Nutrient and micro-nutrient requirements of cereals

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Abstract

The theoretical relationships of yield and nutrient content are discussed. Concentrations of nitrogen and other elements in cereals are controlled, by mechanisms which are not yet understood, acting on uptake rates in relation to growth. The concentration of nitrogen in grain is affected by crop size and by nitrogen supply rates, as is that of some trace elements.

Supply of nitrogen from soil is as mineral N only, and the amounts of this available to the crop may vary widely. It is now becoming possible to measure or predict these. Current fertilizer rates for the major nutrients are compared with average and maximum offtake rates. The efficiency of use of fertilizers by the crop is considered.

Introduction

This paper aims to discuss the quantity of nutrients required by a cereal crop for maximum yield and quality, in relation to that which is supplied. The amount contained in a crop varies with its stage of development, and the rate of uptake at different times is important. The amount contained at harvest (or at the time of maximum content, if this occurs earlier) depends upon the total dry matter and upon the mean concentration in the tissues. As different tissues may vary in their nutrient concentrations, and as nutrients are re-circulated or transferred from one type of tissue to another, the concept of a "mean concentration" is not very realistic, but it is helpful in discussion.

The idealised relationship of nutrient supply, total dry matter and grain yield, percentage composition and total nutrient content is in Figure 1. With increasing external supply of a nutrient (the actual levels will vary with the external system used and the levels of other nutrients) the dry matter yield will increase smoothly to a maximum. The percentage composition will increase similarly, but continues to rise up to much higher levels of nutrient supply than does dry matter. On occasions a negative slope is found when the plant or crop is very deficient (the Steenbjerg effect) but this is usually of only academic importance. The total nutrient content in the crop is the product of these two curves, and this will continue to increase to well beyond the point of maximum dry matter yield.

The harvested grain is more important than total dry matter, and this also responds to the nutrient supply in a rather different way. In extreme deficiency, such as occurs infrequently in developed countries, the ratio of grain to dry matter (the harvest index) may be very low—in the extreme, no seed is set at all. The harvest index rapidly increases with nutrient supply, reaches a maximum, and then may or may not decline, depending upon the nutrient. If this is nitrogen, the amount of foliage will continue to increase long after the grain weight has reached a maximum. In the limit, an excessive nutrient supply can decrease both grain weight and even dry matter. Excess nitrogen causes lodging, too much phosphorus can be toxic, and any salt in excess can cause damage to seedlings in soil.

The percentage composition has been presented here simply as an accompanying factor to increasing yield, which also determines the total nutrient demand. In addition, it can have considerable effects on crop quality. In cereals, this is mainly a question of the level of N, or protein, in the grain, but other elements cannot be ignored entirely.

These varied effects need to be manipulated as accurately as possible, to give us the yield and quality aimed at, with minimum cost.

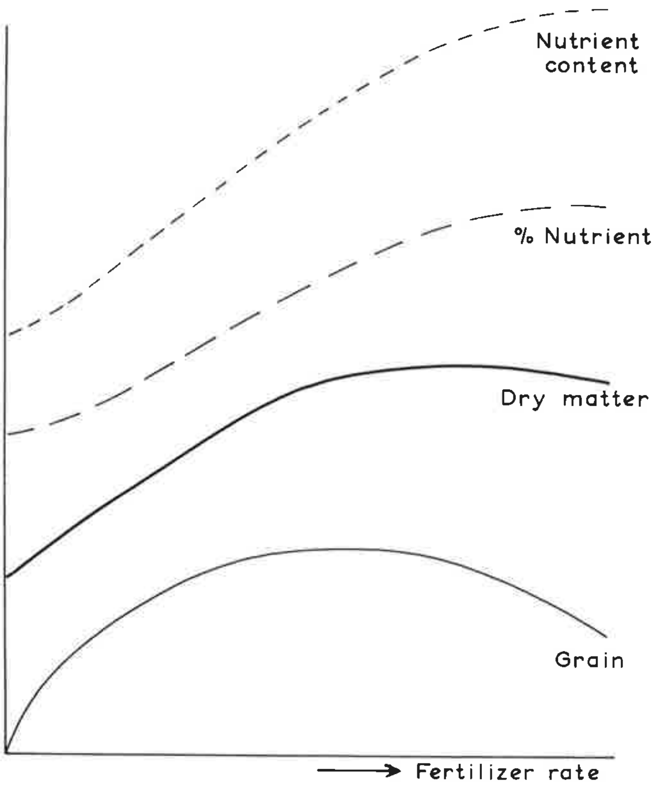

Fig. 1. General effects of fertilizer rate on dry matter yield, grain yield, percentage nutrient in plant, and total nutrient content.

Concentration in tissues

The nutrient concentration varies with time and stage of plant development, with plant part or organ, and with environmental conditions. Indeed, the remarkable thing is that plants manage to maintain as constant a concentration as they do. Thus available nitrogen, phosphorus or potassium concentrations in different soils may vary by factors of up to perhaps 100, but concentrations in plants grown on them will generally vary by at most a factor of 5. In fact the control is even better than implied by this, because these concentrations are expressed on the basis of dry matter. If instead, they are expressed in relation to the water in the tissue, the concentration of some elements can be quite remarkably constant, and is held within a factor of 2 or better (Leigh and Johnston, 1983) (Fig. 2). The implication of this is that much of the difference between the concentrations of a nutrient in a healthy and a deficient crop are due to differences in the percentage of dry matter in the tissues, and the factors controlling tissue hydration in relation to nutrient supply seem to need more investigation. If plants are unable to maintain their concentrations within these narrow limits, growth rate will be reduced. We have almost no idea of how this control over concentration is enforced, and it is one of the remaining major uncertainties in our understanding of plant functions.

