# Soil fertility limitations to wheat yield and quality

W. R. Scott[1], R. J. Martin[2] and K. R. Stevenson[1,3]

[1] Plant Science Department, Lincoln University
[2] New Zealand Institute for Crop & Food Research Ltd, Private Bag 4704, Christchurch
[3] Present Address: Agritek, P.O. Box 19, Lincoln

## Introduction

With the deregulation of the wheat industry in 1987 and consequent competition from imported wheat, New Zealand wheat growers now have to meet stringent quality standards. Most contracts for milling wheat specify certain quality parameters which must be met. In addition to quality, growers must also try to maximise yield if the crop is to be profitable. This paper reviews the effects that soil fertility has on wheat quality and yield but it must be stressed that soil fertility does not act in isolation and needs to be considered along with the effects of genetic, agronomic and other environmental factors discussed elsewhere in this symposium.

The latest Recommended List contains cultivars that have average Mechanical Dough Development (MDD) scores of 26 and which are capable of 30, double the previously acceptable minimum of 15 (Mitchell, 1985a). Such increases in quality have resulted from both breeding and improved management. Wheat quality has been very topical in recent years, increasing grower awareness of the need to produce higher quality wheat. Indeed, no less than five papers on wheat quality were presented at the 1987 conference of this society and there have been several others since. The most recent comprehensive review of factors that affect wheat yield and quality was by Martin *et al.* (1989), and this paper makes extensive use of that publication. In this paper we aim to review relevant work on the influence of soil fertility on wheat yield and quality, emphasising the principles involved. The application of these principles into field practice is discussed by McCloy in a subsequent paper (McCloy, 1992).

## Soil Fertility - What is it?

A fertile soil should be able to provide a crop with an adequate supply of all essential plant nutrients. If this was the only requirement, it could be achieved very simply by providing inorganic fertilisers. However fertile soil provides more than nutrients: soil structure, texture, depth, aeration and the presence of a pan can affect plant growth either directly through physical effects, affecting root growth and contact with the soil solution (Passioura, 1991), or indirectly by affecting mineralisation, the amount of nutrients that can be held in the soil, and soil-plant water relations. Some of these physical properties can be markedly affected by soil management (MAFF, 1975). Higher soil organic matter content can increase yields by improving water and nutrient availability (Johnson, 1986). Levels of soil organic matter are generally well correlated with soil structure (Chaney and Swift, 1984) but a recent study on cropping rotations in Canterbury (Haynes *et al.*, 1991) showed that even short term pasture of 2-5 years had a very beneficial effect on aggregate stability without substantially increasing of soil organic matter content. For wheat a fertile soil could also be considered as one that has not been continually cropped with wheat and is therefore much less likely to harbour soil-borne diseases such as take-all (*Gaeumannomyces graminis*).

## Nitrogen

Large quantitites of nitrogen (N) are required by wheat crops, and it has a large influence on grain yield and quality. The lack of long term storage of plant available (N) in the soil, means that it is the element most likely to be deficient in wheat. The N cycle is presented in Figure I. The supply of N a crop comes from either the soil or fertiliser, usually a combination of both. Organic N must first be mineralised to the ammonium ($NH_4^+$) and nitrate ($NO_3^-$) forms before it can be taken up by plants. The $NO_3^-$ form is likely to be leached if not taken up.

Once inside the plant, nitrogen is built first into amino acids then proteins, both having a key role in plant metabolism and grain quality. The green pigment chlorophyll, for example, contains N and this is one reason why a N deficient crop turns yellow prematurely.

