

## CHAPTER 6

### CROP NUTRITION Scott Black and Graeme Batten

Yield and the quality of products from crops are strongly linked to the supply of nutrients. Changes in the supply of nutrients, for example, have been the major factor influencing the trends in wheat yields since 1860 (Donald, 1965; Angus, 2001). Figure 6.1 shows that depletion in the supply of nutrients resulted in reduced yields from 1860 to 1900. Subsequent improvements in yield were related initially to improvement in the P (and possibly S) supply through the use of superphosphate. Improved N supply via the introduction of legumes and more recently greater use of N fertiliser contributed subsequently. Certainly improvements in crop rotations and introduction of herbicides have enabled these nutritional benefits to be realised. In addition, the quality of wheat grain as measured by the protein content is increased with the supply of nitrogen.

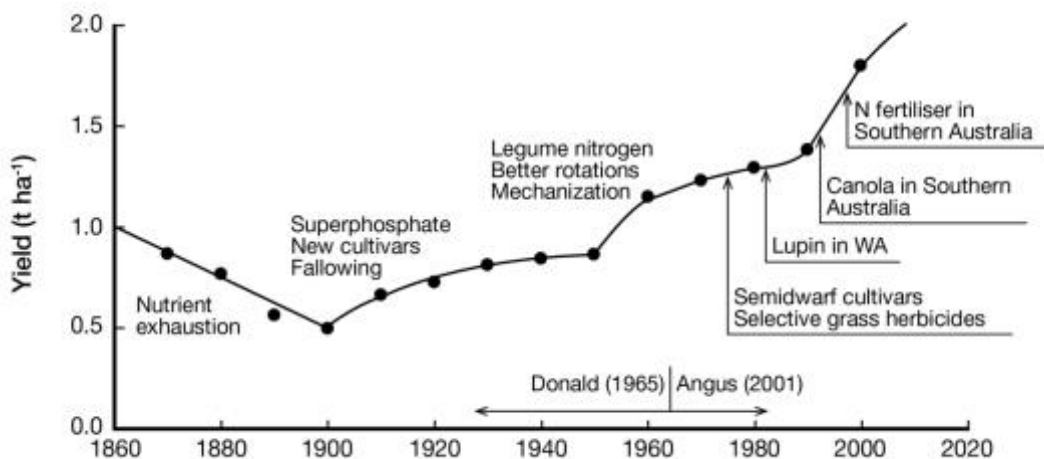


Figure 6.1 Decadal growth in Australian wheat yields influenced by technology developments (Grafton *et al.*, 2015 modified from Donald, 1965 and Angus, 2001).

In the absence of fertiliser application, most nutrients are supplied from the soil. Across Australia, N and P are almost universally deficient except in the virgin Black Vertosols of the Liverpool Plains and the Darling Downs. Sulphur deficiencies have often been masked by the widespread application of single superphosphate but tend to be confined to the 500-800 mm rainfall zones located on tablelands away from the coast. Calcium, Mg and K deficiencies are more common on sandy and/or low pH soils. The micronutrient deficiencies are closely linked to soil pH and aeration status of soils. In general, Fe, Mn, Cu and Zn deficiencies occur at pH above 7 while Mo deficiency occurs when pH is less than 5.

Excessive accumulation of nutrients needed for plant growth (e.g. Mn) and of some non-essential elements (e.g. Al) can depress yield. These toxicities are associated with excessive fertiliser use, pH extremes (Mn at low pH), salinity or sodicity. Accumulation of heavy metals in plant tissues, especially roots, follows growth on mining sites, the application of sludges, or the use of contaminated fertiliser.

The management of crop nutrition depends on an understanding of nutrient retention in soils, nutrient uptake by crops, assessment of the soil chemical condition and use of fertilisers.

### ESSENTIAL ELEMENTS FOR CROP GROWTH

Fifteen chemical elements are considered essential for plant growth, that is, plants will not complete their life cycle if they are not supplied. Each of these essential elements has defined physiological functions that have been described by Mengel and Kirkby (1987).

The composition of a normal plant in terms of these elements essential for plant growth is given in Table 6.1 which also includes oxygen, carbon and hydrogen although these are not normally grouped as nutrients. These are supplied from oxygen and carbon dioxide in the air and water respectively. The nutrients are grouped according to the quantity required for production. *Macronutrients* are needed in concentrations greater than 0.15 % of dry matter or are present at greater than 5 kg/ha in the mature plant tops. *Micronutrients* are those in concentrations less than 0.01% of dry matter or are present at less than about 1 kg/ha in the mature plant tops.

Table 6.1 gives an indication of the average concentrations of elements in crops, the forms taken up, and the quantity of nutrients within plant tops. In particular, Table 6.1 shows that crops remove large quantities of N and K in the harvested products, especially those taken for hay. Examples of P removal at harvest by other crops (kg/t product) are maize 3.3, sorghum 3.7, rice 2.9, field pea 4.9, and cowpea 6.9 (Glendinning, 2000).

Some plant species may require other elements for growth. Sodium may be necessary for plants with the C4 photosynthetic pathway and some halophytes such as saltbush (*Atriplex* spp.). Silicon is important for the strength of stem tissue of some crops such as rice (Savant *et al.*, 1997) and sugarcane. Legumes fixing N symbiotically require cobalt. This is a requirement of the *Rhizobium* spp. but has been observed also in growth responses by subterranean clover (*Trifolium subterraneum*) to cobalt sulphate applications (Ozanne *et al.*, 1963; Gladstones *et al.*, 1977).

Other elements, not essential for growth, may be taken up with soil water. These do not influence growth unless they accumulate in toxic concentrations (for example, Al, Cd, Cr, Pb and Hg).

Table 6.1 Concentrations and yields of nutrients in crops and the form absorbed by plants.

Element	Average elemental composition of tops (%)	Nutrient yield / ha to grow			Ionic form adsorbed
		Lucerne (hay yield of 10 t/ha) Per year (kg)	Wheat 7 t straw (kg)	4 t grain (kg)	
Macronutrient					
s	3-5	350	50	80	NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup>
N	0.2-0.6	35	5	14	H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>
P	2-4	200	42	17	K <sup>+</sup>
K	0.2-0.4	35	8	10	SO <sub>4</sub> <sup>2-</sup>
S	0.2-3.0	100	20	8	Ca <sup>2+</sup>
Ca	0.1-0.3	30	5	6	Mg <sup>2+</sup>
Mg					
	(mg/kg)	(g)			
Micronutrients	15-100	600			Mn <sup>2+</sup>
Mn	45-150	1500			Fe <sup>2+</sup>
Fe	10-90	450			Zn <sup>2+</sup>
Zn	2-20	100			Cu <sup>2+</sup>
Cu	0.1-0.5	15			MoO <sub>4</sub> <sup>2-</sup>
Mo	5-60	450			H <sub>2</sub> BO <sub>3</sub> <sup>-</sup>
B	300-1200				Cl <sup>-</sup>
Cl					
	(%)				
Other	43				
O	43				
C	6				
H					

### NUTRIENT RETENTION IN SOILS

Plants take up most nutrients as ions (Table 6.1) from the soil solution. The concentration of nutrients in solution is normally very low. Available N and P levels, for example, are less than 10 and 0.2 kg/ha respectively. These levels are insufficient to meet plant requirements. To grow a 4 t/ha wheat crop, for example, the above ground vegetation contains 130 and 19 kg/ha of N and P respectively (Table 6.1). However, nutrients are stored out of solution by a number of processes. As nutrients are taken up, the soil solution is replenished from these reserves. The rate of replenishment of nutrients to the soil solution is critical to the maintenance of the growth of a crop. The peak demand for nutrients (kg/ha/d) usually just precedes or coincides with periods of rapid dry matter gain, which occurs in most crops between floral initiation and flowering. If the amount of a nutrient in the soil solution is not

maintained from soil reserves then additions of that nutrient in the form of a fertiliser may be required to maintain plant growth and yield.

*The soil organic matter contains significant reserves of N, P and S within its structure. These organically bound nutrients are not plant available and must be released into solution in ionic forms ( $\text{NH}_4^+$ ,  $\text{H}_2\text{PO}_4^-$ , and  $\text{SO}_4^-$  respectively) following oxidation of the carbon compounds by microorganisms (the process of mineralisation). The rate of this biological process depends on favourable environmental conditions of temperature, moisture, aeration and pH. Net mineralisation occurs if the C:N ratio is greater than about 10.*

Organic matter also retains micronutrients such as Cu through the formation of complexes so that deficiencies can occur in peats and peaty soils. Release is slow depending on biological activity.