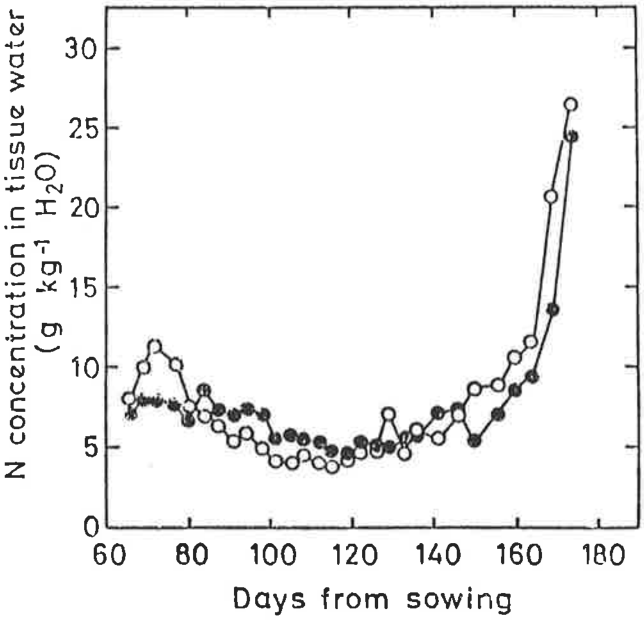

Fig. 2. Nitrogen concentration expressed in relation to tissue water of barley, receiving 48 kg N ha^{-1} + FYM (yield 6.1 t grain ha^{-1}) or no N (yield 1.0 t grain ha^{-1}) (Leigh & Johnston, in press).

Our lack of understanding of this system of control makes any exact modification of crop composition difficult. We are reduced to either adding more of a given nutrient, and hoping that a little more will be taken up, or to using plant breeding to alter plant composition, when this affects crop quality (Pushman and Bingham, 1976).

The most obvious aspect of crop quality in cereals is the percentage of nitrogen in the grain. Plant breeding and selection has given a range of wheats and barleys which differ in %N to dry matter. On top of this is superimposed a range of variation resulting from fertilizer rate, soil supply of N, and climate. As a rough generalization, anything which tends to increase yield also tends to decrease %N, which is usually described as a "dilution effect". These relationships are best explained by graphs as used by Benzian *et al* (1983) (Fig. 3 & 4), which show the *general* inverse relation of yield and %N well. The high %N obtained in very dry years or areas is largely due to this effect.

When the change is produced by the addition of more nitrogen, the inverse relationship of %N and grain yield is reversed. In Figure 4 ~~3~~ are shown results from some recent very high-yielding trials. Whereas the points representing the same rate of N in different trials are very roughly inversely related, the slope of the line representing different rates of N in a single trial is positive. In most cases the increase in total content of N is due in part to both change in yield and change in %N, but this can vary widely. Thus, at Maulden in 1980 %N increased, with little change in yield, but at Saxmundham in 1981 most of the increased uptake of N was due to the increase in yield of grain.

Figure 4 ~~3~~ includes the "envelope curve" established in earlier work on the basis of Rothamsted results over 20 years up to 1973, in which all data points fell within this limit. It is obvious from this recent work that the original envelope curve has now been decisively breached. However, the big change is in the total grain yield; in terms of N in the grain, the difference between the old envelope curve and the highest value found in these trials is only some 20 kg ha^{-1}.

The corresponding figure, but for *un*sprayed plots in the same trials is also shown (Fig. 3 ~~4~~). The omission of fungicides has caused a much sharper break in all the response curves, so that %N has been increased or not changed, whereas the maximum yield is always less.

Whether additional N is supplied as extra soil N (e.g. after ploughing up grassland) or a fertilizer, the scope for altering %N in grain is limited. Benzian & Lane (1982) examined effects on %N in a large number of experiments, and found that the largest was that due to preceding crops of lucerne or a grass clover ley. On average, the later fertilizer nitrogen was applied, the more effective it was in increasing nitrogen concentration. Attempts have been made to increase the %N in the grain by the late application of foliar sprays of fertilizer such as urea (Pushman & Bingham, 1976). Penny *et al* (1983) found that two late sprays totalling 50 kg N ha^{-1} on average increased the N concentration by 0.23%.