## Yield and Yield Components

There are many ways to look at yield, the simplest being to say that the aim is to produce the maximum

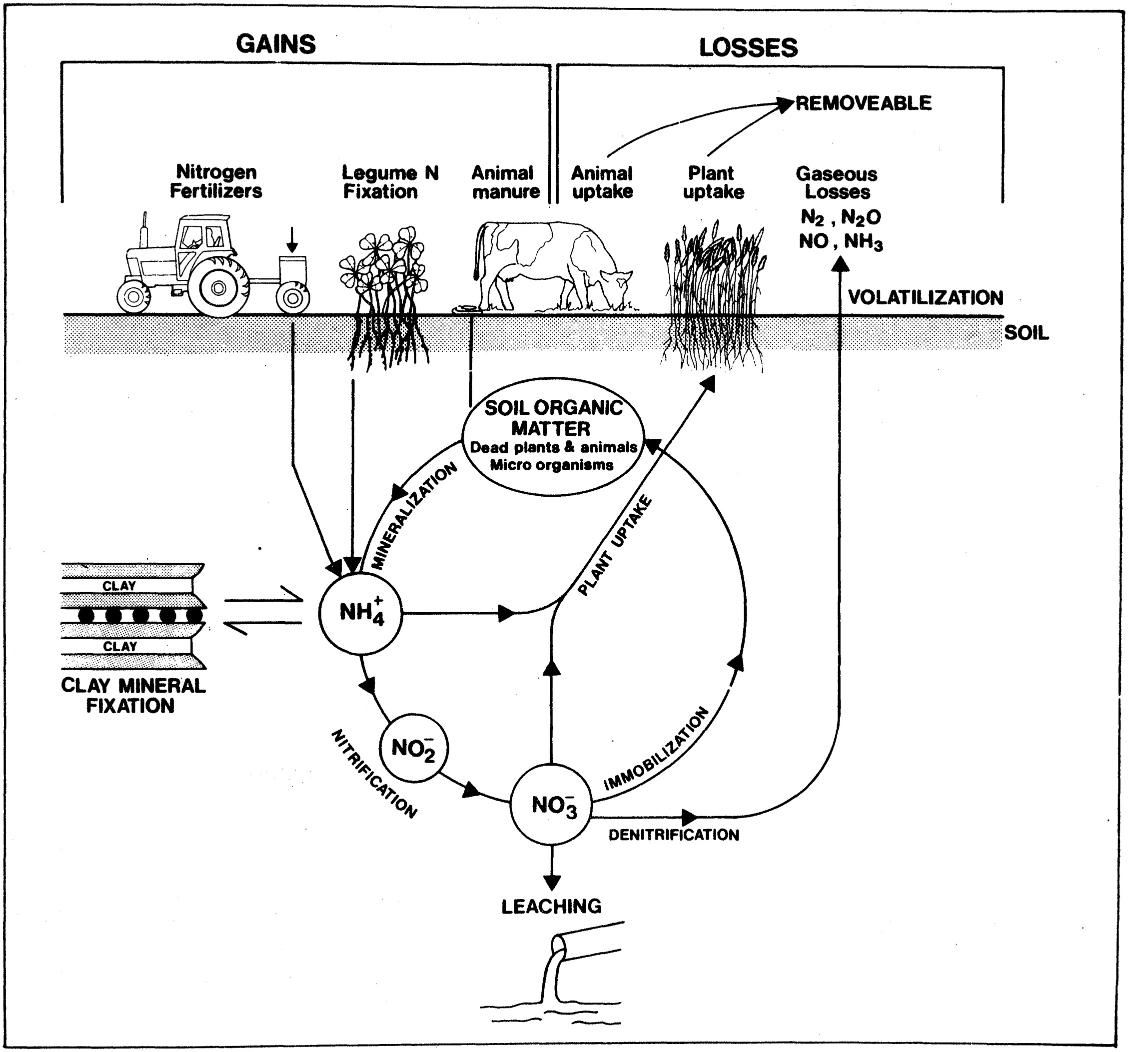


**Figure 1. The nitrogen cycle in agricultural soils (from McClaren and Cameron, 1990).**

number of grains per unit area and that each grain should be of adequate size for milling purposes. Thus a crop yielding 8 t/ha could consist of 20,000 grains/m$^2$ weighing 40 mg on average. Most New Zealand wheat crops yield less than 8 t/ha mainly because they produce fewer grains. When the number of grains is restricted there is an upper limit to which they can grow, so the system is not fully compensatory.

