disease incidence and cereal quality as well as yield than in the case of pests and weeds, though overall weeds rank as the key thieves of cereal yields and quality. There is also greater scope to select and breed disease resistant cultivars. Crop structure and the consequent type of microclimate within the cereal crop affects the suitability for some diseases. Dwarf HYVs at high density with irrigation and ample fertiliser inputs are especially prone to problems; their breeding makes them inherently responsive to fungicides – or dependent upon them within intensive systems, depending on how one chooses to look at it! For example, UK winter wheat varieties are currently capable of around 2.5 t/ha response to fungicides and the gap between treated and untreated yields is widening during the past decade or more. Humid, dense crops with soft tissues and high sugar contents favour many foliar diseases, such as mildew (*Erysiphe graminis*) when given generous N fertiliser doses. However, FYM tends to give lower incidence and potash is the least likely inorganic fertiliser to favour mildew; on the contrary, some farmers consider it confers some protection from the impacts of cereal diseases by contrast with other N, NP or NPK sources. In Rumania, Kemmler (1983) reports 35% incidence of ear *Fusarium* in irrigated wheat with K fertiliser as against 75% incidence with NP fertiliser. *Fusarium* does not appear to reduce yield much but it can notably affect cereal quality by producing mycotoxins. He also noted that glume blotch (*Septoria nodorum*) can be alleviated by K fertiliser. Many farmers find that stem-based diseases Take-All (*Gaeumannomyces graminis*) and Eyespot (*Cercosporella herpotrichoides*) can be suppressed by good nutrient management and some find that N as calcium cyanamide ($CaCN_2$) appears to help suppress stem-based diseases. Careful crop monitoring should seek to minimise disease by informing better timing of N and other treatments. It is not sense in practice to maximise cereal yield and quality if that is only attainable with unduly high expenditure on fungicides. Organic cereals frequently contain many pathogens but these relatively rarely seem to develop into epidemic levels. Any nutrient shortage, including trace elements, which weakens a crop, predisposes it to other problems, including disease outbreaks. One of the most potentially damaging groups of cereal pathogens are the rust fungi, especially black stem rust (*Puccinia graminis*) which can spread thousands of miles and colonise crops in virtually any rotational context in the many agro-climates where it thrives.

There is a genuine appeal for the vast majority of farmers in a more integrated system of farming - be it fully organic or simply 'more sustainable' - which stresses the positive interdependence of organisms (including humans), which reduces pollution and wastage of energy, and which values long-term land care. To achieve this requires:

- Skill to manage several integrated enterprises synergistically.
- Patience to wait for cumulative rewards.
- Willingness to research/try an appropriate mix of complementary crops.
- Discernment to avoid glib, over-sophisticated or over-expensive advice.
- A positive approach to 'health' (of soils, crops, animals, humans).
- Courage, determination and faith to adopt new cultivation techniques.
- A clear focus on getting nutrients in and keeping weeds out of the system.

Chapter 8 now considers some key aspects of nutrient management practice.

Chapter 8: Fertiliser and Nutrient Management Practice for Small-Grain Cereals

8.1. Desiderata for a nutrient supply programme

The farmer has to choose from different types of fertiliser and manure, varying storage options, alternative handling and application systems. The timing of applications in practice is determined not only by ideal crop requirements but also by feasible soil and weather conditions to travel, except in the rare instances for cereals where aerial application is adopted. Even then, wind levels would affect suitability for application. Farmers also need to monitor the changing relative costs of different alternative sources of each particular nutrient in order to try to predict cost/benefit within their overall cropping enterprise.

A manuring and fertiliser programme needs to:

- *Provide* all essential elements.
- *Start* the crop off well.
- *Sustain* supplies of nutrients through to harvest.
- *Build* up a 'bank deposit' of soil nutrient reserves.
- *Stimulate* beneficial biological activity of both microbes and roots.

Suitable manures and fertiliser materials are those which:

- *Store* well.
- *Spread* easily and accurately.
- *Resist* losses by rapid breakdown, volatilisation and leaching.
- *Leave* soil pH unaffected (unless specifically chosen to change it).
- *Benefit* soil structure and soil moisture-supplying characteristics.

In relation to applying fertilisers, four key questions have to be considered:

- What materials to use?
- How much?
- When?
- How to apply differentially within variable fields by attention to detail?

8.2. Using organic manures

These materials are relatively bulky, slow-release sources of nutrients. Their use is limited or nil on many cereal crops for the following reasons:

- Cartage of large quantities is expensive in fuel, time, equipment and labour.
- Incorporation is difficult or impossible with reduced cultivation systems.
- Supplies are decreasingly coincident with cereal-growing fields.

Nevertheless an ample level of OM is essential in the soil, as its quality and a good rate of turnover must be maintained in the long term. Many cereal farmers do use available manures and substantially reduce fertiliser bills, typically supplying up to two-thirds of cereal nitrogen requirement and most of the other nutrient needs. Light sandy soils will run short of OM unless supplies are replenished. In these soils, organic manures are a valuable adjunct to crop residues as a source of humus which fulfils the roles of nutrient and moisture-retention carried out by clay in heavier land. Where livestock production and cereal growing are integrated within the same farm or occur on adjacent farms, organic manures can be beneficially utilised. In the livestock sector, especially in North America and Europe, livestock manures often become a threatening pollutant rather than a nutrient resource and there has been considerable concern for proper nutrient management plans (Van Donkersgoed, Canada, 2002; MAFF/WOAD, 1998; Bloxham, 1999). The Netherlands has long struggled with intensive livestock effluents and high water tables on level, intensively cropped land. In France, Ingénieries-EAT (1996) collated the main issues affecting various European countries (Table 8.1).