*The nutrients present as cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$ ) are principally stored on negatively charged sites (cation exchange sites) on the clay minerals such as kaolinite, illite and smectite and on organic matter. These exchangeable cations rapidly replenish the soil solution as cations are taken up by plants.*

*Potassium and  $\text{NH}_4^+$  are also trapped in the interlayer spaces of clay layer silicate minerals especially, illite and vermiculite. Release of this 'fixed' K and  $\text{NH}_4^+$  is slow.*

*The anions, especially phosphate and molybdate, are adsorbed on the surfaces of clay minerals, particularly kaolinite, and the oxides and hydroxides of Fe and Al. The adsorption process does not depend on charge attraction, is rapid and strong bonds are formed. Consequently desorption back into the soil solution is a slow process.*

*Nitrate is not normally adsorbed on the soil clays so is readily lost by leaching in water that percolates through the soil. There are a few soils that have positive charge on their surface and the rate of nitrate leaching is reduced (Black and Waring, 1976b).*

## **NUTRIENT UPTAKE BY CROPS**

For a plant to be able to acquire any nutrient, the nutrient must be accessible to the plant, be in a form that the plant can acquire and the plant must be actively growing.

Most nutrients enter plants via the root system. However, some elements in a gaseous form enter via the stomata in leaves while others can enter through the foliage when present on the surface.

The root surface contacts nutrients in the soil solution through:

- *mass flow of soil solution* to the root, largely driven by extraction of water from the soil by roots to balance losses due to transpiration in the shoots of the plant. The resulting water potential gradient conveys water and the nutrients it contains towards the root.
- *growth* that extends the root allowing it to make direct contact with nutrients.

- *movement of nutrients* to the root surface along a concentration gradient within the soil solution. As a root removes a nutrient from the soil solution, the concentration of that element in the soil solution adjacent to the root surface falls. The concentration of P in the soil solution can be 25 times higher 2 or more millimetres from the root surface compared to the concentration within 1 mm of the root surface (Hendriks *et al.*, 1981).

The volume of soil explored by roots relates to the distance ions have to move for uptake. Root volume is influenced by:

- *environmental conditions* Roots proliferate in areas of soils where moisture or nutrients are more abundant. Fewer roots are found in areas of the soil which are dry, compacted, infertile or in portions of the profile with high concentrations of  $H^+$ ,  $Mn^{2+}$ ,  $Al^{3+}$  or other toxic ions.
- *the presence of symbiotic mycorrhizal associations* These are infections of fungi which utilise carbon from the host plant and may provide, in return, an enhanced ability of the roots to acquire water and nutrients such as phosphorus and zinc. The effectiveness of mycorrhizal associations is generally greatest in infertile soils but is reduced or eliminated when inorganic phosphatic fertilisers are applied (Marschner, 1986).

Table 6.2. Root cation exchange capacity of a number of plant species grown under two levels of nitrogen (Asher and Ozanne, 1961).

Plant	Root cation exchange capacity (meq/100g dry weight of root)	
	High nitrogen	Low nitrogen
<i>Legumes</i>		
Field pea	32.4	33.9
Barrel medic	26.6	32.3
Subterranean clover	28.9	25.6
Lupins	16.8	19.8
<i>Herbs</i>		
Canola	32.7	36.3
Tomato	18.6	20.9
Capeweed	21.2	16.8
<i>Grasses</i>		
Annual ryegrass	22.1	12.0
Maize	12.0	8.8
Oats	7.4	9.5
Wheat	10.2	6.3
Barley	7.6	7.7

Other root properties, for example the cation exchange capacity, influence the balance of nutrients taken up by the roots. Plant roots with high cation exchange capacity, such as legumes and broadleaf plants, tend to absorb more divalent than

monovalent cations. The legumes and broadleaf plants tend to accumulate higher concentrations of calcium and are more susceptible to potassium deficiency than grasses. Root cation exchange capacities for several legume, broadleaf and grass species are shown in Table 6.2. The exchange capacity of some grasses is reduced under a low nitrogen supply but there is little influence on other species.

The intake of a nutrient by plants can be by:

- *a passive process* if the concentration gradient from the soil to the root across the plasmalemma favours influx of an ion, for example, Ca.
- *an active and selective mechanism* If nutrients are present in the soil solution at concentrations that are low relative to the concentrations within the root, uptake occurs against a concentration gradient. Common examples are  $K^+$ ,  $NO_3^-$  and  $H_2PO_4^-$ . This active uptake process of nutrient transport possibly involves different transporters for nutrient groups. Active nutrient uptake is very sensitive to oxygen supply and temperature changes.

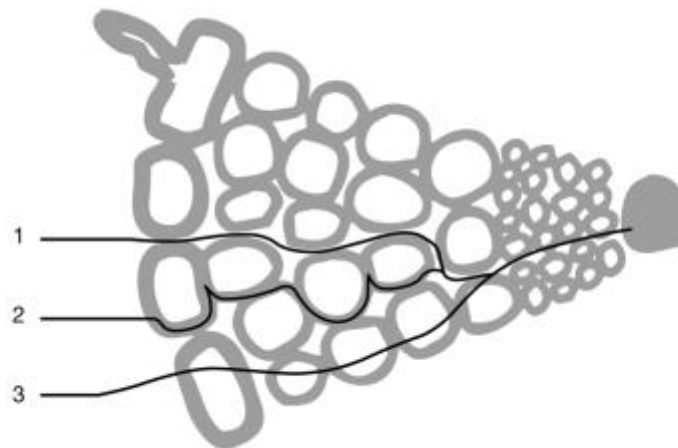


Figure 6.2. Pathways for ion movement into the root (1) via apoplasm, (2) via symplasm and (3) transcellular through the vacuoles (adapted from Atwell *et al.*, 1999).

Figure 6.2 illustrates the three proposed pathways of nutrient transfer across the root cortex to xylem after entry via the epidermis. These are: (1) apoplasmic (extra cellular) (2) symplasmic (intracellular) and (3) transcellular (that involves movement through the vacuoles of cells, that is, transvacuolar) pathway. At the endodermis or Casparian Strip the pathway to the xylem vessels is via the symplasmic pathway.

A small proportion of the nutrients taken up return to the soil from the roots (efflux or release of nutrients from roots). The rate of efflux relative to uptake becomes critical in plants under stresses such as calcium and zinc deficiency (Welch, 1995). High soil salinity can cause substitution of sodium for calcium in the plasmalemma resulting in disruptions to nutrient transport and loss of selectivity.

Elements in soil that are non-essential or toxic to plants may be taken up by roots or selectively excluded. Wheat genotypes have been selected with the ability to exclude  $\text{Al}^{3+}$  ions (Scott and Fisher, 1989).

Transport of nutrients to shoots and leaves is rapid and largely by mass flow in the transpiration stream. After being deposited into shoot tissues, some nutrients can be transferred within the plant via the phloem. So called phloem-mobile nutrients include N, K and P while phloem immobile nutrients include Ca. Nutrients such as copper are of variable mobility, being translocated if the plant has adequate amounts of Cu and N but are not retranslocated if the plant is in a deficient state.

### DIAGNOSING NUTRIENT DEFICIENCIES AND TOXICITIES

*Early diagnosis of nutrient deficiencies is critical to achieving yield potential.* In addition, as fertilisers are a major variable cost in cropping, accurate and timely diagnosis of fertiliser requirements affects profitability.

For research on plant nutrition and diagnosis of problems related to nutrient supply, Andrew and Fergus (1976) described the use of solution culture and glasshouse and field experiments.

- *Solution culture* is growth of plants in water to which each of the essential elements may be added in various concentrations. This technique is used to confirm that an element is essential and to enable deficiency and toxicity symptoms to be identified and related to the concentration of elements in plant tissues.
- *Pot experiments* where soil is placed in containers to enable rapid initial evaluation of the relative chemical fertility status of many soils under controlled environmental conditions at a moderate cost. Where only surface soil is used, supply of nutrients from the subsoil, especially N as  $\text{NO}_3^-$  and S as  $\text{SO}_4^{2-}$ , cannot be assessed. The temperature and moisture conditions in the glasshouse relative to the field alter the availability of many nutrients. For example, careful control of soil water in the pots is necessary to prevent of  $\text{NO}_3^-$  losses by leaching or denitrification.
- *Replicated field experiments* including rates of fertiliser application are costly because of distance between sites and the need to conduct the experiments over at least three years to include the effects of seasonal variation in climate. The data on growth response to fertiliser application from these experiments remain the benchmark against which soil and plant analysis techniques can be assessed.

For routine assessment of nutrient supply from soils for management purposes, techniques such as field test strips, soil analysis, observation of visual symptoms and plant analysis are used.

- During crop establishment, a series of *unreplicated strips* within the field can have fertiliser added or omitted (Dear and Smith, 1983). For example, where a crop is receiving single superphosphate and urea, strips without urea or superphosphate may be included within the paddock. Crop growth and colour can be observed

where both were added and where each was omitted. Results are a guide to fertiliser needs in the next season.