The components of wheat yield can be expressed as: Grain yield/ha = ears/ha x spikelets/ear x grains/spikelet x kernel weight.

One or more of these yield components is being determined from the day a wheat crop is sown. Figure 2 shows the approximate time period over which each yield component is determined in relation to the standard Feekes scale of development.

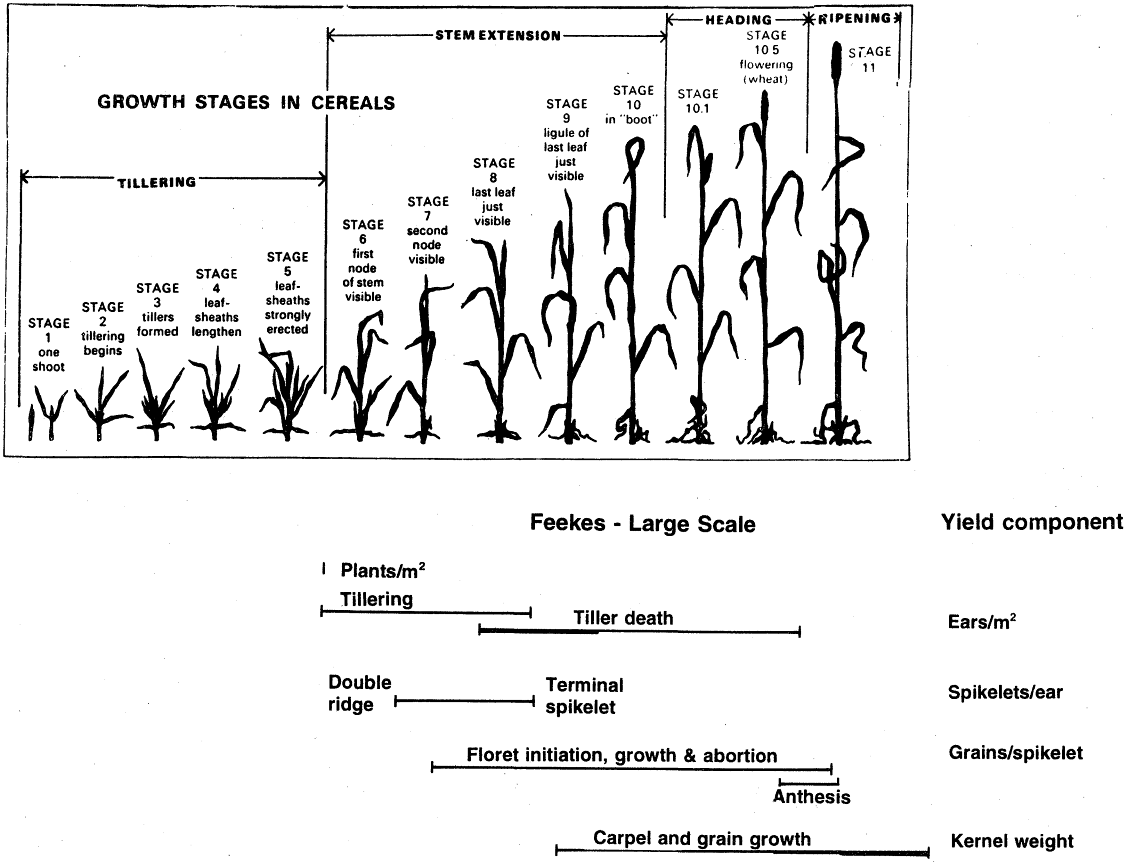


**Figure 2. Growth stages of wheat in relation to the timing and duration of physiological events determining the yield components (adapted from Scott, 1978a).**