Organic manures have four categories of effects:

Chemical: Previously living matter has acquired all the essential elements for life and thus, potentially, can return them all to the system. It is possible to calculate ample availability of the total nutrients used as NPK fertilisers within human effluents and the manures produced on farms. The problem is balanced composting and distribution which is usually only considered feasible in labour-intensive agriculture. Thus fertilisers have become an indispensable input for cereal crops now. However, Vogtmann *et al*. (1989), Lee (1997) and Baars (2001) outline scope and practice for larger-scale composting.

Physical: BOM affect the physical state of the soil. Humus will improve the structure of lighter soils helping to bind sands and increase their plant-available water-holding capacity. Bulky manures help to open out heavy land.

Biological: Organic manures stimulate beneficial organisms such as earthworms and useful microbes. However, spreading these manures may also disperse weed seeds, parasites and diseases if decomposition is only partial, which is frequently the case.

Economic: Organic manures make mixed farms more self-sufficient and thus less dependent on bought-in fertilisers. It is possible to supply all the requirements except nitrogen for high-yielding cereals from FYM (farmyard manure) or other manures. This can reduce the costs of nutrients used, depending on the system and distances involved in handling the manure. Organic cereal growers depend heavily on organic sources of nutrients along with some slow-release natural rock sources.

Table 8.1. Management of livestock manures in selected EU countries.

Country	Main pollution concern(s)	Storage regulations	Other guidelines	Treatment technologies
Denmark	Nitrate pollution	9 months storage; cover slurry stores	Use green cover crops	Biogas central processing
France	Nitrate pollution	6 months storage	Apply slurries on cereal crops	Aerobic treatment to remove nitrogen
Germany	Nitrate pollution; ammonia emission	6 months storage	Compensation for low yields as a result of lowering nutrient input	Aerobic treatment; central processing
Greece	Odors organic pollution	6 months storage	Reduction of organic load before spreading on land	Anaerobic lagoons
Ireland	Phosphorus pollution of surface waters	6 months storage	Optimize nutrient utilization for grassland	Acidification to reduce ammonia emissions
Italy	Nitrate pollution	4 – 6 months storage; biogas recovery	N maximum application depends on soil type	Aerobic and anaerobic treatments
Netherlands	Ammonia emission phosphorus	6 months storage; cover slurry stores	Mineral bookkeeping balance	Redistribution of manures; central processing
Norway	Nitrate pollution		Fertilising plants	Co-processing (organic mineral fertiliser)
Portugal	Nitrate pollution			Aerobic and anaerobic lagoons
UK	Nitrate pollution odours	4 months England/Wales 6 months Scotland	Codes of good agricultural practice	Odour abatement techniques

Adapted from: lngénieries-EAT, 1996.

FYM taken from cattle yards may typically contain the following amounts per 25 tonnes: 40 kg N, 50 kg P_2O_5, 115 kg K_2O, and 20 kg Mg.

Pig slurry at 6% DM contains around 2.5 kg/m³ of available N, 1.5 kg/m³ of available P_2O_5 and 2.7 kg/m³ of available K_2O.

At 60% DM, poultry manure contains per tonne around 10 kg available N, 25 kg total P_2O_5, 18 kg total K_2O. Regularly applied at around 8 t/ha this can supply all the nutrient requirement of a high yielding cereal crop, and some two-thirds of the N. Therefore, it is of great interest to organic growers of cereals who use it in conjunction with legumes to give the extra N requirement for cereal crops in rotation.

In practice, slurry or manure used as a planned part of the fertiliser policy should be analysed from time to time because its composition varies with:

- Class of livestock producing it.
- Diet of livestock producing it.
- Type and amount of bedding used.
- Period and method of storage used.
- Dilution with rainwater, milking parlour-washings and other water sources.

Maize is particularly responsive to slurry or FYM that may then benefit subsequent small-grain cereal crops. Stubbles before maize also provide a convenient place to spread manure during the earlier part of the year. Vegetable and root crops benefit from the deep cultivations and rich conditions after incorporation of BOM and this is the point in mixed arable rotations when they are most conveniently and strategically applied, rather than to cereal crops directly. However, in Germany, Lorenz & Steffens (1992) reported good responses from slurry N alongside fertiliser N on cereals. Winter wheat given 120 kg slurry N + 90 kg/ha fertiliser N produced 3.74 t/ha extra grain yield, while winter rye gave 3.58 t/ha extra grain from 160 kg/ha slurry N + 60 kg fertiliser N.

There are flowable materials available that are manufactured from organic sources, such as fish offal, coupled with mineral salts. These combine the slower-release properties of organic manures with the ready and tailored availability of most inorganic salts. Sensible management of OM is a necessary base to any sustainable agriculture and a prerequisite of long-term fertiliser policy.

Sewage sludge, including more expensive pelleted forms of it, can well sustain cereal yields not only by its supply of the diverse essential nutrients but also by increasing the water-holding capacity of soils (Al Mustafa *et al.*, 1995). It needs to be screened for metal contamination, notably cadmium, lead and nickel. Furthermore, it can be problematic, especially as a source of tomato and other seeds that may retain viability though passed through the human digestive tract. However, in regions where fertiliser supply is either erratic or prohibitively expensive to poor farmers, proper hygienic management of human excreta as both urine and faeces offers a readily available resource if cultural taboos can be overcome.