- *Soil analysis or testing* is a widely used technique to monitor changes in chemical soil fertility and to estimate fertiliser requirements. Peverill *et al.* (1999) provide an extensive review of this topic. Soil testing involves the collection of soil samples, extraction and analysis of a chemical fraction and interpretation of the data in terms of likely crop performance in a given environment.

*Because of high spatial variability, both horizontally and vertically, collection of the soil sample is the major source of error in soil analysis data. A sample must be representative of the field being sampled. Where the soils or crop performance are known to vary within a field, a sample is collected from each major area. Small areas of different soil may be ignored. Commonly 15-20 locations per sample are necessary to minimise the effects of soil variability. The depth of sampling is commonly 0-10 or 0-15 cm for most crops and nutrients. However where subsoil accumulations of available forms of nutrients contribute to crop growth, deeper sampling is recommended. For example where NO<sub>3</sub><sup>-</sup> accumulates in the subsoil prior to sowing, sampling to 60 or 80 cm is common.*

Other activities can increase the variability in soil properties, for example, grazing and fertiliser, lime or gypsum application. To manage this variability, soil should not be collected within 1 month of fertiliser application or grazing or 6 to 12 months after liming.

Table 6.3. A brief description of the common soil tests used for phosphorus (Holford *et al.*, 1985).

Soil test	Extractant	pH	Soil/solution ratio	Shaking time
Bray <sub>2</sub>	0.03 M ammonium fluoride +0.01M hydrochloric acid	1.0	1:7	40s
Bray <sub>1</sub>	0.03 M ammonium fluoride +0.025M hydrochloric acid	3.0	1:7	60s
Mehlich	0.025 M sulfuric acid +0.05M hydrochloric acid	1.0	1:4	5mins
Truog	0.002 M sulfuric acid +0.3% M ammonium sulfate	3.0	1:200	30mins
Lactate	0.02 M calcium lactate +0.01 M hydrochloric acid	3.7	1:50	1.5h
Fluoride	0.5 M ammonium fluoride	8.5	1:50	30mins
Olsen	0.5 M sodium bicarbonate	8.5	1:20	30mins
Colwell	0.5 M sodium bicarbonate	8.5	1:100	16h



Even for a specific nutrient, many soil analysis procedures are used. Table 6.3 shows that for assessment of P availability, numerous chemical extraction procedures have been reported. Criteria for selecting the test for use in crops for a region is based on the correlation between soil test values and crop response derived from extensive field experimentation, that is, how well the test is calibrated with yield. The relationship can vary between crop species. Figure 6.3 shows that for one selection of soils the Colwell test has a better correlation than the Truog test. The critical value for the Colwell test, that is, the test value over which response to fertiliser is unlikely, was  $42 \mu\text{g P/mL}$  of soil. Commonly the calibration curves are used to provide broad ranges. For example, in Figure 6.3, responsive, response uncertain and response unlikely ranges would be: less than 30, 30 to 50 and greater than 50 respectively. Other considerations in the selection of a test include the safety of chemicals used in the laboratory and ease of analysis.

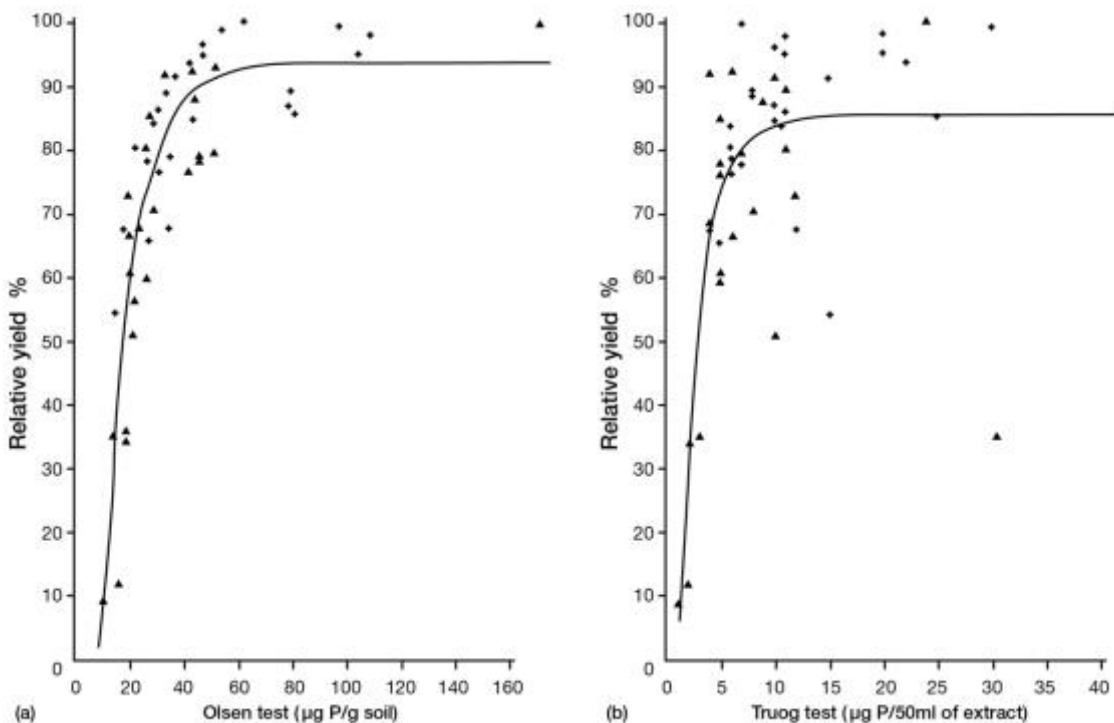


Figure 6.3. Soil test calibration curves for wheat using (a) Olsen and (b) Truog procedures (from Grigg, 1977).

*The final decision on fertiliser requirements must be based on more than the soil test data alone.* Soil tests are calibrated for 90 or 95 % of maximum yield. Fertiliser inputs would be less than predicted from the soil test if management of weeds or diseases is inadequate or other soil problems or adverse climatic conditions restrict yield. Decision support systems such as 'Nitrogen calculator' (Bowden and Diggle, 1995), maNage rice (Angus *et al.*, 1996), SUPERATE (Maling *et al.*, 1984) and Lim-it (Hochman *et al.*, 1989) that include the many variables above plus economic consequences from fertiliser application aid in achieving the final recommendation.

- *Plant analyses* provide a measure of the concentration(s) of elements in plants, both essential and toxic, and provide a basis for fertiliser applications. The sampling intensity is usually less than for soils as plants analyses indicate the fertility of the soil in the root zone. Reuter and Robinson (1997) provided a major review of plant analysis.

There are two broad types of analysis:

- *Total or quantitative analysis.* Plant samples are analysed in a laboratory for the total element concentration. The need for chemical analysis may increase the time between sampling and the availability of the data. Rapid analysis of samples in the laboratory has been successfully achieved through the adoption of near infrared reflectance spectroscopy (Batten, 1998)
- *Tissue tests.* These are normally done in the field and determine the concentration of the element in the sap and cell contents. Sap is placed on paper containing chemicals which changes colour as the concentration of the element in the sap changes.

For diagnostic purposes, there must be a correlation between the nutrient concentration and yield as shown in Figure 6.4. Once a critical concentration is achieved, yield does not change until affected by toxic concentrations (Figure 6.4).

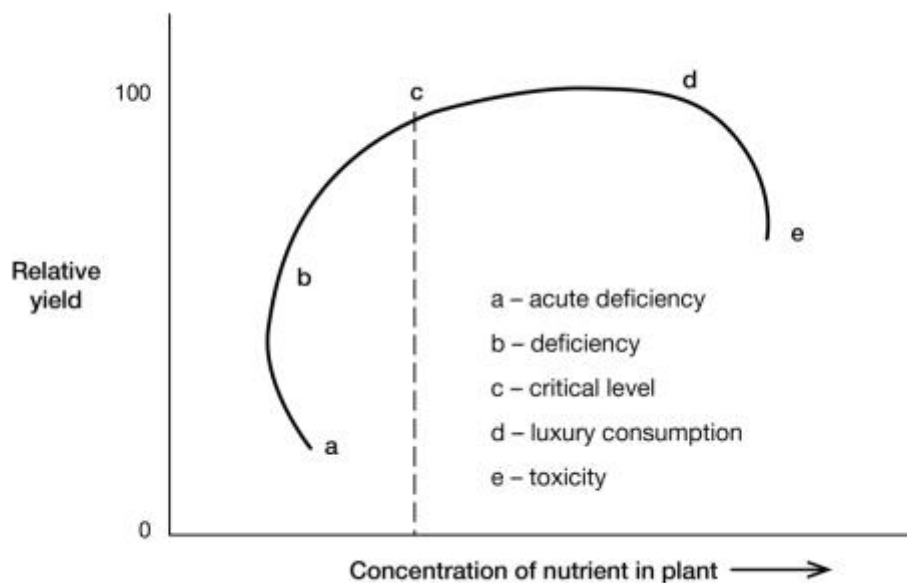


Figure. 6.4. A typical relationship between relative yield and nutrient concentration in plant tissues.