### Number of ears/m²

In New Zealand, wheat yields are often related closely to the ear population (Hampton *et al.*, 1981). The final ear population is the end result of production and tiller survival as shown by the data of Thorne and Wood (1988) in Figure 3. Extrapolating these data to New Zealand conditions means that in winter wheat the number of tillers reaches a peak in September and is followed by a rapid decline. Higher order tillers have greater mortality than lower order ones, with mainstems having nearly 100% survival. Both within and between tiller categories, shoots that are produced last die first. More than half the tillers that are produced die without producing an ear. N supply strongly influence tiller production and survival (Power and Alessi, 1978). To maximise ear population on yield, N fertiliser should be applied during tillering (e.g., Stephen *et al.*, 1985). In addition, stresses caused by disease or lack of water should be avoided to minimise tiller death and therefore to maximise the ear population.

In a wheat crop with a population of 200 plants/m² and a target population of 600 ears/m², an average plant produces only three ears, on the mainstem and two tillers. Thus, although fertiliser N may substantially increase the number of tillers produced per plant, its main role is to increase the size of tillers 1 and 2 so that they survive to produce ears. However, it is important to bear in mind that applying all the N at tillering can often reduce kernel weight, as discussed later.

### Number of spikelets/ear

Ear growth in wheat is determinate and the final number of spikelets per ear is determined at least one month before the ears appear (Kirby, 1974). In a N deficient soil the addition of N fertiliser before the double ridge stage can add an extra 2 - 3 spikelets per ear (Table 1).

### Number of grains/spikelet

Each wheat spikelet produces about 8 - 9 florets (Hanif and Langer, 1972) but it is rare that more than four of these set grain. The mean number of grains per spikelet in a crop is usually around two, but there is considerable variation among spikelets within the ear (Scott *et al.*, 1975; 1977). As with the other yield components N can increase the number of grains per spikelet. It does this if applied at tillering by affecting the floret growth and development which occur subsequently (Langer, 1979). Stevenson and Daly (1991) found that later applications of N could also increase the number of grains per spikelet.

Together, the numbers of spikelets/ear and grains/spikelet determine the number of grains/ear, the yield component which most frequently responds to N in the U.K. (Gales, 1983), but results in New Zealand are less conclusive (Stephen *et al.*, 1985).

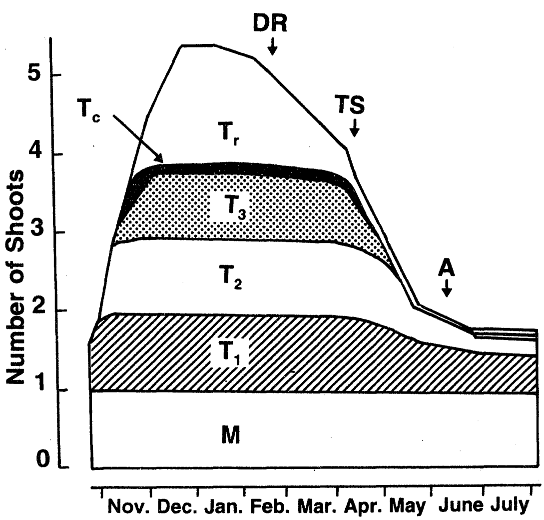


**Figure 3. Changes with time in numbers of shoots in different categories of winter wheat sown on 18 September in the U.K. M, mainstem; T - $T_3$, tillers in axils of first - third mainstem leaves; $T_c$, coleoptile tiller $T_r$, other tillers. Arrows indicate dates of double ridge (DR) and terminal spikelet (TS) stage of the mainshoot and 50% anthesis (A) of the whole crop (from Thorne and Wood, 1988).**