8.3. Liming

Before any individual elements are considered it is essential to ensure that the correct pH is attained. The over-riding importance of this factor cannot be over-stressed. The British tendency is towards lower pH, i.e. acidity problems (‘sour’ soils) which are rectified by liming. For cereals the optimum pH is between 6.5 and 7.0. Critical pH level, i.e. below which performance is significantly impaired, is:

5.9	for barley (and maize)
5.5	for wheat and triticale
5.3	for oats
4.9	for rye

To allow for the sampling error it is wise to add 0.2 to each of these to give the lowest acceptable level in practice. It is even wiser to maintain lime status to give the target pH 6.5 to 7.0. This is the setting within which the rest of the fertiliser given will produce the best results. In soils where high pH can be a problem, barley can tolerate up to 8.5 whereas wheat prefers to be below 8, and oats and rye below 7.

Statistics indicate an alarming and steady decline in the use of lime in many countries. Shortfalls in lime use compared with need probably amount to 20% or more.

Lime is lost from the system by:

- *Leaching:* This is obviously related to rainfall amounts but is never less than 250 kg/ha/year of calcium carbonate equivalent and maybe sevenfold this quantity (Strutt, 1970; Russell, 1973).
- *Crop uptake:* Cereals remove about 2 kg of calcium carbonate equivalent per tonne of grain and 6 kg/tonne of straw. Higher yields thus remove more, though straw burning returns calcium.
- *Use of acid-forming fertilisers:* Most nitrogenous fertilisers tend to acidify the soil as pointed out by Strutt (1970). Even ammonium nitrate needs at least the same weight of calcium carbonate (ground chalk or limestone) to neutralise it.

The rule is to lime light soils little and often whilst heavy land needs liming less frequently but with higher doses. Table 8.2 gives an approximate liming guide.

Table 8.2. A guide to lime need in relation to soil type.

Soil type	Lime or calcium carbonate equivalent needed per 0.5 pH rise (kg/ha)
Sandy, light	1,250-1,850
Medium, loams	c. 2,500
Heavy, organic	c. 4,000

Adapted from: Wibberley, 1989.

Obviously the cereal grower must:

- Monitor the need or otherwise for lime by regular pH checks. Note that acid soils can even overlie chalk and limestone. Apart from a pH test, acidity is indicated by the prevalence of certain weeds such as corn spurrey and corn marigold, by sickly crops and by slow decomposition of crop residues.
- Have deficient soils analysed to determine how much lime is needed to rectify the low pH. There is a danger of overliming light soils to the detriment of crops. Whilst barley can tolerate pH 8.5, the other cereals are not suited to this level.

Liming is chiefly a contractor's job in many countries. Many can supply magnesian limestone which not only provides calcium but also replenishes magnesium. The application of a little lime to cereal straw and stubbles assists decomposition. Indeed, the use of nitro-chalk (CAN, or calcium ammonium nitrate) at the equivalent of 10 kg N/tonne of straw is a sensible practice when chopping and ploughing in unless this practice has become the regular straw disposal procedure. This material supplies a little lime as well as nitrogen, both of which promote bacterial activity and hence favour more rapid decomposition of trash.

8.4. Using solid fertilisers

These consist of granular, compacted or prilled materials classified as follows:

- Straights supplying chiefly one major element, for example:

Ammonium nitrate	(34% N)
Calcium ammonium nitrate	(21-23% N)
Urea	(46% N)
Superphosphate	(18-21% P_2O_5)
Triple superphosphate	(45 - 47 % P_2O_5)
Muriate of potash	(60% K_2O)
Sulphate of potash	(48 - 50% K_2O)
Kieserite	(16% Mg)

- Compounds supplying several major elements together, usually N, P and K, for example:

%N	% P_2O_5	% K_2O	
9	24	24	winter cereals
0	20	20	winter cereals
20	10	10	spring cereals
10	25	15	soils of low P index

Many more exist and manufacturers usually supply ample literature. In practice, various combinations of straights and compounds are used. Some larger cereal growers find economies in supplying all nutrients as straights. Most growers find convenience in using compounds for basal (seedbed) dressings and then give nitrogen as 'straight' top-dressings. Big packs and pallet systems have eased handling whilst better wide-spreaders and tramlines have improved accuracy of application on a large scale. Significant amounts of solids may be top-dressed from the air particularly when land conditions remain wet but weather is mild. The cost of doing this is not prohibitive at present: returns from timely application are usually reckoned to offset any extra costs.
Fertiliser blends are now being offered which can be convenient and cost-effective providing ingredients are compatible chemically and in terms of particle size and shape to allow homogeneous spreading. Application costs may thus be saved, though this may not compare favourably with rotational fertilising using 'straights' of P and K every third or fourth season to keep up established good soil indices.

8.5. Using liquid fertilisers

These are aqueous, non-pressurised solutions; only aqueous ammonia is under pressure and must be injected into the soil. They are not the same thing as foliar sprays which are dilute solutions, usually of trace elements, applied as 'first aid' treatments for rapid leaf absorption or in drier weather later in the crop's life, e.g. ear applications for milling wheats. Most nitrogenous solutions contain ammonium nitrate and urea and can give typically 33 - 37 % N. Compounds usually contain ammonium polyphosphates for N and P, plus muriate of potash for K. Solid crystals suspended in liquid fertiliser are used to achieve similar nutrient concentrations to solid compounds, and these require constant agitation to prevent crystal growth.

Advantages of liquid fertilisers:

- Ease of handling (pump, don't hump!). However, one-tonne bags and pallets for solids help them to compete on this point.