When interpreting plant nutrient analyses it is important to appreciate situations which influence the relationship between nutrient concentration and final yield.

- In very young plants, the nutrient requirements are low leading to high tissue concentrations regardless of the final yield. When plants are sampled later, the tissue concentrations reflect the nutrient supply from the soil. However by that time, the crop may have reached a stage of growth where fertiliser application may be too late to achieve a yield response.

- Different plant parts show different relationships between yield and nutrient concentration leading to different values for the critical concentration. Stem tissue generally has a lower nutrient concentration than leaf tissue.
- The critical concentration during early stages of growth is normally higher than as the crop approaches maturity, that is, it decreases as the crop matures.
- Critical values differ between crop species and even cultivar.

*Limitations to the use of plant analysis are managed by specifying plant part and age, for example, the youngest fully expanded leaf.*

*Visual symptoms* occur on plants subjected to stress. Symptoms include chlorosis (N, S, and Mo deficiency), necrosis (Ca deficiency), deformed growth (Mn toxicity) or simply reduced growth. The age of the tissue and the distribution of the symptoms, especially on leaves, give a good guide to the causal nutrient deficiency or toxicity. Descriptions of symptoms for different crops can be found in Grundon (1987) and Reuter and Robinson (1997). While symptoms are easy to see, interpretation can be difficult. The following difficulties are encountered:

- deficiencies of several nutrients may cause the same symptoms - for example N, S and Mo deficiency all cause chlorosis.
- different crop species show different symptoms for the same nutrient deficiency.
- symptoms may be due to a combination of nutrient deficiencies, or other stress factors such as climatic extremes, disease or insect attack.

A major drawback to the use of visual symptoms is that by the time symptoms occur, yield has been generally permanently lost.

*The rate of fertiliser application needs to be estimated* once a deficiency has been diagnosed. *This decision may be based on:*

- *local knowledge* of crop responses, commonly used.
- *soil tests* to estimate the rate of fertiliser application. Additional information for example with P estimates of the P buffer capacity (the change in available P concentration with increasing P input) are required. Figure 6.5 shows that for a Colwell P test value of 30  $\mu\text{g/g}$  a soil with a low buffer capacity requires no fertiliser. The second soil with the same test but with a moderate buffer capacity, requires 12 kg P/ha.

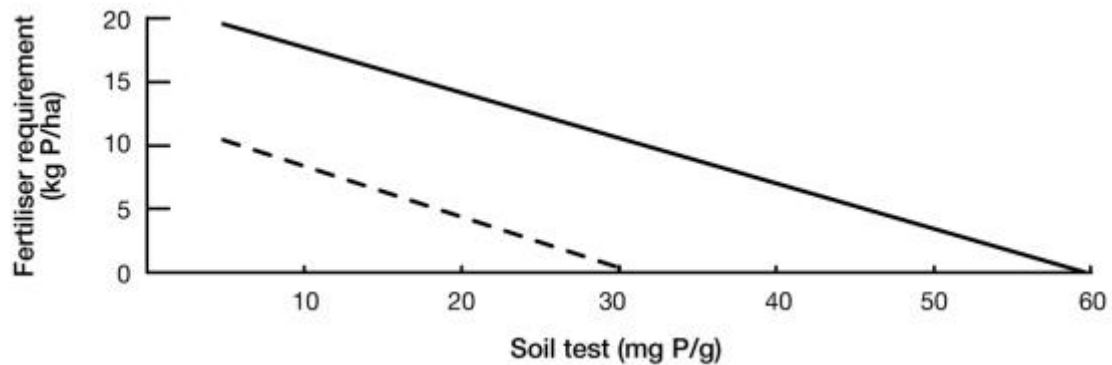


Figure 6.5. Fertiliser required to give 90% of maximum yield based on the Colwell soil test. Buffer capacity moderate (line) and low (dashed line) (Redrawn from Holford and Cullis, 1985).

- *Nutrient budgeting* where estimates of product removal and other losses are used to estimate the minimal requirement for any nutrient in a cropping system. Table 6.1 shows that a wheat crop yielding 4 t/ha removes 14 kg P/ha in the grain. Unless the quantities removed are replaced the P concentrations in soil will decrease.

### CORRECTION OF DEFICIENCIES

Most nutrient deficiencies in soil are overcome by the use of fertilisers. To reiterate, Australian soils are universally deficient in phosphorus, so P fertilisers are the most commonly used. Nitrogen deficiency is also a major problem, but legume-based pastures grown in rotation with crops provide much of the N required in cropping areas of southern Australia. The N inputs to soil from pasture and grain legumes have been reviewed by Peoples *et al.* (1992).

The average ratio of use of N:P fertilisers on an Australia-wide basis was 1:13 until 1960. This reflected the widespread use of single superphosphate, with legumes as the N source for crops. Soil limitations and variable climate suggest that a combined cropping/livestock program with legume-based pastures providing N is likely to continue in the southern wheat belt areas. However, between 1970 and 1985 the ratio of N:P fertilisers used in Australia declined to 1:1, and by 2001 was almost 3:1 as a result of greater N fertiliser use on cotton, sugar cane, wheat, rice and for production horticulture. More recently, Angus (2001) concluded that there was no evidence that increasing dependence on fertiliser N was weakening in mixed cropping in southern Australia.

Many existing sulfur deficiencies have been overcome by the extensive use of single superphosphate. Major S deficiencies occur in the greater than 500 mm annual rainfall belt because of S loss by  $\text{SO}_4^{2-}$  leaching (Blair and Nicholson, 1975). In coastal areas, S deficiency is less common because of S returns from the atmosphere. Potassium and Mg deficiencies are confined to sandy soils, especially if the soils are acid, or to soils where the removal of nutrients by harvesting is high.

The extent of micronutrient deficiencies in soils used for crop and pasture production was reviewed by Donald and Prescott (1975). Specific reviews have also been published for manganese (Graham *et al.*, 1988), copper (Loneragan *et al.*, 1981) and zinc (Weir, 1987). Zinc deficiency is now widely recognised in alkaline clay soils in northern New South Wales and the Darling Downs in Queensland. In these areas, substantial yield responses to zinc supplements are obtained in grain sorghum, cotton and soybeans. Manganese and iron deficiencies occur on calcareous soils, while manganese toxicity occurs when the pH declines below 5.5 or the soils become waterlogged. Molybdenum deficiency is common where soils have become acidic because of the decreased availability at low pH. Wheat yield responses to molybdenum have been obtained on soils high in nitrate (Lipsett and Simpson, 1971). Correcting micronutrient deficiencies normally involves topdressing with micronutrient fertilisers, mixed into superphosphate, to ensure even distribution. Most micronutrients are applied at 3 to 10 year intervals.

### **Principles of Fertiliser Management**

There are two key principles for successful fertiliser management:

- *Management attempts to maintain the balance between the nutrient uptake by crops and the supply from soil and/or fertiliser sources (Myers, 1988).* Implicit in this statement is the need to know the nutrient uptake pattern by crops. Figure 6.6 shows the typical pattern of uptake in most crops. Of particular importance is the observation that the rate of uptake of N, P and K occurs at or just prior to the high rate of dry matter accumulation. The association between N, P and K uptake and dry matter yield for grain sorghum (Jacques *et al.*, 1975) and soybeans (Hanway and Weber, 1971) has been described in detail. In addition, if nutrients are to be applied, it is necessary to appreciate factors which control the release of the soil nutrient reserve throughout the cropping period.
- *Management attempts to minimise adverse effects associated with fertiliser application.* The effects of particular concern are:
  - reactions in soil which reduce the availability of applied fertiliser.
  - adverse side effects including pH extremes and toxicities induced by fertilisers, salinity hazards associated with application of high rates of soluble fertiliser and contamination of soil with non-essential elements such as Cd.