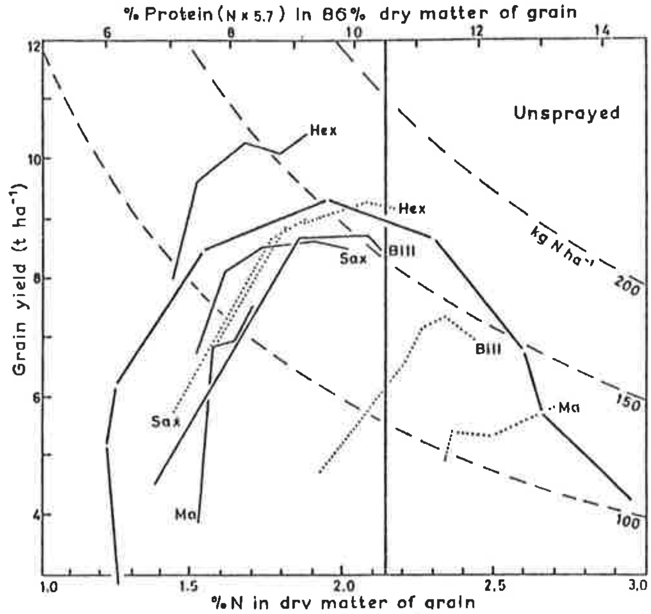

Fig. 3. Relation of %N and grain yield for several unsprayed *Rothamsted experiments in 1980 (– – –) or 1981 (——). Results for plots ~~sprayed~~ with fungicides. See text for details. (Benzian* et al, *1983).*

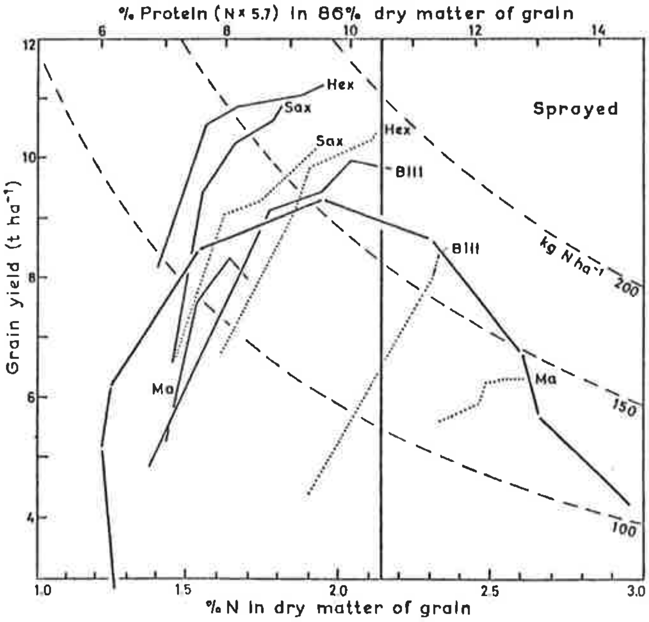

Fig. 4. Relationship of %N and grain yield for several Rothamsted experiments in 1980 (– –) or 1981 (——). Results for plots [redacted]*treated with fungicides. See text for details. (Benzian* et al, *1983).*

Trace element composition has received rather little attention so far. There has been much interest in sulphur, though this can scarcely be regarded as a micronutrient. The content of metals in the tissue can also vary quite considerably (Welch & Cary, 1975) and this may need more attention at a time when public concern over the distribution of heavy metals in the environment is rising. We are following the concentration of a range of elements in some of our highest-yielding crops, to see whether there is any tendency to internal dilution. So far, this does not seem to be happening except on light soils (McGrath, private communication) and in some cases levels of zinc and iron actually increase with nitrogen level and yield (Fig. 5 & 6).

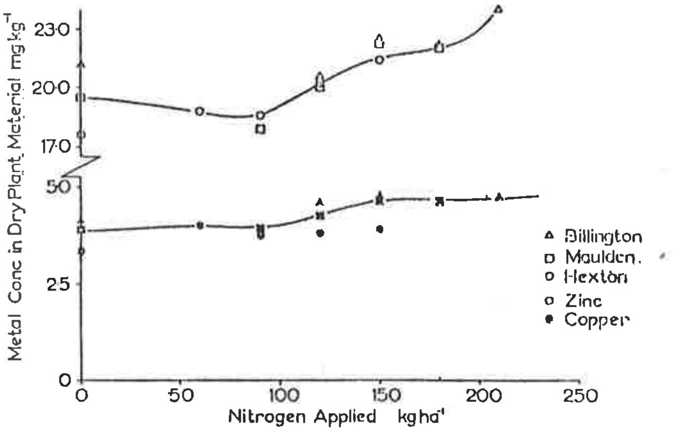

Fig. 5. Zinc and copper in winter wheat grain from three experiments, in relation to nitrogen application. (McGrath, private communication).

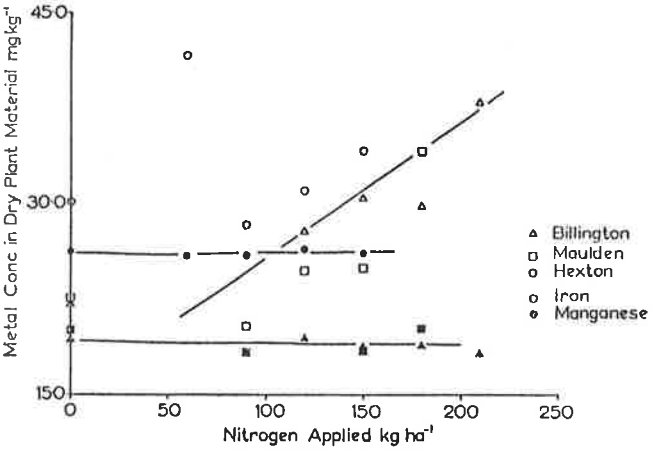

Fig. 6. Iron and manganese in winter wheat grain from three experiments in relation to nitrogen application. (McGrath, private communication).