- Speed of application has favoured liquids owing to faster filling time and large boom widths still giving accurate application. However, accurate 20 m and wider solid spreaders are now available.
- Flexibility of application. Liquids can be applied from trailed sprayers (which can do other spraying jobs when not in use for this, though they should not be the sole spraying tackle available to a serious cereal grower if timeliness of other treatments is to prevail). They can also be applied from mounted tanks - front, rear or saddle. Narrow-row cereal drills that can normally apply seed only can be converted into combine drills with the liquid application kits available. This gives the advantages of closer fertiliser on poorer soils without reducing work rates since liquid can be quickly pumped whilst seed hoppers are refilled.

Disadvantages of liquids:

- Cost and siting of storage tanks. Tanks can be hired, but they are costly. Whilst filling time is rapid, tractors may have to travel some distance to refill unless one is able to justify several strategically placed smaller tanks.
- Scorch of cereal leaves has been a problem. Some dismiss this and crops scorched prior to stem extension certainly grow out of it surprisingly well. However, no farmer likes to see scorch. The use of dribble bars (tubes to trickle liquid down as larger droplets) or stream jets to give similarly big droplets have reduced, though not eliminated, cases of scorch. Liquid top dressings applied earlier in cold weather can still create problems.
- The cost per kg of nutrient is generally some 5-10% higher than for solid form.
- The concentration of compound liquids cannot be easily made as high as solids. However, owing to the greater bulk density of liquids, the weight of total material to be carried per hectare for an equivalent NPK dose is similar to solids.

The system remains popular with a proportion of larger-scale cereal growers. In the absence of scorch, liquids have not been shown to give any consistent differences in yield performance per kg of nutrient compared with solids. However, for many farms cheaper costs of solids outweigh the use of liquids, as for urea except where solid N applied to dry soils would not give a response (Readman *et al.*, 2002).

8.6. Calculating fertiliser rates

It is very important to be clear about figures used in the calculation of fertiliser rates:

- A 50 kg bag of ammonium nitrate (34 per cent N) contains 17 kg N, thus 3 bags (150 kg) of fertiliser would give 51 kg N.

- A 50 kg bag of 20-10-10 contains 20% N, 10% P_2O_5 and 10% K_2O i.e. 10 kg N, 5 kg P_2O_5 and 5 kg K_2O. Thus to give 100 kg N, 50 kg P_2O_5 and 50 kg K_2O would require 10 bags (500 kg) of fertiliser. It seems very straightforward but it is all too easy to confuse 'bags of fertiliser' and kg of nutrient required! It is better to think in terms of kg of nutrient you intend to apply and then work out the weights needed of the particular forms of fertiliser in which it is to be given, and the total number of bags per field.
- For liquid fertiliser, an 11-11-11 compound, for instance, will provide 55 kg each of N, P_2O_5 and K_2O at 500 litres per hectare; 77 kg/ha of each is given by 700 litres.

8.7. Practical N fertiliser policy

Extra N above the optimum dose *may* depress yields and may increase other costs including extra need for fungicides, growth regulators and greater harvesting and drying costs.

Because N is such a key factor there is the danger of looking to variations in rates and timing of this alone to give magic results irrespective of other factors. In reality a farmer's policy should be based primarily *on judgment* and *opportunity:* it is likely to vary with experience and with season as well as with new N fertilisers, new varieties or more proven methods of prediction which may come. It seems unlikely that a precise formula will be found and farming remains a skilled art. Real policies are likely to allow a margin of safety to ensure enough N is available to meet demand at all crop growth stages.

The actual N dose will be adjusted in practice according to the following factors:

- *Expected crop yield*: prediction based on past experience of that field.
- *Variety*: e.g. HYVs can use more N.
- *Soil type*: heavier soils are more retentive than light sands.
- *Previous cropping*: see SNS section, Chapter 4.
- *Seasonal weather*: e.g. plus or minus 10 per cent if above or below 300-450 mm winter rainfall (1 October - 1 April in UK); extra N late if moisture is available for uptake without detriment.
- *Crop appearance*: which includes such observations as colour, density and progress being made in the crop's development. A crop with yellowing leaves and with the lower ones dying prematurely from the tips is probably short of N. The significance of this for final yield depends on *when* it arises, how long it persists and how much capacity the crop has left for compensation. Certainly, dramatic cosmetic effects can be produced by giving N to yellowed crops! However, not all yellowing is due to N

deficiency, though it is often an associated factor. Sulphur deficiency can look very similar to N shortage symptoms in cereals. However, if a thin crop is struggling, the only obvious thing a farmer can do in most cases is to give a little N (analogous to a little glucose for an ailing child). If it is behind in development and/or at a stage when the needed tillers could be lost or grain sites fail to be set, then adequate N must be ensured. Thus crop appearance is more a guide to timing than the amount of N to be used; but a treatment in response to crop appearance could well boost the total N used for the crop beyond a planned level.

- *Interactions*: Yield responses to N depend on a willingness to support the extra ensuing growth with fungicides and growth regulators if necessary. If irrigation is possible then there is positive interaction with N.
- *Cost*: The relative kg cost of N and price/kg received for the particular cereal clearly determines the economic optimum N dose. Hitherto the economic optimum dose has almost coincided with the technical optimum needed to maximise yield in most cereal systems.

National advisory services give N recommendations (see Chapter 4). Commercial fertiliser companies have sought to incorporate other considerations of crop management into computerised advice ‘packages’ known as ‘balance sheet’ approaches to N advice. Universities have devised computer models to guide advice such as WHEATMAN Decision Support System for wheat growers in NE Australia (Hayman & Easdown, 2002). In practice, the weather and the farmer’s own judgement may prevail in deciding what actually happens.