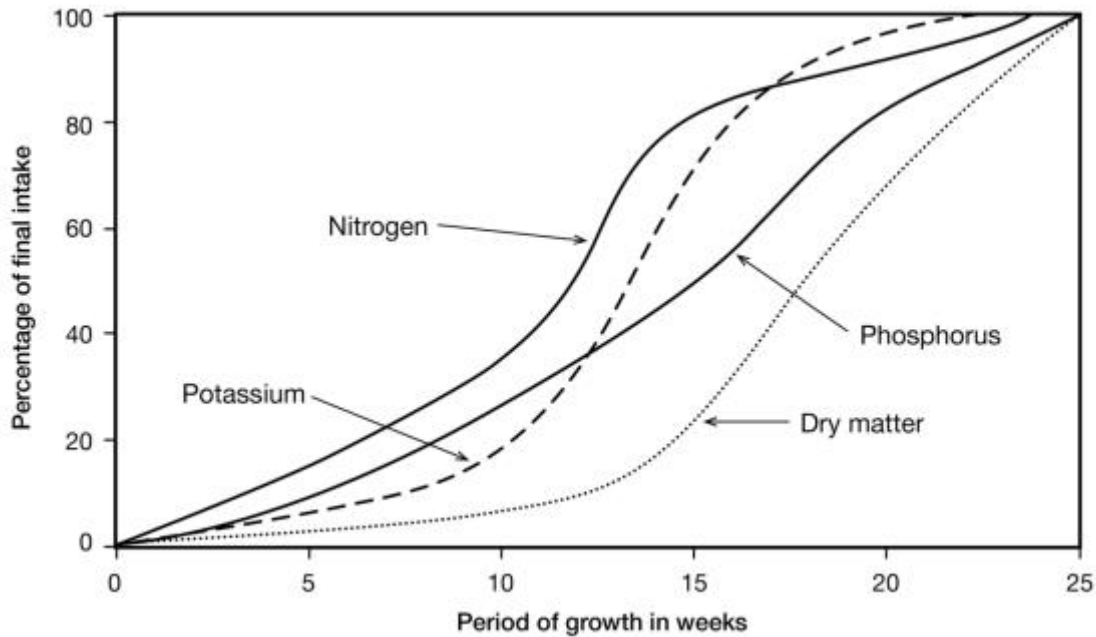


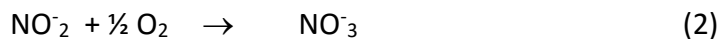
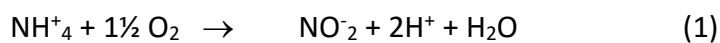
Figure 6.6. Uptake of nutrients and production of dry matter in barley (Wild, 1988).

To illustrate these points, examples with N, P and K fertilisers are set out below.

### **Nitrogen Fertiliser**

The N yield in plant tops ranges from 50 to 350 kg N ha<sup>-1</sup> (Table 6.1). Figure 6.7 shows the pattern of accumulation of N by wheat grown at Harden, NSW (Stein *et al.*, 1987). The period of maximum N accumulation in the plant tops occurs during August and early September. The principal form of N taken up by crops is NO<sub>3</sub><sup>-</sup> although NH<sub>4</sub><sup>+</sup> can be utilised.

Over 95 % of N present in soil occurs in organically bound forms. Soil microorganisms must mineralise organic N before it is available to the plant. The oxidation of NH<sub>4</sub><sup>+</sup> to NO<sub>3</sub><sup>-</sup> (nitrification) is a two-stage biological oxidation carried out by a few chemoautotrophs. The processes can be written as



*Nitrosomonas* and *Nitrosococcus* spp. are active in the first oxidation, and *Nitrobacter* spp. are responsible for the second.

Because both mineralisation and nitrification are biological processes, environmental factors such as temperature, aeration, pH and moisture content control the rate of these processes. Haynes (1986) reviewed these processes and the effect of environment on the rate of transformation. Figure 6.7(b) shows an example of the close association between seasonal changes in temperature and net mineralisation under a wheat crop (Stein *et al.*, 1987). A comparison of Figures 6.7(a) and (b) shows that, in spring, the rate of N uptake and net mineralisation increase at the same time. This is a good example of a balance between N supply and plant requirement. Figure

6.7(b) also shows that a proportion of soil N is mineralised in autumn, indicating a lack of balance between N supply and N uptake. Nitrate formed in autumn may be lost by leaching or denitrification before uptake can occur. In the winter cereal growing areas of Queensland there is poor balance between soil mineralisation and crop uptake (Myers, 1988). Nitrogen is mineralised during January to April when temperatures and moisture are favourable whereas the maximum rate of crop uptake does not occur until August to September. On the heavy clay soils, losses of  $\text{NO}_3^-$  are common.

The coincidence of conditions slowing mineralisation in spring (for example, by low soil temperatures) with the period of high plant demand can result in the N supply from soil controlling crop growth. Angus (1988) defined the following situations where fertiliser N responses by wheat are likely: soil pH above 4.5, no serious soil-borne disease or weeds, 'normal' sowing date, adequate soil water, low crop-nitrogen status, low tiller numbers and N fertilisation no later than DC30.

The introduction of reduced tillage has influenced the depth from which N is mineralised. Purnomo *et al.* (2000) found that approximately 30 % of the N taken up by a wheat crop was derived from mineralisation in the surface 2 cm of soil. Over 60 % was derived from the surface 6 cm. Less disturbance of soil has concentrated the easily decomposable organic matter in the very surface soil.

#### **ADVERSE N FERTILISER REACTION**

The application of nitrogen fertilisers can have unintended consequences. For the crop this can mean reduced plant available N than that applied. There can also be some adverse side effects.

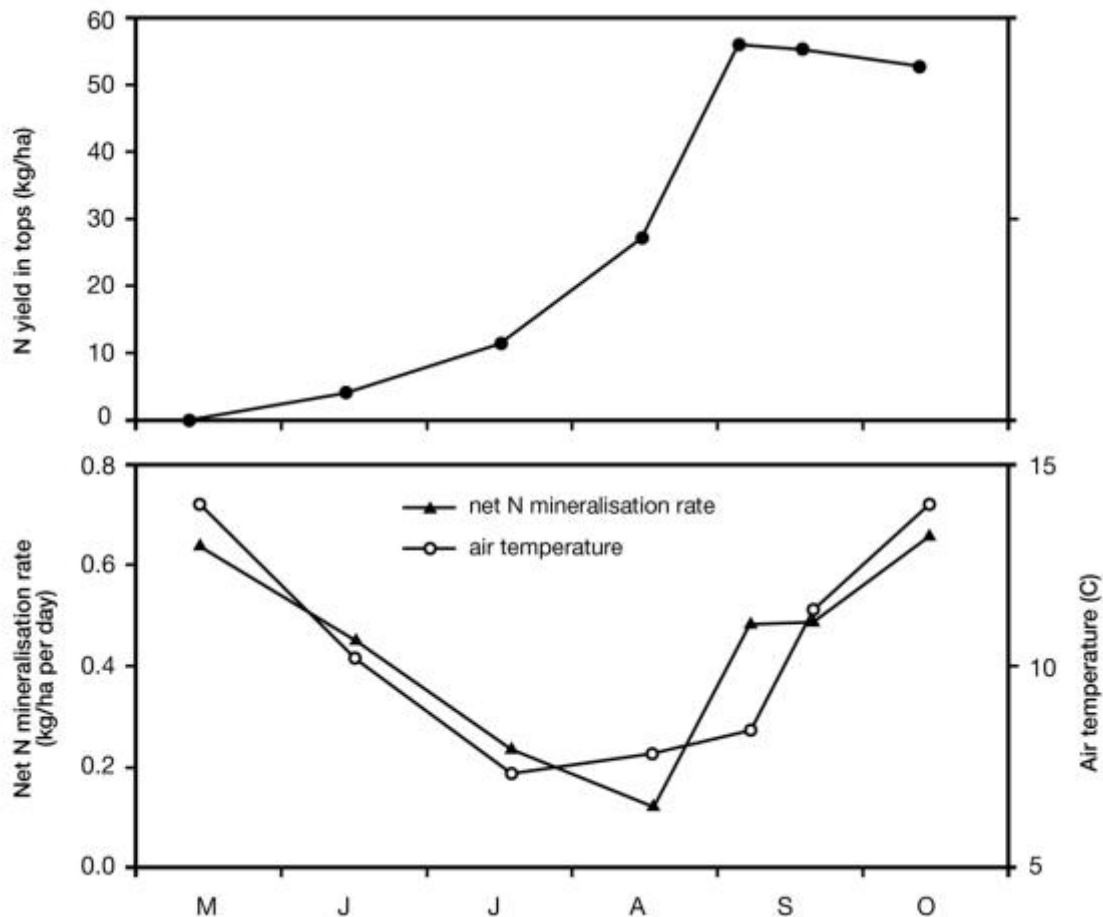


Figure 6.7. The seasonal pattern of (a) N uptake by wheat and (b) N mineralisation rate and soil temperature (Stein *et al.*, 1987).