Uptake rates

For a winter cereal, uptake rates of nutrients are slow at first (Fig. 7). The accumulation of N by the spring can be 10–60 kg N ha^{-1} depending upon the size of the crop, and this can be an important aspect of saving naturally present soil N, which otherwise would be leached out during winter. In April, the uptake rate accelerates sharply, as the crop enters the phase of rapid linear growth. In this stage, uptake rates for a large crop will be around 2 kg N ha^{-1} d^{-1}, with corresponding values for other nutrients. This is not a particularly large value: some leafy vegetables, or rapidly growing crops such as maize in warmer climates can require 4–5 kg N ha^{-1} d^{-1}.

We are only just beginning to get some idea of whether soil conditions can limit these rates and hence crop growth. As long as the soil profile is moist, and there is adequate nitrate-N present, there should be no restriction on uptake of N. Cereal root systems are extensive and for winter wheat, they are well formed before the rapid uptake phase in spring. Very great differences can be caused by date of sowing, but in normal circumstances it seems unlikely that lack of root length or poor distribution would cause problems. However, there is the possibility of special conditions. Firstly, if the topsoil dries out rapidly, the subsoil nutrients and root length may be inadequate. Secondly, the effect of root disease cannot be neglected. The action of the take-all fungus (*Gaumannomyces graminis*) is, in effect, to destroy part of the wheat root system, and the questions raised here should be considered carefully in the context of root disease. The conclusion is not always clear, however. If the attack is moderate, so that the root system is less efficient, then more nitrogen or earlier nitrogen may be valuable, but if the attack is so severe that crop size is greatly diminished, then less nitrogen in total may be required (Dilz *et al*, 1982). Thirdly, mechanical impedance to root growth by soil pans can have an analogous effect. We have examples in which the root system is largely confined to the topsoil by pans, especially early in the season, though the total length is not reduced. If this zone remains moist, we find that the crop does not suffer, but it is vulnerable to dry spells.

Root systems of cereals are fairly lengthy. Thus Nye & Tinker (1977, Table 8.2) list values of around 100 cm cm^{-2} (length of root per unit surface of land) for maize, barley and spring wheat when near maturity. Whilst this appears to be exceeded by some forage crops, it is a considerable length in relation to many herbs and tree crops. This value equals 10 km m^{-2}, and since this table was compiled, even larger values have been found. Gregory *et al* (1979) reported up to over 30 km m^{-2} for winter wheat. Even longer lengths were found by Barraclough (1982), who studied the differences between root systems of winter wheat sown early and sown late, the maximum lengths being respectively 35 and 21 km m^{-2}. These enormous lengths represented only 167 and 110 g of dry matter respectively, indicating how very efficient a root system is at developing a large absorbing surface.

These lengths develop gradually. In terms of the supply to the plant, the important question is how large the uptake per unit length of root has got to be. Because of the rapid growth of the root system, it is reasonable to assume that nearly all the root length is still active in uptake, at least for the major nutrients N, P and K.

The uptake rate into unit length of root (the inflow) is certainly not constant. Gregory *et al* (1979) found that, for nitrogen, it ranged from 28 to 2×10^{-14} mol cm^{-1} s^{-1}. Remarkably, the highest value was in December for winter wheat, followed by a steady decline to March, after which a rapid increase occurred, presumably caused by the speed of growth in spring. Later the inflow declined again. This stresses the importance of the nutrient uptake in winter, as the plant is developing its root system and beginning to tiller. These values for inflow are not large in relation to some which have been published. Thus the maximum inflow for nitrogen in maize reported by Mengel & Barber (1974) was 226×10^{-13} mol cm^{-1} s^{-1}.

The above argument implies that the inflow to the roots is a function of the demand for nutrients by the plant. This is supported by later work of Barraclough (in preparation), in which he found that the inflow of *all* nutrients into the root system of winter wheat decreased sharply during a period of nitrogen deficiency. When nitrogen was supplied, and the growth re-started, the inflow for all nutrients increased rapidly again, from 7 to 230×10^{-15} mol N cm^{-1} s^{-1}, with rather smaller changes

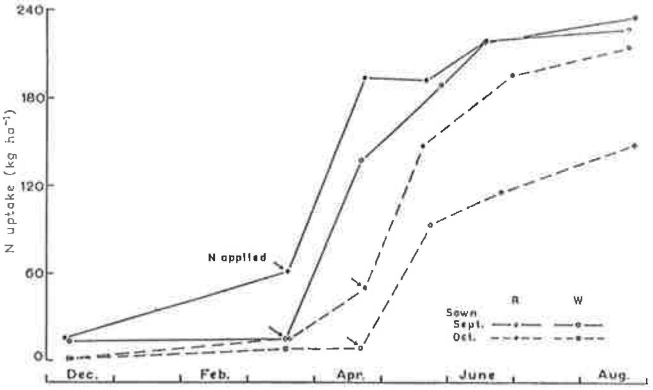

Fig. 7. Total nitrogen content of a winter wheat crop sown early and sown late, on a clay loam (Rothamsted) or a light sand (Woburn). Arrows indicate dates when fertilizer was applied. (Barraclough, private communication).

for the other ions. On correcting a deficiency, the inflow is therefore increased most for the deficient element, but the increased growth rate causes all inflows to be sharply increased. The ability of the plant to do this is the basis of the accurate control over its composition which was mentioned earlier.