In practice, with current varieties in high-yielding systems, up to the total doses shown in Table 8.3 may be used to good effect.

The rate of N use on winter wheat increased dramatically, especially during the 1980s in Western Europe and North America. Rates are now climbing elsewhere. This is due partly to increased yield expectations and partly to the fact that wheat is much more often grown in mainly cereal rotations now. In general the use of N on spring barley is overcautious, no doubt because of bad experiences in the past with lodging in the absence of any means to control it. Certainly spring barley follows a wider range of crops and manurial residues than any other cereal in the UK and some caution is necessary. However, there is fair potential in this crop if high-yielding newer varieties are planted early and densely enough and fed optimally. N treatments should be completed early for malting barleys - by early April in England.

Table 8.3. Typical maximum rates of N for most high yielding cereal crops.

	kg/ha of nitrogen	
Winter wheat	200	+50 -70 late on quality varieties if ample moisture
Spring wheat	175	+35 late if ample moisture
Winter barley	175	
Spring barley	150-175	Caution above 120 for malting even on HYVs
Oats	130	
Rye	130	
Triticale	160	

Adapted from: Wibberley, 1989.

It cannot be overstressed that N use alone cannot compensate for other gross yield restrictions and surplus N fertiliser will be wasted and even positively harmful in unresponsive situations. However, when higher yields are being consistently harvested owing to ample N as part of good general husbandry, then soil N reserves will also be incidentally built up.

Timing of N

Attempts to time N dose to internal development stage are often overridden by seasonal variation but the quantity available needs to match crop demand at all times. The problem lies in the ready solubility of fertiliser N used. Progress with controlled-release forms of N is slow. However, urea is available in formulations treated with sulphur or with resins or as urea-formaldehyde or as isobutylidene-di-urea (IBDU). Commercial products such as *Didin* and *Alzone* may reduce total N need by up to 10 per cent through slower release and eliminate the need for at least one extra separate top dressing. The principal form of N used is still ammonium nitrate that is not only readily available to the crop soon after application but also vulnerable to leaching and it induces soil acidification. Leaching rate depends on:

- Rainfall receipts surplus to transpiration plus any existing SMD.
- Soil type: the clay-humus complex can hold ammonium whilst there is some limited retention of nitrate within pores of crumb-type soil aggregates. In UK, the maximum percentage of applied N likely to be leached over winter is 20%.

The significance of leaching therefore is greatest:

- Over winter.
- On lighter soils, especially sandy land.

- Where root volume and depth are limiting the capacity of the cereal crop to recover percolating nitrates. To some extent, roots will seek to develop in search of a moving nitrate-rich solution.

Owing to the risk of leaching, some farmers, especially in Germany, have tried to ‘spoon feed’ cereal crops with frequent small doses of N fertiliser. Whilst this may be technically logical, it is neither economically nor practically feasible to carry out many individual dressings. The number of splits of the total N application will depend on the system. When making split dressings some growers like to add a little of other elements, especially K, e.g. using a 25-0-16 or 29-5-5 solid or an N + K liquid.

8.8. N timing – a UK case study

For autumn cereals, from time of sowing to the middle of February it is not wise to apply more than a total of about 40 kg N/ha (some 25% of the total dose for the crop); many growers do not exceed 25 kg N during this period. However, winter barley is likely to take in N more voraciously than winter wheat over this time. Reasons for suggesting these limits are leaching and the limited capacity of crops to absorb N until springtime. The case for more frequent rather than single or no doses of N over the period from sowing to the end of February is greatest when:

- High total N rates are planned owing to yield potential of early sown crops.
- Crop establishment is disappointing, in which case two doses of some 15 kg N may be given as the only action possible at that stage which might help a crop.

Early springtime is the period for the majority of N to be given, to coincide with stem extension during the crop’s exponential growth phase.

Seedbed N for autumn cereals

Up to 25 kg N/ha may be given in the seedbed. None is needed when:

- Richer N residues from previous crops are present.
- Sowing takes place early when soil temperature thus N mineralisation rate is higher.
- Time is pressing to get sowing done and omission of fertiliser will hasten the job.

Retaining the N dose until a little later in autumn gives greater management control - some fields may need more encouraging, some none at all. Nevertheless, some farmers like to use seedbed N, justifying it as follows:

- The job is over and done with, perhaps, for the autumn.
- It is an insurance that is beneficial on poorer soils and may show a benefit on better land in some seasons for modest cost.

- It has never been shown to be detrimental to the crop at around 25 kg/ha.

Later autumn N

Especially where no seedbed N has been used, a dose of 30-40 kgN/ha is likely to be given at any time from late October to December, according to opportunity (i.e. no other work, mild but not wet weather or on a frosted field which allows traffic). High-yielding crops may be given two autumn doses (e.g. 15 kg seedbed plus up to 25 kg in November) or similar doses in October and December. Such double dosing is favoured by:

- The existence of tramlines.
- Wide-spreaders.
- Specialised cereal systems where it is used as an opportunity to inspect crops.