- (i) Reduced plant availability – Nitrogen fertilisers are applied usually as either:  
 $\text{NH}_4^+$ , for example: sulfate of ammonia,  $(\text{NH}_4)_2\text{SO}_4$   
 ammonium nitrate,  $\text{NH}_4\text{NO}_3$   
 diammonium phosphate (DAP),  $(\text{NH}_4)_2\text{HPO}_4$   
 monoammonium phosphate (MAP),  $\text{NH}_4\text{H}_2\text{PO}_4$
- (ii)  $\text{NH}_4^+$ -producing forms, for example: urea,  $(\text{NH}_2)_2\text{CO}$   
 anhydrous  $\text{NH}_3$

An accumulation of  $\text{NH}_4^+$  can result in loss by  $\text{NH}_3$  volatilisation if the soil pH exceeds 8. A major review of the process was reported by Freney and Black (1988). This high pH may result from fertiliser reaction such as urea hydrolysis or occur when soils have a naturally high pH. Losses by volatilisation may be negligible but can exceed 20% if urea is broadcast onto wheat in spring (Black *et al.*, 1987).

Following nitrification, further N losses can occur via denitrification or leaching. Denitrification occurs when soils become anaerobic and  $\text{NO}_3^-$  is used as the electron acceptor for soil biological oxidation processes. The products are the gases  $\text{N}_2\text{O}$  and  $\text{N}_2$ . The principal cause of low oxygen levels in soils is waterlogging. In well-drained cropping soils, losses range from 0 to 30 % of the N fertiliser applied (Haynes and Sherlock, 1986), but where  $\text{NO}_3^-$  accumulates in soil before flooding (such as under



rice) almost all  $\text{NO}_3^-$  is lost by denitrification. Simpson (unpublished data) found recovery of  $^{15}\text{N}$  fertiliser in the soil and wheat tops was 92 % in a well-drained Red Chromosol at Wagga Wagga and 46 % on a poorly drained Sodosol at Whitton, NSW. Because of the impervious B horizon and associated waterlogging in the Whitton soil, the losses were attributed to denitrification.

*Losses of N by denitrification can be reduced in arable crops by:*

- ensuring that fertiliser application is split (the bulk of the fertiliser N being applied after the period of waterlogging).
- the use of  $\text{NH}_4^+$  forms amended with N Serve<sup>®</sup> which slows the rate of  $\text{NO}_3^-$  accumulation though the effects may be short lived.
- the use of slow release fertiliser forms.

*Leaching losses of  $\text{NO}_3^-$  are rapid and most severe in high rainfall environments.* Black and Waring (1976a) showed that  $\text{NO}_3^-$  leached to a depth of 2 m following 2800 mm of rainfall at Redland Bay in Queensland. In contrast, Storrier (1965) found that under wheat in southern NSW in a 500 mm/annum rainfall environment,  $\text{NO}_3^-$  was leached to 0.6 m during the winter months but was later recovered by the crop during spring as the  $\text{NO}_3^-$  remained within the root zone.  $\text{NO}_3^-$  leaching represents not only a loss of N for crop growth but also results in acidification of surface soil where fertiliser forms other than  $\text{NO}_3^-$  are used. Pollution of ground waters can also occur. In the southern Australian wheat belt, the quantity of N leached can be reduced by early sowing of crops (Strong, 1992) which ensures that N mineralised during the autumn break is recovered by plant uptake before leaching commences. Leaching of  $\text{NO}_3^-$  has been reviewed by Cameron and Haynes (1986) and White (1987).

*Adverse Side Effects* – there are some negative effects to crop and soil from Nitrogen fertilisation.

*$\text{NH}_3$  or  $\text{NO}_2^-$  toxicity* can occur when anhydrous ammonia is injected into soil or high rates of urea are applied. Under these conditions, high pH at the point of application can result in inhibition of the second stage of nitrification. Passioura *et al.* (1972) demonstrated that the accumulation of  $\text{NO}_2^-$  restricted root development in the zone of urea fertiliser placed in bands. Anhydrous and aqua ammonia should be placed at least 7 cm from the seed, while urea should not be banded with seed at rates over 40 to 60 kg N ha<sup>-1</sup>.

*Salt damage*, especially to germinating seedlings, can occur if the N fertilisers are placed near growing plants. Most N fertilisers are highly soluble salts so they will reduce water availability. The resultant damage is a salt effect similar to that in saline soils.

*Acidification of soil can result following the application of  $\text{NH}_4^+$  and  $\text{NH}_4^+$ -producing fertilisers.* The protons produced during the first stage of nitrification can be neutralised, in part, by alkali excretion during  $\text{NO}_3^-$  uptake. The protons remaining in the surface soil after  $\text{NO}_3^-$  leaching are a major cause of acidification in soils (Helyar and Porter, 1989). Cregan and Helyar (1986) grouped the N fertilisers as follows:

high acidification	$(\text{NH}_4)_2\text{SO}_4$ , $\text{NH}_4\text{H}_2\text{PO}_4$
medium acidification	$(\text{NH}_4)_2\text{HPO}_4$
low acidification	urea, $\text{NH}_4\text{NO}_3$ , anhydrous ammonia
alkaline fertilisers	$\text{Ca}(\text{NO}_3)_2$ , $\text{NaNO}_3$

Henzell (1971) reported that, following six annual applications of  $(\text{NH}_4)_2\text{SO}_4$ , urea and  $\text{NaNO}_3$  at 448 kg N/ha to a Red Chromosol, the change in pH to a depth of 15 cm was -1.1, -0.3 and + 1.0 respectively.

*Eutrofication* of creeks and other water bodies occurs if contaminated by N and P fertilisers.

### **Phosphorus Fertiliser**

The P uptake by plant tops ranges from 10 to 34 kg P ha<sup>-1</sup> with  $\text{H}_2\text{PO}_4^-$  being the form taken up from the soil solution (Table 6.1). Between 50 and 80% of soil P is associated with organic matter (Dalal, 1976) and release by mineralisation is subject to environmental parameters as with N. The remainder is associated with the inorganic fraction.

### **ADVERSE P FERTILISER REACTIONS**

(i) *Reduced Plant Availability - Immobilisation* of between 40 and 100 % of applied phosphatic fertiliser occurs under pastures when organic matter levels are increasing. In contrast, only 13 % (McLaughlin *et al.*, 1988) and 11 % (Friesen and Blair, 1988) of applied fertiliser P entered the organic fraction under cropping. McLaughlin showed that 71 % of applied P entered the inorganic fraction.

The mechanisms by which soluble fertiliser P enter the inorganic fraction and become much less available include *precipitation* of insoluble Ca, Fe and Al phosphates, and *adsorption* onto soil mineral surfaces (Fe and Al oxides, in particular). Sanyal and Datta (1991) and Greenland and Hayes (1981) have given comprehensive reviews of these processes. Following the rapid reactions which occur on fertiliser addition, slow reactions continue which result in a decrease in the levels of soluble P in soils with time. Barrow (1974) demonstrated very clearly the decline in available P as P was exposed to soil for prolonged periods, especially at higher temperatures. These reactions are sufficiently strong that, in most soils, P is not leached and accumulates at the depth of placement.

*Management of adsorption reactions with soluble P fertilisers often involves drilling near the germinating seedling to:*

- ensure rapid uptake of P through close contact.
- restrict the volume of soil in contact with applied fertiliser and the time of contact before plant uptake.

Rudd and Barrow (1973) reported a number of field trials which showed that drilling superphosphate at sowing gave superior yield responses compared to mixing it with soil at sowing or applying the fertiliser several months before sowing.

*Leaching of P fertiliser below the root zone rarely occurs.* The distribution of total soil P with depth after application of superphosphate for 35 years to a silt loam soil is shown in Table 6.4. There is evidence of accumulation of P to the 150-225 mm depth interval but not below this depth. Most of the accumulation occurred in the surface 150 mm. Leaching does occur in soils where the reactive clay component is absent, such as the deep sandy soils in Western Australia (Bolland, 1986) and South Australia (Lewis *et al.*, 1981).

Table 6.4. The amount of total P (kg/ha) in four soil depths after 35 years of superphosphate application at three rates (from Nguyen *et al.*, 1992).

Soil depth (mm)	1952	1987			
		Rate of single superphosphate applied (kg/ha)			
		0	188	376	standard error
0-75	538	598	704	871	9.2
75-150	558	595	737	841	10.1
150-225	554	577	627	683	8.7
225-300	470	465	465	474	8.7

*The use of less soluble forms of P*, especially finely ground reactive phosphate rock, reduces the impact of soil reaction and leaching. Rock phosphates are variable in composition and low in solubility. Because of their low solubility, they must be mixed through soils with a pH of less than 5 (0.01 M CaCl<sub>2</sub>) to achieve agronomic response in crops (Bolland *et al.*, 1988).

(ii) *Adverse Side Effects - Salt hazards are not normally associated with P fertilisers* as they are not sufficiently soluble. The exceptions to this are the more soluble ammonium-based P fertilisers (DAP and MAP). Superphosphate can adversely influence *Rhizobium* spp. survival if the seed is mixed with the fertiliser.