Quantity and speed of uptake in relation to soil supply

The following paper in this seminar will deal with fertilizer requirement prediction. In this section the amounts taken from the soil are compared with those normally present, and the average levels of fertilizers applied. The average yield level for grain in Britain is now approaching 6 t ha^{-1} for wheat and 5 t ha^{-1} for barley, and the offtake in the grain will be of the order of 120–100 kg N ha^{-1}, 25–18 kg P ha^{-1}, 80–60 kg K ha^{-1} or 25–20 kg S ha^{-1} for winter wheat and spring barley respectively (Cooke, 1982, p. 85). We assume for the time being that all residues return to the land. According to the 1982 Survey of Fertilizer Practice (Church & Leech, 1983) (Table 1) the average application of phosphorus is only 25 kg P ha^{-1}. Thus this element is being only barely replaced. Some loss of phosphorus from the available pool may occur, by reversion to forms of lower chemical potential, so it may be that there is a small net reduction in the phosphorus status of soils carrying frequent cereal crops in Britain. The average potassium application is about 46 kg K ha^{-1}. This is appreciably less than the average offtake, and the latter will be increased where the straw is carted off. By contrast, a surplus of nitrogen is supplied, on average.

By contrast with the average offtake, a reasonable estimate of the maximum total nutrient content in the shoots of a really large wheat crop are around 200 kg N ha^{-1}, 35 kg P ha^{-1}, and 200 kg K ha^{-1}. The contents of some nutrients, especially K, may decrease before final harvest, but the supply must be geared to the maximum value. Very few soils can supply the 200 kg N ha^{-1} or more required, and accurate nitrogen fertilizer policy is vital for getting high and consistent yield. The potassium and phosphorus requirements are more likely to be met on fertile arable soils, because of the residues accumulated, and the buffering action of the soil for these nutrients. However, the average rates of application will not replace what is removed by a large crop. At present, policy on whether very large crops require proportionately more fertilizer is not very precise, either for them or for succeeding crops. Certainly one would expect there to be a need for larger maintainance dressings where a farmer regularly achieves exceptional yields. Theory would also suggest that a very large crop, with correspondingly high contents of nutrients, would need a larger concentration of nutrients in the soil to maintain the more rapid flow of nutrients to the roots which is required. So far, however, this has not been proven in practice.

The implications of these quantities are discussed for each element in turn.

(a) *Nitrogen.* Only the mineral forms of nitrogen in the soil are in practice available to crops. These are produced at varying rates by mineralization and nitrification, and are lost by leaching or denitrification. All the processes are subject to the weather, and the prediction of how much nitrogen a given soil will supply during a year is exceedingly difficult (Jenkinson, 1982). Many methods have attempted to do this in the past, with scant success. This history of failure was almost certainly due firstly, to the fact that attention was nearly always focused on one aspect only, and secondly that processes were treated as single occurrences rather than long and variable sequences. In this complex position the new possibilities of simulation modelling are beginning to prove of exceptional value (Greenwood, 1982, Frissel & van Veen, 1981). Relatively simple simulation models have been used to predict the amount of mineral N in the profile in spring (Tinker & Addiscott, 1983).

Many direct measurements of these values are now also available. The results vary widely, depending upon soil type, weather pattern in autumn and winter, and the

Table 1

Fertilizer practice on winter wheat and spring barley after different numbers of cereal crops (Church and Leech 1983)

	Consecutive cereal crops	% area getting N	P	K	FYM	average actual kg/ha N	P	K	% crop area
WINTER WHEAT	1	98	74	68	9	154	25	47	34
	2	100	94	87	7	168	25	45	25
	3–4	100	96	85	15	175	26	44	19
	5+	100	98	81	11	185	25	47	22
SPRING BARLEY	1	98	88	88	21	83	17	34	27
	2	98	95	96	24	91	17	37	15
	3–4	99	97	97	27	97	18	37	33
	5+	98	96	93	23	107	20	39	25

preceding crop, and can range from almost nothing up to 200 kg N ha^{-1} (Widdowson *et al* 1982). Where the previous two or more crops have been cereals, the amount in spring is rarely more than 60–80 kg N ha^{-1}. Further mineralization during the growth period will rarely produce more than 30–40 kg N ha^{-1}, so the total supply, to 90 cm depth, will rarely exceed 100 kg N ha^{-1}, and may be much less. The measurements show clearly that nitrate-N may be leached, and the only complete protection is to get it absorbed by a growing crop at an early stage. A large, early-sown winter crop is thus a good preserver of soil nitrogen.

Uptake of nitrate down to 90 cm in the profile would be expected to be highly efficient (Burns, 1980), and nearly all available nitrate to this depth is readily taken up though there is considerable uncertainty about whether nitrate at deeper levels is available also. This almost complete extraction of a defined form of nitrogen allows one to balance supply and demand relatively simply (Remy & Viaux, 1982). There is almost always a deficit which needs to be met by fertilizer, and this approach allows the amount to be calculated. However, questions of efficiency of uptake and use are important, and are discussed below.