### Kernel weight

The yield components discussed so far influence yield by affecting the number of grains produced. In contrast, the final yield component, namely kernel weight, affects both yield and quality. The effects of N on kernel weight are more complex than for the other yield components (Stephen *et al.*, 1989). N applied at tillering generally decreases kernel weight (Drewitt and Dyson, 1987; Feyter and Cossens, 1977; Scott *et al.*, 1975) or has little effect (Martin, 1987). Over six sites in Canterbury, Stephen *et al.*, (1985) found that the response to N applied at tillering ranged from a decrease of 45.5 to 38.5 mg through to an increase of 39.8 to 41.6 mg. Without detailed measurements of the environment experienced by each crop and close monitoring of crop growth and development it is impossible to explain some of these inconsistencies. It is known that early N may produce extra tillers which are smaller and hence produce fewer and smaller grains (Power and Alessi, 1978). Late aplication of N usually improves kernel weight (Drewitt and Dyson 1987, Martin 1987) mainly to improve leaf area duration (Spiertz and Ellen, 1978) as up to 95% of the assimilate required for grain filling is produced by photosynthesis after anthesis (Evans, 1975). Along with N, adequate disease control and water supply are also vital at this time.

**Table 1. The effect of nitrogen fertiliser applied at tillering on the number of spikelets/ear of wheat (Scott, 1978b).**

| Rate of N (kg/ha) | No. spikelets/ear |
|---|---|
| 0 | 16.8 |
| 25 | 17.8 |
| 50 | 18.8 |
| 100 | 19.1 |

## Grain Quality

Wheat quality indexing was first adopted in New Zealand in 1985, with the value of grain being indexed against the ruling Australian Standard White (ASW) price during the week of delivery. The system has been revised several times since then so that contracts may now include standards for any of the following parameters: cultivar, protein, screenings and foreign matter, falling number, kernel weight, moisture content and some allowance for storage. Among these, the ones that can be influenced by soil fertility are grain protein, kernel weight and baking score.

### Grain Protein and Kernel Weight

Many purchasing contracts for wheat now include specifications for grain protein content, usually measured by Near Infra Red Reflectance at the time of delivery. Grain for bread making requires protein contents of at least 10% while biscuit making requires grain protein contents of 8 - 10%.

Wheat grain at 14% moisture contains 50-60% carbohydrate and 1.2 - 3.0 % N, the latter as result of the amount of starch and N in the grain. There is often an inverse relationship between kernel weight and N content (Figure 4), although in some cases one parameter can change without the other being affected. Changes in grain N content could reflect either changes in N uptake or dilution of N by changes in carbohydrate levels.

Nearly all the carbohydrate in the wheat grain is derived from photosynthesis in the ear and upper one or two leaves. Under normal conditions, 10-12% of grain carbohydrate comes from remobilization of stem reserves but this can increase under drought or heat stress (Rawson and Evans, 1971). The N in the grain comes from two sources: a) that taken up before flowering and stored in the upper leaves and stem, and then remobilized to the grain after flowering. and b) that taken up after flowering and translocated directly to the grain.

The proportion remobilized can vary from 50-90% i.e., considerably more than the comparable proportion of carbohydrate (Gregory *et al.*, 1981). If there is little or no available N left in the soil, then most of the N in the grain comes from remobilization. The main sources of this N are the chlorophyll molecules together with the enzymes and proteins involved in photosynthesis and carbohydrate translocation. In cases of severe N deficiency this remobilization causes yellowing and premature senescence of the top leaves of the plant, including the flag leaf. Thus, as remobilization of N increases, photosynthesis and grain filling are reduced prematurely (Gregory *et al.*, 1981; Spiertz and de Vos, 1983) leading to reduced kernel weights and higher N concentrations, although there is considerable cultivar variation (Van Sanford and MacKown, 1987).

If adequate N is available from the soil or from foliar applications, then it is taken up and remobilization from the leaves is reduced. Thus photosynthesis and carbohydrate translocation continue unhindered resulting in larger grains or, perhaps better expressed, the grains are able to grow to their potential size. The final grain N content depends on the relative uptakes of N and carbohydrate. Both are influenced by factors such as temperature and plant water status, which can cause wide variations among crops both within and between seasons in kernel weight and grain N content under the same irrigation and N treatments (e.g., Daly and Dyson, 1987).