*The addition of the heavy metals* such as Zn, Cu, Mn and especially Cd to the soil is a possible problem with the use of P fertilisers (Tiller, 1989) with root crops. McLaughlin *et al.* (1996) reviewed the risks associated with the accumulation of As, Cd, F, Pb and Hg. They considered that inputs to soil in fertilisers and removal in harvested crops indicated that Cd and F accumulated in fertilised soils at a faster rate than As, Pb or Hg. They reviewed the major factors affecting the accumulation of fertiliser-derived Cd, F, Hg and Pb in soils and their transfer to agricultural crops. The availability of Cd generally decreases with increasing pH (Gray *et al.*, 1999; Oliver *et al.*, 1998) so acidification of soils could increase plant uptake of Cd.

### **Potassium Fertilisers**

After N, K is the element taken up by plants in greatest quantities (Table 6.1). The pattern of K uptake by crops (Figure 6.6) indicates that K must be present in adequate supply early in the growth period.

## **ADVERSE K FERTILISER REACTIONS**

(i) *Reduced Plant Availability - Leaching is not normally a problem with K fertilisers.* Most available  $K^+$  is retained on the cation exchange sites in the clay fraction. However, when soil has a low CEC, leaching of  $K^+$  may occur following heavy rainfall (Phillips *et al.*, 1988).

*Potassium fixation reduces fertiliser K availability.* In soils which have a high content of the clay mineral vermiculite and to a lesser extent smectite, the availability of K to plants can be limited. The fixed K is only slowly released back into the soil solution.

(ii) *Adverse Side Effects - Salt effects are common.* The two most common K fertilisers, KCl and  $K_2SO_4$ , are highly soluble and can cause salt effects if drilled at high rates with seed.

*Quality of the product may be affected by the form of K fertiliser used.* Although both fertilisers provide K in equally available forms, the quality of tobacco and some horticultural crops such as potatoes is impaired if Cl levels are high. For these crops the more expensive  $K_2SO_4$  form must be used.

*Calcium and Mg deficiencies can be induced following K application,* especially if the supply of these in the soil is marginal.

## **CONCLUSIONS**

The chapter has identified the critical importance of nutrient supply from soil to crop yield improvement in Australian agriculture over the last century. While N and P are almost universally deficient, other nutrient deficiencies limit yields especially where the soils have high or low pH or are coarse textured.

Utilising an understanding of crop requirements and soil factors influencing the availability of nutrients can provide a first step in identifying likely nutrient deficiencies. However, the correct use of tools such as soil and plant analysis reduce the risk in decision making with respect to fertiliser requirements.

The key principles of fertiliser management are outlined using N, P and K as examples. Management should endeavour to maintain the balance between the nutrient uptake by crops and the supply from soil and/or fertiliser as well as minimising adverse effects that can arise from fertiliser use.

## **PRINCIPLES**

- Nutrient supply is a major factor influencing crop yield and quality.
- Most nutrients are taken up from the soil solution.
- If there is insufficient nutrient in the soil solution to grow crops to maturity, factors controlling the rate of release of nutrients from the soil reserves are critical to meeting crop nutrient requirements.

- Nutrient uptake into roots depends on movement of nutrients to roots by mass flow or diffusion or growth of roots to the location of the nutrient.
- Entry into the root may be passive (diffusion or mass flow) or active (where the plant expends energy to take the nutrients up against concentration gradients).
- Early diagnosis of nutrient deficiencies is essential to achieving yield potential. Techniques to assess fertiliser requirements include the use of visual symptoms, soil and plant analysis.
- Correct sampling is critical for successful use of both soil and plant analysis.
- The key principles of fertiliser management are to:
  - maintain the balance between the nutrient uptake by crops and the supply from soil and/or fertiliser sources.
  - minimise adverse effects.

### **References**

Andrew CS and Fergus IF (1976) Plant nutrition and soil fertility. In NH Shaw and WW Bryan (eds) *Tropical Pasture Research - Principles and Methods*, Commonwealth Agricultural Bureaux, Hurley, 101-133.

Angus JF (1988) Strategies and tactics for fertiliser nitrogen usage. *Proceedings of 17<sup>th</sup> Riverina Outlook Conference*, Riverina-Murray Institute of Higher Education, Wagga Wagga, 73-79.

Angus JF (2001) Nitrogen supply and demand in Australian agriculture. *Australian Journal of Experimental Agriculture* **41**, 277-88.

Angus JF, Williams RF and Durkin CO (1996) MaNage rice: Decision support to tactical crop management. *Proceedings of 8th Australian Society of Agronomy Conference*, Toowoomba, 72-75.

Asher CJ and Ozanne PG (1961) The cation exchange capacity of plant roots and its relationship to the uptake of insoluble nutrients. *Australian Journal of Agricultural Research* **12**, 755-66.

Atwell BJ, Kreidemann PE and Turnbull CGN (eds.) (1999) *Plants in Action*. Macmillan Education Australia, South Yarra.

Barrow NJ (1974) The slow reactions between soil and anions: I. Effects of time, temperature and water content of a soil on phosphate for plant growth. *Soil Science* **118**, 380-6.

Batten GD (1998) Plant analysis using near infrared reflectance spectroscopy: the potential and the limitations. *Australian Journal of Experimental Agriculture* **38**, 697-706.

- Black AS and Waring SA (1976a) Nitrate leaching and adsorption in a Krasnozem from Redland Bay, Qld. I. Leaching of banded ammonium nitrate in a horticultural rotation. *Australian Journal of Soil Research* **14**, 171-180.
- Black AS and Waring SA (1976b) Nitrate Leaching and Adsorption in a Krasnozem from Redland Bay, Qld. III. Effect of Nitrate Concentration on Adsorption and Movement in Soil Columns. *Australian Journal of Soil Research*, **14**, 189-95.
- Black AS, Sherlock RR and Smith NP (1987) Effect of timing of simulated rainfall on ammonia volatilisation from urea, applied to soil of varying moisture content. *Journal of Soil Science* **38**, 679-87.
- Black AS, Sherlock RR Smith NP and Cameron KC (1989) Ammonia volatilisation from urea broadcast in spring on to autumn-sown wheat. *New Zealand Journal of Crop and Horticultural Science* **17**, 175-182.
- Blair GJ and Nicholson AJ (1975) The occurrence of sulphur deficiency in temperate Australia. In KD McLachlan (ed), *Sulphur in Australasian Agriculture*, Sydney University Press, Sydney, 137-144.
- Boland MDA (1986) Residual value of phosphorus from superphosphate for wheat grown on soils of contrasting texture near Esperance, Western Australia. *Australian Journal of Experimental Agriculture* **26**, 209-15.
- Bolland MDA, Gilkes RJ and D'Antuona MF (1988) The effectiveness of rock phosphate fertilisers in Australian agriculture. *Australian Journal of Experimental Agriculture* **27**, 655-68.
- Bowden JW and Dingle A (1996) *Nitrogen Calculator*. Agriculture Western Australia
- Cameron KC and Hayes RJ (1986) Retention and movement of nitrogen in soils. In RJ Haynes (ed) *Mineral Nitrogen in the Plant-Soil System*, Academic Press, New York, 166-241.
- Cregan PD and Helyar KR (1986). Non-acidifying farming systems. *Proceedings of 15<sup>th</sup> Riverina Outlook Conference*, Riverina-Murray Institute of Higher Education, Wagga Wagga, 49-62.
- Dalal RC (1976) The supply of phosphorus from organic sources in soil and possible manipulations. In GJ Blair (ed) *Prospects for Improving Efficiency of Phosphorus Utilization*, The University of New England, Armidale, 47-51.
- Dear BS and Smith AN (1983) Fertilizer test strips for the identification of superphosphate responsive pastures. *Australian Journal of Experimental Agriculture and Animal Husbandry* **23**, 201-7.
- Donald CM (1965) The progress in Australian agriculture and the role of pastures in environmental change. *Australian Journal of Science* **27**, 187-98.