Early new year N

Again, backward and very forward crops are more likely to attract attention at this time than are average crops. Crops may receive 15 kg N/ha in January or 35 kg N/ha between mid and late February. Such dressings are particularly appropriate on shallower soils with early-drilled crops (especially winter barley). An important argument in favour of such early new year dressings is one of taking advantage of an opportunity when it is offered. Having made these dressings, one is less anxious about the date of achieving the next (often substantial) dose. It is a fact that in many districts and seasons, March is characterised by few travelling days. Thus unless one is prepared to give N from the air in March, one may be unable to apply any at all. The same applies to a lesser extent to April. Therefore, apart from direct (and certainly cosmetic) effects in early New Year, dressings at this time are an insurance rendering the date of the next application less critical. Crops that are earlier-drilled and therefore deeper-rooted into warmer soils are more likely to respond to N over winter. A thin, backward crop may be aided in tiller survival by small N dressings over winter.

It is important to have some early dressing for high yields, but not before February (by GS 25 for winter barley especially).

Main spring N top-dressing

This may be given any time during the period late March to late April/early May, depending on:

- How much N has recently been applied to the crop.
- How early the season is: in a wet March a lot of N may leach *if* a large dose is given early so farmers need to defer applications in such seasons.

- What the weather allows.

On forward crops receiving a high total N dose, this main dressing may be split one-third/two-thirds between late February/early March and late March/early April (i.e. at GS 31 and GS 32), or even in three lots, perhaps equal or 1:2:1. In general for logistic as well as risk-minimisation reasons, it is not advisable to apply much more than 100 kg N/ha in a single dose (with current fertiliser materials).

Mid-April is a suitable time for winter barley to receive its main N dressing (i.e. by GS 31), whilst wheat may be sensibly dosed from then to early May depending on district and its own advancement. Where wheat has been drilled straight after barley, many growers would give N dressings in the same order, quite closely as opportunity allows. Too much N early in this period encourages excessive tiller survival in thick crops and soft straw growth, as well as higher disease incidence.

For malting varieties of winter barley it is important not to restrict total N dose, which should relate to yield potential, and to complete all top dressing early, ideally by the end of March to avoid prohibitive N levels in the grain (i.e. complete by GS 30).

For low-yielding winter cereal crops or low total requirements owing to high SNS (soil index), all the spring N may be given in a single dose in March/April.

Later N

In conditions of ample moisture supply, crops may respond to a late dressing of N (late May/early June at GS 37). This can boost grain protein content. The importance of this may be marginal for feed barleys but could be of significant value for quality wheats sold on protein level. There is no evidence to suggest that doses greater than 50 kg N/ha are worthwhile at this stage; 35 kg N may be enough. Response in any event is related to ample moisture for uptake. This late dose should be in addition to the earlier yield-building N doses; it is not a partial substitute for them. Urea is suitable before green leaf is lost and two or three 15 kg N doses have proved useful, though the economics of this treatment are likely to be marginal and only worthwhile if protein level is pushed up into a premium price category.

For spring cereals, timing of nitrogen is more straightforward than with autumn-sown cereals. This is partly because crops have a compressed period of growth and partly because the risk of leaching is reduced or even eliminated for later sown spring crops. To try to encourage rapid rooting, some farmers broadcast their N ahead of sowing so that it has moved into the soil profile.

At the total levels now beneficial on high-yielding spring cereals, many growers like to split the N dose into two, even for later sown crops. This is for two reasons - logistics of application and fear of possible harm if too much N is available in the soil at once. For this latter reason, many do not favour combine drilling of high fertiliser rates for spring cereals. With spring wheat, a late bonus N dose for grain protein could be worthwhile on a good crop in a moist season. However, spring wheat varieties are generally superior to winter ones in protein.

In all countries, farmers are urged to use N fertilisers responsibly and avoid nitrate pollution of water caused by excessive or untimely applications, or by leaving fertile land fallow too long.

8.9. Phosphate and potash manuring practice

Both these nutrients may be given less often than annually on rich soils where they are well supplied already. They may not be given directly to cereals but preferentially applied to more demanding crops which may be in the rotation, such as potatoes.

Since P is relatively insoluble, it is often not appreciated that care has to be taken with phosphorus fertilisers to avoid excess as well as deficiency. Edwards & Withers (1998) report the average surplus under cereals in Europe to be equivalent to 12 kg/ha/year of P_2O_5 and this can lead to eutrophication in nearby watercourses. However, the earlier discussion, especially of chapters 4 and 6, has indicated the importance of proper attention to these nutrients in more usual cereal cropping contexts. When planting of winter wheat is delayed on soils of low to very low P, seed applied P (at up to 33 kg/ha) performed better than band-knifed phosphate (Sander & Eghball, 1999).

Even in the UK, during the decade from 1984-94, P and K balances (inputs minus off-takes) were kept positive but they have become negative during the decade 1994-2004 (Armstrong, 2004). Many cereal crops are not receiving any potash fertiliser. The British Survey of Fertiliser Practice (Chalmers *et al*., 2002) showed that 43% of winter wheat, 59% of spring wheat, 25% of winter barley and 31% of spring barley crops did not receive any K fertiliser. Of course, this may be compensated by rotational K applications to other, more demanding crops in some cases, yet 37% of winter oilseed rape and 6% of potato crops received no potash either. Soil K reserves may be deemed adequate on some fields, but more than 20% of UK cereal land is reckoned to be below soil index 2 for potash and less than 25% is reckoned to be at index 3 or more. By contrast, over half of UK arable land is reckoned to be at index 3 or more for available phosphorus. Since many farmers apply P and K together in compounds of particular composition, it may well be that the proportion of K contained is not high enough. The solution is to apply each as straights separately in higher doses (in order not to increase the number of passes during a rotation) or else to select better balanced compounds or blends. In order to maintain soil reserves of

P and K at the rate of removal by cereal crops, compounds or blends with the following ratios of P_2O_5:K_2O should be chosen: all cereals grain only = 1.4:1; winter cereals, grain+straw removed = 1:1.3; spring cereals, grain+straw removed = 1:1.6; oats, grain+straw removed = 1:2 (*adapted from*: PDA).