Clearly, high grain protein content requires an adequate supply of N during grain growth and development. Where the supply of N from the soil is inadequate, so-called "late" applications of N fertiliser can dramatically improve grain protein content. This is demonstrated in Table 2. Increasing rates of N

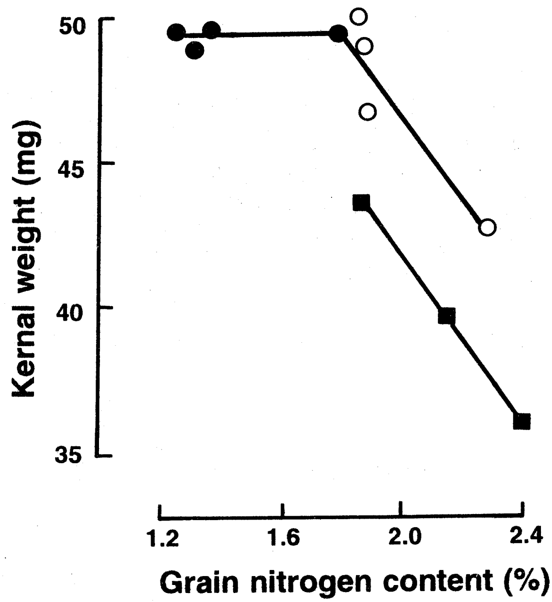


**Figure 4. The relationship between kernel weight and % grain nitrogen for Rongotea wheat over three seasons : ■ = year 1, O = year 2, ● = year 3 (Martin *et al.*, 1989).**

application at tillering substantially increased yield but not grain protein content. In contrast, increasing N application rates at stem elongation had a small effect on yield but a large effect on grain N content. The results in Table 2 also demonstrate that high yielding crops are not necessarily low in grain N content as the highest yielding crop also had the highest grain N content. Stevenson and Daly (1991) found that the yield and protein responses to 20 kg N/ha applied as a late foliar spray were often comparable to the responses to 40 kg N/ha applied to the soil.

If N fertiliser is applied to biscuit wheats where low grain N contents are required, it should all be applied early to maximise yield while minimising grain N content.

### Baking Score

Since 1981 the MDD (Mechanical Dough Development) test has been used to assess the baking quality of New Zealand wheat (Mitchell, 1985b). The test is conducted by the Grain Processing Laboratory at Lincoln using a 500 g grain sample. Like any laboratory test, the results are only as reliable and representative as the sample supplied. The practical implications of obtaining a representative 500 g sample from a 50 t silo are mind boggling.

Soil fertility is one of the many factors that affect the MDD score. However the results from recent studies of fertility effects on MDD are not consistent. Drewitt and Dyson (1987) found that N fertiliser applied at booting increased the MDD score while Martin (1987) found that the effect of splitting the N application between early and late in crop growth was cultivar dependent. Daly and Dyson (1987) found that the MDD score increased with increasing rates of N up to 200 kg/ha but the results were not consistent. Investigations of the effects of N on MDD score by Douglas (1987) over a ten year period found that N generally increased MDD score by only one or two units with very little difference in effect of varying the time of application.

The experiments on MDD score referred to above together with ones conducted earlier (e.g., Wright, 1969; Malcolm, 1977) have generally found that grain protein content usually responds more predictably to variations in N supply than does MDD score, presumably because not all the extra N goes into the proteins that influence quality. MDD score is also influenced by many other factors such as cultivar, location, time of sowing, season and irrigation, as reviewed by Stevenson (1987a). It is of interest to note that MDD score does not feature in some of the recent contracts offered to New Zealand growers.