(b) *Phosphorus.* No simple balancing is possible for this element, because it is extensively sorbed and precipitated. It is a question of maintaining a chemical potential, or a concentration in the soil solution, rather than supplying a given amount. The total amount, or even the labile pool of phosphorus in the soil is usually ample for several years cropping. However, there is a clear link between the chemical potential or availability, and quantity. Continued extraction of phosphorus is possible, but at steadily decreasing rates, and at some point deficiency must be encountered.

Recent work at Rothamsted has studied the effect of infection with vesicular-arbuscular mycorrhizal fungi on the ability of barley and wheat to take up phosphorus, because all cereals are always heavily infected (Buwalda *et al* 1983). We have shown that these fungi are important in supplying phosphorus to cereals, but virtually all soils should have enough inoculum naturally present, so there seems to be no scope for improving phosphorus nutrition by artificial inoculation. However, this work should allow us to understand the phosphorus supply to cereals better.

(c) *Potassium.* Similar considerations to those for phosphorus apply, and again it is not possible to define a precise quantity which is available. The position is complicated by the release of non-exchangeable potassium in a number of soils, when these contain micaceous clays with inter-layer potassium. Thus a Beccles series soil on Chalky Boulder clay can release at least 200 kg K ha^{-1} to large cereal crops regularly. However, the exact definition of the possible rate of release, in relation to crop type and growth rate, on different soils is by no means complete, and requires more research.

(d) *Other elements.* It is difficult to assess the supply of most of the other nutrients in terms of the contents in the crop. For example, much of the supply of sulphur comes as rainfall or dry deposition, and in most of Britain this is amply large enough for a normal, or even a very large wheat crop, bearing in mind that the sulphur is supplied in a readily available form. In some less industrialised parts of the country, S deficiencies have recently appeared in grasses, but these are still in the nature of special cases. For minor elements, there appears to be no difficulty in supplying them in sufficient quantity and at sufficient rate. British wheat-growing soils are generally sedimentary, and have in many cases been transported or disturbed relatively recently by glacial action. Marked trace element deficiencies are therefore rare. Copper deficiency has occurred on some defined soil types, but repeated dressings of copper salts have made this condition also rather rare now. Copper-nitrogen interactions have occurred, as the behaviour of these elements in the plant is closely related (Loneragan, Snowball & Robson 1980).

Timing, rates and forms of fertilizer

Phosphorus and potassium can be applied at almost any time up to the seeding of the crop, including fertilizing for a rotation or for two or three years of a single crop, because of the buffering actions of the soil and the effectiveness of fertilizer residues (Johnston *et al* 1978). These fertilizers are often ploughed down, and the aim is simply to maintain a sufficient soil status. Almost all forms contain only water-soluble salts at present, so that all have virtually the same result.

The timing and splitting of nitrogen dressings is in contrast a point of considerable debate. Particularly on the continent quite elaborate systems of splitting nitrogen dressings have been developed with up to five separate dressings of N. Dilz *et al* (1982) report results showing generally higher yields with a two-way, and occasionally with a three-way split. However, British experience (Needham 1982) has shown relatively little benefit from splitting N dressings, unless there was good reason to believe the crop was running short of N. A good example of this is in Fig. 7. The early-sown Woburn crop received its spring fertilizer in early April, and grew away at once. On this light soil there was almost no residual nitrate at this time, so a delay in applying N to the late-sown crop resulted in similarly delayed growth. In contrast, at Rothamsted this delay in applying N had no similar adverse effect, because this more retentive soil still contained appreciable amounts of nitrate.

Efficiency of use of nitrogen

It is often stated that our crops only recover some 50% of the nitrogen fertilizer applied to them. This is, of course, in the harvested part, and as some must be contained in roots and straw, 100% recovery in grain is not possible. However, as a rough average we can assume that about 70–75% of the N taken up by the crop remains in the grain, though consistent and agreed figures are difficult to obtain. For example Remy and Viaux (1982) assume that 30% of the total N content is in the roots alone, though 10% appears more usual. Of that in the grain, straw and chaff, 80–85% is in the grain.

Efficiency can be calculated in two general ways. The first relies on relating either nitrogen uptake, (into grain or whole crop), or grain yield to nitrogen fertilizer rate (Fig. 1), the slope representing the efficiency in each case. If 75% of absorbed N goes into grain with 2% N, then the maximum efficiency, in terms of grain produced per kg of nitrogen fertilizer applied, is 37.5 kg grain kg^{-1} N. Efficiency defined in this way and measured in field experiments depends greatly upon the rate of N applied. The initial application may give over 30 kg N per kg N fertilizer, with smaller returns for high levels (Fig. 8). Some response data may be interpretated as two straight lines (Boyd *et al* 1976) with a constant efficiency up to the break point, and a marginal efficiency of almost zero thereafter, so the mean efficiency would depend heavily upon the level selected. Needham (1982) gave a mean value of 16–18 kg grain kg^{-1} N in many experiments. Bearing this in mind, it is remarkable that the national average yield of grain per kg N fertilizer stayed remarkably close to 24 kg grain kg^{-1} N over some 40 years (Fig. 8). Though the axes are the same, the interpretation of the lines in Figure 8 is quite different. In single experiments, the causative variable is solely nitrogen, all other factors being constant. In the national averages, nitrogen is only one of many variables, of which variety is probably the most important. On average, the British farmer thus seems to have shown very good sense in adjusting his fertilizer rate through a period of rapid change. Certainly there is little sign of increasingly wasteful and unprofitable use of N in Figure 8. Indeed, as the energy cost of producing nitrogen fertilizer has declined by about 50% over the same period (Lewis & Tatchell, 1979), we now get grain at about half the *fertilizer* energy cost to that in 1945.