Recommended P and K fertiliser application thus varies especially with:

- Expected crop yield (t/ha).
- Whether or not straw is removed from the field as well as grain.
- Existing soil index.

For example, oats or triticale grown at soil index 1 for P and 1 for K, and yielding 5 t/ha of grain with straw removed also will need 5 x 8.8 + 25 = 69 kg/ha of P_2O_5 and 5 x 17.3 + 25 = 111 kg/ha of K_2O (see Tables 4.3 & 4.5, chapter 4). K_2O as muriate is generally about half the price of N and of P_2O_5 per kilogram (depending on chemical sources and purchasing arrangements).

8.10. Permitted practice for organic farming

In some countries, there is an established market not simply for sustainably produced food but there are legally defined standards for organic products (e.g. in the UK via UKROF – UK Register of Organic Food Standards - and *The Soil Association*). It is then important for farmers to avoid forbidden products. The criteria for disqualification of materials for organic farming are chiefly ‘too high solubility’ and ‘contamination with pollutants’. Thus manufactured compounds, blends, liquid and suspension fertilisers are excluded, as well as industrial by-products such as fibrophos (from poultry litter), and any manures from intensively farmed livestock. Potash fertilisers are subject to different certificates and in some countries are approved for organic farming.

In order to enrich soil with nutrients, organic farmers have to rely more on crop rotations, usually but not always with livestock within the system, coupled with inputs of permitted nutrient sources. Permitted sources include manures from extensively-farmed livestock (not necessarily themselves farmed organically), composts, seaweed products, straw and other plant residues, wood-ash, slow-release rocks including rock phosphate and stone meal (for potash, including Adularian shale feldspar from Scotland which contains around 10% K_2O). Other crude salts are permitted in cases of need such as kieserite (for magnesium), and sulphate of potash.

8.11. Precision farming

Precision farming aims to adjust applications of fertiliser nutrients, especially nitrogen (or other inputs – such as herbicides for weed patches) to take account of variations in crop need across a field. Substantial variations in soil fertility can occur from place to place within a field, especially when fields are enlarged by eliminating hedgerows which formerly marked boundary changes of soil type. Godwin *et al.* (2002) reported the results of five years of research co-ordinated by Cranfield University, UK, where they used aerial digital photography to measure shoot density and green leaf area of crops as a guide to nitrogen fertiliser policy and its adjustment within a variable crop. Soils can be mapped also, using EMI (Electro-Magnetic Induction) equipment. Much precision farming is based on sophisticated electronic technology to map within-crop yield variations (the results of field variations) as measured through GPS (global positioning system) equipment on the combine harvester and is thus suited for large mechanised farming systems. However, the principles can be and sometimes are applied by any farmer even using a hand hoe but knowing the variations by observation, experience and recording. Matthews & Cosser (1997) reported major influence of within-field variations in soil depth on yield, particularly in dry years and precision farming giving a saving of up to 25% of fertiliser input. Through precision farming, not only may fertiliser cost be saved (though account must be taken of the cost of the electronic monitoring kit!) but also the environment is protected from excessive applications on parts of a field which do not need it. Nevertheless, there is no electronic substitute for direct field inspection.

It is important that fertiliser spreaders should be correctly calibrated and regularly checked for blockages and other faults that make them a potential source of variation in nutrient application. Farmer group members may share calibration equipment and use it to prepare their fertiliser distributors before the growing season. Liquid fertilisers are easier to apply more uniformly than solids and more logically fit a precision farming approach.

8.12. Micronutrient fertilisers for cereals

Where specific trace elements (micronutrients) are needed, they may be given by alternative methods as shown in Table 8.4. In some cases, chelated formulations are used for ‘first aid’ treatments (such as EDTA for foliar applications of copper, iron or manganese; EDDHA for soil applied iron).

8.13. Fertiliser practice – a checklist

Good fertiliser practice requires:

- Regular soil testing (annually for N; every 3rd to 5th year for pH, P, K, Mg).
- Well-managed nutrient cycling through suitable rotations.
- Utilisation of available organic manures taking full account of their nutrients.
- Calculating requirements for each crop using intelligent local field records.

- Calibrate fertiliser application equipment properly.
- Use field monitoring to adjust rates according to soil variations.
- Monitor salinity when irrigating, especially with fertigation.
- Safe fertiliser storage.
- Purchasing fertiliser at the right time and price.

Table 8.4. Trace elements and application methods for wheat and other cereals.

Element	Source	Broadcast (kg/ha)	Band-placed (kg/ha)	Foliar (kg/ha)
Boron	Sodium tetraborate	0.6-1.2	-	'solubor'
Copper	Copper sulphate	4-15	1-4.5	0.1-0.5
Iron	Ferrous sulphate	-	-	5-10
Manganese	Manganous sulphate	20-130	6-11	0.5-2
Molybdenum	Sodium molybdate	0.07-0.2	-	0.1-0.15
Zinc	Zinc sulphate	5-20	3-5	0.015-0.25

Adapted from: Katyal & Friesen, 1988.

Note: Molybdenum can be given as part of seed dressing in known deficient areas.