**Table 2. The effects of rate and timing of nitrogen fertiliser application (kg N/ha) on grain yield (t/ha) and grain protein content (%) (figures in parenthesis). Derived from Martin *et al.* (1989).**

| N applied at tillering | N applied at boot stage | | |
|---|---|---|---|
| | 0 | 25 | 50 |
| 0 | 4.7 (10.0) | 5.1 (10.7) | 5.3 (11.4) |
| 25 | 5.4 (9.70) | 6.0 (10.5) | 6.5 (11.4) |
| 50 | 6.1 (10.1) | 6.7 (11.0) | 6.8 (11.4) |
| 75 | 6.7 (10.4) | 6.8 (11.1) | 7.3 (12.0) |

## N Losses

N uptake by the wheat crop from sowing through to maturity has seldom been monitored in experiments in New Zealand. Stevenson (1987b) found that the total amounts of N accumulated by four cultivars increased early decline in growth in the 3 - 4 weeks prior to anthesis, but then continued to increase at a linear rate between anthesis and maturity (Figure 5). Quin and Drewitt (1979) attributed these reductions to gaseous losses of volatile N compounds exceeding the rate of uptake of soil N. A large series of experiments conducted recently in Australia (Stapper and Fischer, 1990) showed that uptake of N at anthesis varied from 82 to 118% of final uptake i.e., while some crops accumulated 18% of their total N between anthesis and maturity, others lost a similar amount. Papakosta and Gagianas (1991) also found that in a Mediterranean climate some wheat crops lost up to 77 kg N/ha from the herbage between anthesis and maturity. Such losses are important and may well have been underestimates as the calculations did not take account of any N absorbed between anthesis and maturity.

## Prediction of Crop Nitrogen Requirements

The objective of any fertiliser programme for wheat must be to maximise grain yield and quality by balancing the N supply from the soil and fertiliser with the crop demand. Both Wright (1967) and Malcolm (1977) established that the preceding crop had a major influence on both yield and quality. Wheat following pasture or other restorative crops had a higher yield and MDD score than when it succeeded N depletive crops, particularly cereals. Presumably, where high levels of soil organic N are present, mineralisation is able to supply adequate levels of available N throughout the growth of the crop. However this is not always a safe assumption. For example, low soil temperatures may inhibit the rate of mineralisation or high intensity rainfall may cause leaching of N (Feyter, 1974; Feyter and Cossens, 1977; Ludecke 1972, 1974) especially where mineralisation is well advanced by early cultivation (Francis *et al.*, 1992).

Goh (1983) reviewed various methods of soil testing for N and concluded that actual soil N supply was difficult to determine. More recently Selvarajah *et al.*, (1987) suggested the following methods of assessing N availability:

1. measurement of field-moist soil residual N levels, and
2. boiling KCl hydrolysable N or 7-day field-moist soil anaerobic incubation.

They also recommended that the anaerobic test replace the 7-day aerobic incubation test offered by the Ravensdown Fertiliser Co-operative at that time.

The MAF soil fertility N index described by Montgomery *et al.* (1986) and Metherell *et al.* (1989) offers another useful tool for farmers to use in predicting N requirements. This index is based on a 0-10 scale where 0 is a paddock with 5 or more years of continuous cereal cropping and 10 is a clover based pasture five or more years old. Crop fertiliser requirements are calculated using the crop N demand, paddock index, previous N fertiliser and expected winter nitrate leaching. When the predictions using this model were tested against experimental data some anomalies and deviations were apparent. The model has been adopted by the MAF Soil Fertility Service as a first assessment of the crop's fertiliser requirement, with reassessment during the early part of the growing season being recommended.

The uncertainty in any method of predicting N fertiliser requirements is due to the weather which affects both soil and plant processes. Since no one method is perfect, farmers need to take account of several factors such as paddock history, expected yield, soil tests, sap nitrate tests, paddock index and, last but not least, availability of water, whether from soil storage, rainfall or irrigation.