- Donald CM and Prescott JA (1975) Trace elements in Australian crop and pasture production. In DJD Nicholas and AR Egan (eds) *Trace Elements in Soil-Plant-Animal Systems*, Academic Press, New York, 7-37.
- Friesen DF and Blair GJ (1988) A dual radio trace study of transformations of organic, inorganic and plant residue phosphorus in soil in the presence and absence of plants. *Australian Journal of Soil Research* **26**, 355-66.
- Freney JR and Black AS (1988) Importance of ammonia volatilization as a loss process. In JR Wilson (ed) *Advances in Nitrogen Cycling in Agricultural Ecosystems*, Commonwealth Agricultural Bureaux, Wallingford, 156-173.
- Glendenning JS (2000) *Australian Soil Fertility Manual*. CSIRO, Melbourne.
- Gladstones JS, Loneragan JF and Goodchild NA (1977) Field responses to cobalt and molybdenum by different legume species, with inferences on the role of cobalt in legume growth. *Australian Journal of Agricultural Research* **28**, 619-28.
- Grafton RQ, Mullen J and Williams J (2015) Australia's Agricultural Future: Returns, Resources and Risks. A report for the Australian Council of Learned Academies, ACOLA, Melbourne.
- Graham RD, Hannam RJ and Uren NC (1988) *Manganese in Soils and Plants*, Kluwer Academic Publishers, London.
- Gray CW, McLaren RG, Roberts AHC and Condon LM (1999) Effect of soil pH on cadmium phytoavailability in some New Zealand soils. *New Zealand Journal of Crop and Horticultural Science* **27**, 169-179.
- Greenland DJ and Hayes MHB (1981) *Chemistry of Soil Processes*. John Wiley and Sons, Chichester.
- Grigg JL (1977) Prediction of plant response to fertiliser by means of soil tests. V. Soil tests for phosphorus availability in brown-grey and dry-subhygrous yellow-grey earths. *New Zealand Journal of Agricultural Research* **20**, 315-26.
- Grundon NJ (1987) *Hungry Crops: a Guide to Nutrient Deficiencies in Field Crops*. Queensland Department of Primary Industries, Brisbane.
- Hanway JJ and Weber CR (1971) Accumulation of N, P and K by soybean plants. *Agronomy Journal* **63**, 406-8.
- Haynes RJ and Sherlock RR (1986) Gaseous losses of nitrogen. In R.J. Haynes (ed), *Mineral Nitrogen in the Plant-Soil System*, Academic Press, New York.

- Helyar KR and Porter WM (1989) Soil acidification, its measurement and the processes involved. In A.D. Robson (ed) *Soil Acidity and Plant Growth*, Academic Press, Sydney, 61-109.
- Hendriks SB, Claasen N and Jungk A (1981) Phosphatverarmung des wurzelnahen bodens und phosphataufnahme von mais und raps, *Zeitschrift Pflanzenernährung Bodenkunde* **144**, 486-499.
- Henzell EF (1971) Recovery of nitrogen from four fertilizers applied to Rhodes grass in small plots. *Australian Journal of Experimental Agriculture and Animal Husbandry* **11**, 420-30.
- Hochman Z, Godwyn DL and Scott BJ (1989) The integration of data on lime use by modelling. In AD Robson (ed) *Soil Acidity and Plant Growth*, Academic Press, Sydney.
- Holford ICR and Cullis BR (1985) Effects of phosphate buffer capacity on yield response curvature and fertiliser requirements of wheat in relation to soil phosphate tests. *Australian Journal of Soil Research* **23**, 417-26.
- Holford, ICR, Morgan JM, Bradley J and Cullis BR (1985) Yield response and response curvature as essential criteria for the evaluation and calibration of soil phosphate tests for wheat. *Australian Journal of Soil Research* **23**, 167-80.
- Jacques GL, Vanderlip RL and Whitney DA (1975) Growth and nutrient accumulation in grain sorghum: I. Dry matter production and Ca and Mg uptake and distribution. II. Zn, Cu, Fe and Mn uptake and distribution. *Agronomy Journal* **67**, 607-16.
- Lewis DC, Clarke AL and Hall WB (1981) Factors affecting the retention of phosphorus applied as superphosphate to the sandy soils in south-eastern South Australia. *Australian Journal of Soil Research* **19**, 167-74.
- Lipsett J and Simpson JR (1971) Wheat responses to molybdenum in southern NSW. *Journal of the Australian Institute of Agricultural Science* **37**, 348.
- Loneragan JF, Robson AD and Graham RD (1981) *Copper in Soils and Plants*. Academic Press, Sydney.
- Maling I, McKinlay J and Horton B (1984) *SUPERATE: The Theory, Biology and Economics*. Technical Report Number 10, Department of Agriculture, Victoria.
- Marschner H (1986) *Mineral Nutrition of Higher Plants*. Academic Press, London.
- McLaughlin MJ, Alston AM and Martin JK (1988) Phosphorus cycling in wheat pasture rotations. III. Organic phosphorus turnover and phosphorus cycling. *Australian Journal of Soil Research* **26**, 343-53.



- Mclaughlin MJ, Tiller KG, Naidu R and Stevens DP (1996) Review - the behaviour and environmental impact of contaminants in fertilizers. *Australian Journal of Soil Research* **34**, 1-54.
- Mengel K and Kirkby EA (1987) *Principles of Plant Nutrition*. International Potash Institute, Berne.
- Myers RJK (1988) Nitrogen management of upland crops: From cereals to food legumes to sugarcane. In JR Wilson (ed) *Advances in Nitrogen Cycling in Agricultural Ecosystems*, Commonwealth Agricultural Bureaux, Wallingford, 257-273.
- Nguyen ML and Goh KM (1992) Nutrient cycling and losses based on a mass-balance model in grazed pastures receiving long-term superphosphate applications in New Zealand. 1. Phosphorus. *Journal of Agricultural Science* **119**, 89-106.
- Oliver DP, Tiller KG, Alston AM, Cozens GD and Merry RH (1998) Effects of soil pH and applied cadmium on cadmium concentration in wheat grain. *Australian Journal of Soil Research* **36**, 571-583.
- Ozanne PG, Greenwood EAN and Shaw TC (1963) The cobalt requirement of subterranean clover in the field. *Australian Journal of Agricultural Research* **14**, 39-50.
- Passioura JB and Wetselaar R (1972) Consequences of banding nitrogen fertilizers in Soil. II. Effects on the growth of wheat roots. *Plant and Soil* **36**, 461-73.
- Peeverill KI, Sparrow LA and Reuter DJ (eds) (1999) *Soil Analysis an Interpretation Manual*. CSIRO, Melbourne.
- Peoples MB, Brockwell J and Bergersen FJ (1992) Factors affecting nitrogen fixation: Scope for Improvements. In J.F. Angus (ed), *Transfer of Biologically Fixed Nitrogen to Wheat*. Grains Research and Development Corporation, Canberra.
- Phillips IR, Black AS and Cameron KC (1988) Effect of cation exchange on the distribution and movement of cations in soils with variable charge. II. Effect of lime or phosphate on potassium and magnesium leaching. *Fertiliser Research* **17**, 31-46.
- Purnomo E, Black AS, Smith CJ and Conyers MK (2000) The distribution of net nitrogen mineralisation within surface soil. 1. Field studies under a wheat crop. *Australian Journal of Soil Research* **38**, 129-40.
- Reuter DJ and Robinson JB (2000) *Plant Analysis: an Interpretation Manual*. Inkata Press, Melbourne.
- Rudd CL and Barrow NJ (1973) The effectiveness of several methods of applying superphosphate on yield responses by wheat. *Australian Journal of Experimental Agriculture and Animal Husbandry* **13**, 430-3.

- Sanyal SK and De Datta SK (1991) Chemistry of phosphorus transformations in soils. *Advances in Soil Science* **16**, 1-120.
- Savant NK, Datnoff LE and Snyder GH (1997) Depletion of plant-available silicon in soils - a possible cause of declining rice yields. *Communications in Soil Science and Plant Analysis* **28**, 1245-1252.
- Scott BJ and Fisher JA (1989) Selection of genotypes tolerant of soil acidity. In AD Robson (ed), *Soil Acidity and Plant Growth*, Academic Press, Sydney, 167-204.
- Stein JA, Sageman AR, Fischer RA and Angus JF (1987) Soil nitrogen supply of wheat in relation to method of cultivation. *Soil and Tillage Research* **10**, 23-58.
- Storrier RR (1965) Leaching of nitrogen and its uptake by wheat in a soil from southern NSW. *Australian Journal of Experimental Agriculture and Animal Husbandry* **5**, 323-8.
- Strong DT (1992) Early plant establishment reduces nitrate leaching. In KR Helyar (ed) *Predicting Lime Response and Managing Acid Soil Infertility*, Final Report for the Wool Research and Development Council, 342-73.
- Tiller KG (1989) Heavy metals in soils and their environmental significance. *Advances in Soil Science* **9**, 113-142.
- Wild A (1988) *Russell's Soil Conditions and Plant Growth* (11<sup>th</sup> edn). Longman, Harlow.
- White RE (1987) Leaching. In J.R. Wilson, (ed) *Advances in Nitrogen Cycling in Agricultural Ecosystems*, *Advances in Nitrogen Cycling in Agricultural Ecosystems*, Commonwealth Agricultural Bureaux, Wallingford, 193-211.
- Weir RG, Holland JF and Doyle AD (1987) *Zinc Deficiency in Field Crops*. Department of Agriculture NSW, Sydney.
- Welch RM (1985) Micronutrient nutrition of plants, *Critical Reviews in Plant Science* **14**, 49-82.