8.14. Farmers' study groups for cereal management

All farmers have faced the challenge of business survival in recent years and need to assess all their farms' assets as potential resources for improved management in order to gain a sustainable livelihood. All over the world, farmers prefer to learn from other farmers (practitioners of any kind prefer to learn from other practitioners). Therefore, enable this by studying together in practically focused groups – *FARMS Groups.* A farmer-chosen agenda provides suitable opportunity for this and for trust to grow without which any sort of collaborative business co-operation cannot work. Such future collaboration may be in the interests of group members but they must decide if this is to be so after they have come to know and trust each other - which happens most naturally during learning together in the field.

Groups need to meet on each other's farms at least say ten times a year, maybe more often in the more communal cultures of Asia and Africa. They need to be chaired by a farmer, to invite specialists (technical, extension and commercial) on farmers' terms and to try to take food together to facilitate enjoyment of the learning and sharing process which encourages the development of friendship and trust. Such group work harnesses farmers' experience to generate suitable technology (Rhoades & Booth, 1982) and can lead to collaborative research (Barling, 1980; Wibberley 1984b, Jordan & Stinchcombe, 1986; Jenkinson & Wibberley, 1986; Carver, 2000). This Farmer-Dominant Study Group (FDSG) approach has long been monitored and proven beneficial in practice in a cereal management context (Wibberley, 1984b, 1988, 1993, 1997).

8.15. Cereal nutrient management policy summarised

Sustainable farming in any country requires farmers who will:

- Maximise the capture and recycling of available nutrient sources.
- Optimise rather than necessarily maximise yields.
- Return to a policy of maximising first wheats (thus eschewing longer cereal runs and rediscovering rotations).
- Adopt rotational manuring to suit crops and to reduce application costs.
- Adopt rotational deeper cultivations or subsoiling rather than overcultivating every year (adhering as nearly as possibly to zero-tillage or CF where feasible in drylands).
- Maintain control of their fixed (overhead) costs.
- Especially in family farming, prioritise household and local food security.

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- Department for International Development (DFID) www.dfid.gov.uk
- Food & Agriculture Organisation of the UN www.fao.org
- Home-Grown Cereals Authority (UK) www.hgca.com
- International Federation of Organic Agriculture Movements www.ifoam.org
- International Fertilizer Industry Association www.fertilizer.org
- International Food Policy Research Institute www.ifpri.cgiar.org
- International Institute for Environment & Development www.iied.org
- International Potash Institute www.ipipotash.org
- Organic Agriculture Worldwide www.soel.de/oekolandbau/weltweit.html
- Potash Development Association (PDA) www.pda.org.uk/

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Glossary of Acronyms

Fertilising small-grain cereals for sustainable yield and high quality

ASEAN	Association of South-East Asian Nations
ATP	Adenosine triphosphate
BCSR	Base cation saturation ratio
BOM	Bulky organic manures
BSN	Basal stem nitrate
CCC	Chloro-choline chloride (a PGR)
CEC	Cation exchange capacity
CF	Conservation farming (reduced tillage with disciplined agronomy)
CFC	Chloro-fluoro-carbon
CGIAR	Consultative Group on International Agricultural Research
CGR	Crop growth rate
CIMMYT	International Centre for Improvement of Maize and Wheat (Mexico)
CP	Crude protein
DM	Dry matter
FAO	Food and Agriculture Organisation of the United Nations (UN)
FARMS	Farm Asset Resource Management Study (groups of farmers)
FMA	Fertiliser Manufacturers' Association
FYM	Farmyard manure
GM	Genetically-modified
GS	Growth stage
HFN	Hagberg Falling Number
HGCA	Home Grown Cereals Authority (levy-funded by British farmers)

HLW	Hectolitre weight (kg grain per 100 litres volume)
HYV	High-yielding variety
IACR	Institute of Arable Crops Research (UK)
IFOAM	International Federation of Organic Agriculture Movements
IFPRI	International Food Policy Research Institute
IFS	The International Fertiliser Society
IPI	International Potash Institute
IPM	Integrated pest management
ITK	Indigenous technical knowledge
LAD	Leaf area duration
LAI	Leaf area index
mc	moisture content
NAR	Net assimilation rate
NPK	Nitrogen, phosphorus & potassium-containing compound fertiliser
OM	Organic matter
PDA	Potash Development Association (UK)
PGR	Plant growth regulator
SMD	Soil moisture deficit
SMN	Soil mineral nitrogen
SNS	Soil nitrogen supply
TGW	Thousand grain weight
TNC	Trans-National Corporation
USDA	United States Department of Agriculture
WTO	World Trade Organisation

Appendix 1: Some Nutrient Deficiency Symptoms of Cereals

Nitrogen deficiency in cereals

Potassium deficiency in wheat

Phosphorus deficiency in wheat

Magnesium deficiency
in wheat

Calcium deficiency in oat

Manganese deficiency
in wheat

Copper deficiency in barley

Source: K+S KALI GmbH

Appendix 2: Cereals, Nutrients and Soils

Cereals

(Photograph:The Author)

Two-row winter barley ear
(awn primordium stage)

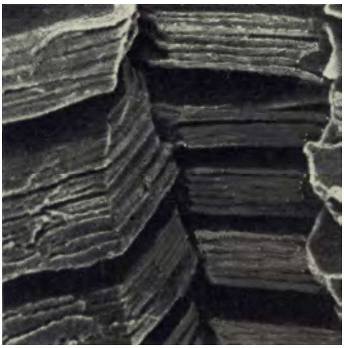
Nutrients

(IPI)

Various rock sources of potash

Soils

(IPI)



Clay plates in a soil of high
K-fixation capacity