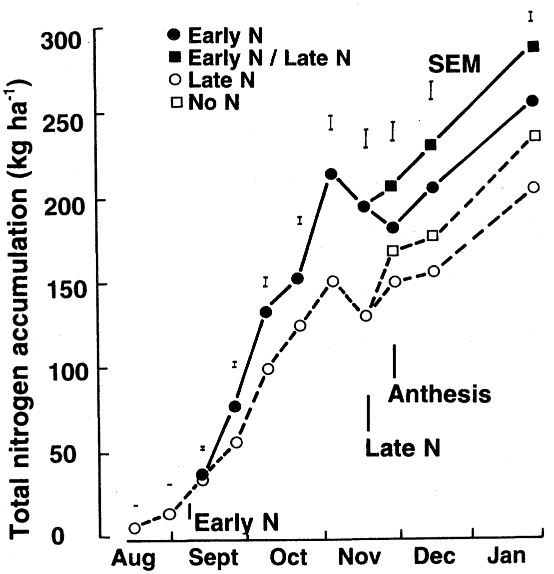


**Figure 5. Effect of 112 kg N/ha applied early and 50 kg N/ha applied late on the accumulation of above ground nitrogen, mean of several cultivars (Stevenson, 1987b).**

## Effects of Other Nutrients

Besides N, the nutrients most likely to restrict wheat yields are phosphorus (P), sulphur (S) and, occasionally, potassium (K). In 186 field experiments in northern Canterbury, Stephen (1980) found grain yield responses to P fertiliser occurred on 73% of the sites. Large responses to P fertiliser can occur on P fixing soils (Douglas and Slay, 1983), with the increases resulting mainly from greater ear numbers and kernel weights (Douglas and Slay, 1983; Douglas *et al.*, 1988). Where successive cropping has occurred responses to P may be limited by the supply of available N (Douglas and Slay, 1983). Unless extremely deficient, P has no major effects of wheat quality (Hanway and Olson, 1980). Unlike N, reliable soil tests are available for determining levels of available P (Stephen, 1974).

The use of superphosphate and mineralisation from soil organic matter usually provide sufficient S for wheat where yield is limited by nitrogen. However, growers should be aware that increasing use of alternate P sources such as rock phosphate and di-ammonium phosphate which do not contain S may lead to a reduction in soil organic S levels and hence the availability of S. Australian work has shown that grain yield responses to S are much more likely to occur where additional N is also applied (Randall *et al.*, 1981). Douglas (1987) and Douglas *et al.* (1988) found no effect of S on grain quality but Randall *et al.* (1990) suggested that a high

N/S ratio may affect flour and dough properties when grain protein is greater than 12.5%.

Yield responses to K fertiliser are rare in New Zealand but small responses have been recorded in Otago by Cossens and Feyter (1974). New Zealand wheat crops are normally grown in a rotation with legumes which require a soil pH of around 6, a level at which wheat is unlikely to respond to extra lime.

Where yield responses to any nutrient other than N occur, then the N content of the grain is likely to decrease due to dilution. Thus Douglas and Slay (1983) found that 0, 250 and 500 kg/ha of superphosphate produced wheat grain with 15.9, 15.0 and 14.3% protein contents respectively. The implications are obvious and apply to more than just plant nutrition: at any one level of available N, any factor which increases yield is likely to decrease grain protein contents.

## Conclusions

1. The relationships between soil fertility, grain yield and grain quality are complex and interact with other factors such as cultivar, season, soil type, disease and pest control, sowing date and soil water availability.
2. N is the nutrient most likely to affect yield and does so when available early by increasing the number of ears and grains per ear. Additional N at this stage can reduce kernel weight. The level of N available during tillering determines yield mainly through affecting tiller production and survival.
3. N is also the nutrient most likely to affect quality by influencing grain protein content. The level of N available during grain filling either from the soil or relocation within the plant, affects grain protein content.
4. The relationship between grain protein content and MDD baking score is positive but not consistent enough to be predictive across cultivars and seasons, especially once a level of about 12% protein content is reached.
5. No single tool or technique can be used to predict the optimum rate of N fertiliser application for maximum yield and quality. Paddock history, yield potential, soil type, paddock index, sap nitrate tests, soil tests, water availability and local experience, either alone or in combination, can assist with formulating fertiliser policies.
6. At any one level of available soil N any factor which increases yield is likely to decrease grain protein contents.
7. It is possible to achieve high yields of wheat with high levels of grain protein.

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