If grain contains 2% N, then this implies about a 50% recovery of N fertilizer in grain, in accordance with normal expectation. At Rothamsted the average uptake in the past was around 45–55% of fertilizer N taken up into the grain, but in very recent years, with heavier crops, values of up to 65% have been found.

In the second method one uses fertilizer labelled with the mass isotope 15N, and measures directly how much of this is absorbed. In principle this appears the more fundamental and reliable method, but in practice the results need interpreting with care (Dowdell *et al* 1983; Jenkinson & Powlson, 1983) because there is the probability of interchange with the exisiting soil N, by immobilization and mineralization. The measured efficiency of uptake of the labelled N thus depends upon the extent of this interchange, which presumably accounts for the findings that efficiency increases as the date of application of N is moved closer to the time of rapid uptake by the crop, and that uptake of soil nitrogen appears to increase where fertilizer nitrogen is applied.

The most up to date information for high-yielding trials indicates that efficiency, in terms of grain uptake of 15N, was 50–60%, but there was clear evidence that some N was lost from the soil-plant system during the period, perhaps by denitrification (Jenkinson & Powlson, 1983).

This type of work is important in relation to the suggestions of pollution by leaching of nitrate from fertilizer. High efficiency in uptake, with exact knowledge of what happens to the remainder, is the best answer to these charges against arable farming.

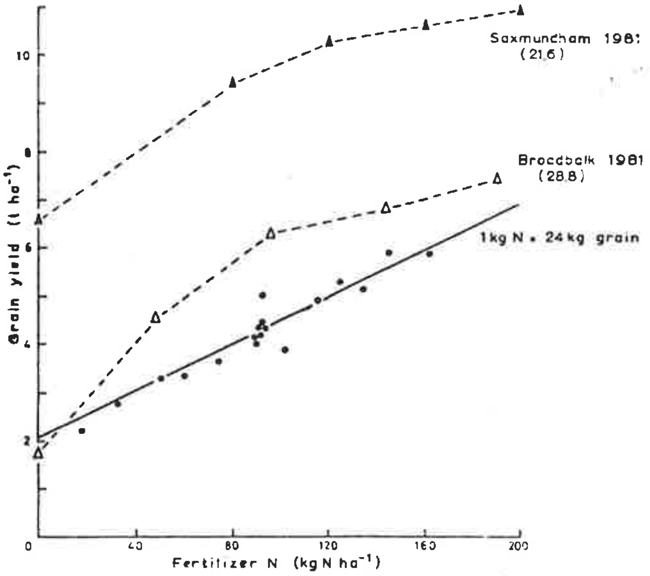

Fig. 8. Relationship of average yields of wheat grain and average rates of N applied to wheat in England and Wales over 40 years, compared with response curves in recent Rothamsted experiments. Figures in brackets are mean yields of grain per kg N fertilizer applied over whole range of rates. From Cooke, 1980; Bingham, 1979; Agricultural Statistics of UK, Ministry of Agriculture; Fertilizer surveys, Ministry of Agriculture, Fisheries & Food. Early yields taken from trend line, not annual yields.

Interactions of fertilizer and other factors

Any factor which diminishes crop size will affect nutrient demand. Modern methods of agronomy and disease control, which promote stability of yield, thus simplify the problem of prescribing the best fertilizer treatments. The use of growth regulators for cereals is now general, and their use has allowed larger rates of N with greater safety. It is often found that control of leaf diseases leads to a larger optimum N requirement (e.g. Tinker & Widdowson, 1982), but the situation with respect to the much more intractable root diseases is less clear.

There is a definite interaction between phosphorus application and take-all (Mattingly, *et al* 1978), in that high rates of phosphorus diminish the extent and effects of the disease, but direct interactions between the different nutrients are not large in the absence of really serious deficiencies.

Conclusion

Questions concerning the nutrition of cereals with elements other than nitrogen are not urgent at present, though they involve appreciable costs, and could become more important if changes in prices demanded a more stringent examination of input levels. It is surprising how little attention is given to the mechanisms of control of the elemental composition of crops and grain, and more resources should be devoted to this topic. Trace element composition of grain may also deserve more attention, because of current interest in these elements, in the environment.

The major problem is undoubtedly with the exact demand and supply of nitrogen, in terms of quantity and timing of application. Closer control of these factors is necessary to ensure our ability to get high yields consistently, to minimise costs, and to show that environmental pollution is being kept to the lowest possible level.

References

Barraclough, P. B. (1982) *Annual Report Rothamsted for 1981* 1, 248.

Benzian, B.; Darby, R. J.; Lane, P.; Widdowson, F. V.; Verstraeten, L. M. J. (1983) Relationship between N concentration of grain and grain yield in recent winter wheat experiments in England and Belgium, some with large yields. *Journal of the Science of Food and Agriculture* 34, 685–695.

Benzian, B.: Lane, P. (1982) Effects of husbandry treatments on nitrogen concentration of grain and related yields in winter wheat experiments made in South-East England. *Journal of the Science of Food and Agriculture* 33, 1063–1071.

Bingham, J. (1979) Wheat bonding objectives and prospects. *Agricultural Progress* 54, 1–17.

Boyd, D. A.; Yuen, Lowsing T. K.; Needham, P. (1976) Nitrogen requirement of cereals. Part 1. Response curves. *Journal of Agricultural Science*, Cambridge 87, 149–162.

Burns, I. G. (1980) Influence of the spatial distribution of nitrate on the uptake of N by plants: a review and a model for rooting depth. *Journal of Soil Science* 31, 155–174.

Buwalda, J. D.; Stribley, D. P.; Tinker, P. B. (1983) *Annual Report Rothamsted for 1982* 1, 271–272.

Church, B. M.; Leech, P. K. (1983) *Fertilizer use on farm crops in England and Wales 1982*. London, Ministry of Agriculture, Fisheries and Food.

Cooke, G. W. (1980) Changes in fertilizer use in the UK from 1950 to 1980. *Proceedings of the Fertilizer Society* 190, 12–28.

Cooke, G. W. (1982) *Fertilizing for maximum yield*. Granada, London, 3rd Ed.

Dilz, K.; Darwinkel, A.; Boon, R.; Verstraeten, L. M. J. (1982). Intensive wheat production as related to nitrogen fertilization, crop protection and soil nitrogen: experience in the Benelux. *Proceedings of the Fertilizer Society* 211, 93–124.

Dowdell, R. J.; Cress, R.; Christian, D. (1983) Uptake of fertilizer nitrogen by arable crops. In *The Nitrogen requirement of Cereals*. (ed. P. Needham). Proceedings ADAS Soil Scientists Technical Conference, Loughborough 1982. (In press).

Frissel, M. J. and van Veen, J. A. (1981) (eds.) *Simulation of nitrogen behaviour of the soil-plant system*. Pudoc, Wageningen.

Greenwood, D. J. (1982) Modelling of crop response to nitrogen fertilizer. *Philosophical Transactions of the Royal Society*, London. B296, 351–362.

Gregory, P. J.; Crawford, D. V.; McGowan, M. (1979) Nutrient relations of winter wheat 2. Movement of nutrients to the root and their uptake. *Journal of Agricultural Science*, Cambridge 93, 459–504.

Jenkinson, D.; Powlson, D. S. (1983) *Annual Report Rothamsted for 1982*, 1, 262–263.

Jenkinson, D. S. (1982) The nitrogen cycle in long-term field experiments. *Philosophical Transactions of the Royal Society*, London. B296, 563–571.

Johnston, A. E.; Poulton, P.; Mattingly, G. E. G. (1978) *Annual Report Rothamsted for 1977* 1, 273–274.

Leigh, R. A.; Johnston, A. E. (1983) Concentrations of potassium in the dry matter and tissue water of field-grown spring barley and their relationships to grain yield. *Journal of Agricultural Science*, Cambridge 101 (in press).

Lewis, D. A.; Tatchell, J. A. (1979) Energy in UK agriculture. *Journal of the Science of Food and Agriculture* 30, 449–457.

Loneragan, J. F.; Snowball, K.; Robson, A. D. (1980) Copper supply in relation to content and redistribution of copper among pests of the wheat plant. *Annals of Botany* 45. 621–632.

Mattingly, G. E. G.; Slope, D.; Gutteridge, T. (1980) *Annual Report Rothamsted for 1979* 1, 227–229.

Mengel, D. B.; Barber, S. A. (1974) Rate of nutrient uptake per unit of corn root under field conditions. *Journal of Agronomy* 66, 341–344.

Needham, P. (1982) The role of nitrogen in wheat production: reponse, interaction and prediction of nitrogen requirements in the UK *Proceedings of the Fertilizer Society* 211, 125–147.

Nye, P. H.; Tinker, P. B. (1977) *Solute movement in the soil-root system.* Blackwells, Oxford.

Penny, A.; Widdowson, F. V.; Jenkyn, J. F. (1983) Experiments with solid and liquid N-fertilizers and fungicides on winter wheat at Saxmundham, Suffolk, 1976–9. *Journal of Agricultural Science,* Cambridge 100, 163–173.

Pushman, F. M.; Bingham, J. (1976) The effects of granular nitrogen fertilizer and a foliar spray of urea on the yield and breadmaking qualities of ten winter wheats. *Journal of Agricultural Science,* Cambridge 87, 281–292.

Remy, J. C.; Viaux, P. (1982) The use of nitrogen fertilizers in intensive wheat growing in France. *Proceedings of the Fertilizer Society* 211, 67–92.

Tinker, P. B.; Addiscott, T. M. (1983) Nitrogen requirement of cereals—modelling methods. In *The Nitrogen requirement of Cereals.* (ed. P. Needham). Proceedings ADAS Soil Scientists Technical Conference, Loughborough 1982. (In press).

Tinker, P. B.; Widdowson, F. V. (1982) Maximising wheat yield and some causes of yield variation. *Proceedings of the Fertilizer Society* 211, 149–184.

Welch, R. M.; Cary, E. E. (1975) Concentrations of chromium, nickel and vanadium in plant materials. *Journal of Agriculture, Food and Chemistry* 23, 479–482.

Widdowson, F. V.; Darby, R. J.; Bird, E. (1982). *Annual Report Rothamsted for 1981* 1, 250–251.