Chapter 3

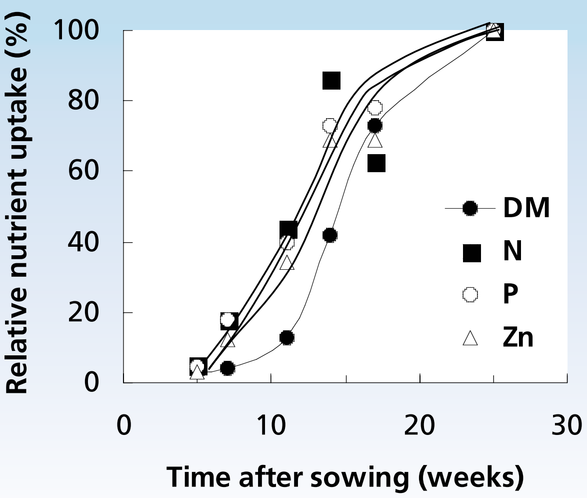
Nutrient deficiencies, toxicities and imbalances

- Plants require a sustained and balanced supply of nutrients during the growing season for maximum growth and yield.
- Subsoils can be a significant source of plant nutrients, especially when the topsoil is dry.
- Many Australian subsoils have poor inherent fertility. Increasing available nutrients in the subsoil can substantially increase yields.
- Some subsoils contain toxic levels of nutrients that can reduce root growth and grain yield.
- Deficiencies, toxicities and imbalances can be diagnosed in plants visually or through soil and plant analysis.

Patterns of nutrient uptake by crops

Plants take up nutrients from the soil throughout the growing season but the pattern of nutrient uptake differs from that of dry matter production (Figure 3.1). Initial uptake of nutrients is more rapid than dry matter production but uptake of nutrients slows as the crop approaches maturity. By anthesis, most of the nutrients present in the crop at maturity have been taken up. The nutritional requirements of the developing grain are largely met by mobilisation from leaf and stem tissues and, to a lesser extent, by absorption of nutrients from the soil.

The difference in the patterns of dry matter and nutrient accumulations shown in Figure 3.1 reflects (i) the high concentration of nutrients in the topsoil which is most available during the early part of the growing season and which is supplemented by fertiliser applied at sowing; (ii) the drying of the topsoil in the latter half of the growing season which reduces nutrient uptake, and (iii) the ability of the crop to mobilise nutrients from old plant tissue to new growth. However, Figure 3.1 clearly shows that a supply of nutrients is needed throughout



	Time to 50% of final value (weeks)
Dry matter	14.0
N	11.5
P	11.5
Zn	12.5

Figure 3.1: The accumulation of nutrients and dry matter production in a bread wheat crop at Palmer, South Australia (adapted from Zubaidi et al. 1999).

the growing season to sustain growth. While the topsoil remains moist the crop's demand can be met largely from the nutrient reserves in the upper soil layers, but as the topsoil dries, uptake of nutrients from the surface soil declines and the nutrient requirements of the crop become increasingly dependent on the reserves of the subsoil and on mobilisation from older plant tissue. The poor nutritional characteristics of the subsoil can be a major limitation to growth and increasing the fertility of the subsoil can lead to large increases in grain yield (Figure 3.2).

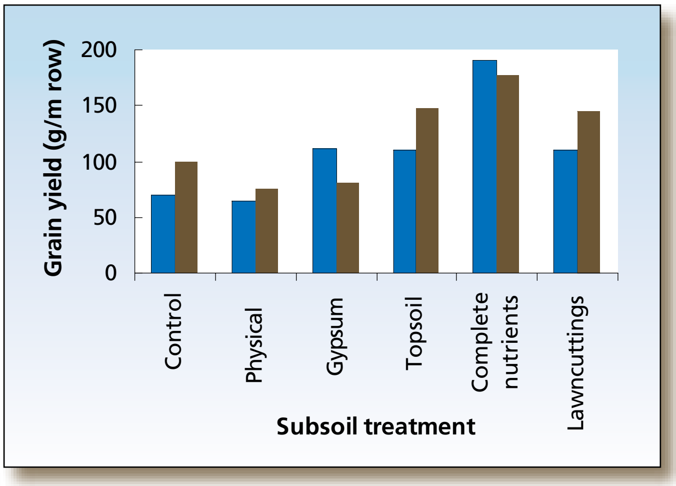


Figure 3.2: The response to subsoil treatments on a calcareous soil at Marion Bay, South Australia in the initial season of treatment (■) and 5 years later (■). The subsoil treatments, to a depth of 1 metre, were: Control – no disturbance; Physical – physical disturbance of the subsoil; Gypsum – physical disturbance plus the addition of gypsum; Topsoil – the subsoil was replaced with topsoil; Complete nutrients – physical disturbance and N, P and trace elements mixed through the subsoil; Lawn cuttings – physical disturbance and lawn cutting mixed through. All the plots were sown with commercial farm equipment by the cooperating farmer using recommended sowing rates and fertilisers (adapted from Graham et al 1992).

Total and available nutrient concentrations in the soil

The total concentration of a nutrient is the amount of all forms of the nutrient in the soil, which includes the nutrients present in organic matter, that attached to clay particles, and minerals and the soil solution. Even in infertile soils, the total nutrient concentration can be high, but most of the nutrients are not immediately available to plants. While the total nutrient concentration can provide an indication of gross soil fertility, it is usually a poor predictor of nutrient sufficiency for plants. Nutrients must be in a chemical form that allows them to enter the soil solution and to be absorbed by plant roots. This is the available nutrient pool. Nutrients in the total pool are made available to plants by the break down of organic matter and soil minerals and by chemical exchange between the soil minerals, organic matter and the soil solution. Soil pH, the presence of chemical species such as calcium carbonate and iron oxides, the soil moisture content and the soil's biological activity are important influences on the availability of nutrients and hence the nutrient status of the plant. These soil properties affect a plant's nutrient status by:

- influencing the inherent fertility of the soil, which determines the total amount of nutrients potentially available to plants
- determining the availability of these nutrients and their movement to the root surface
- influencing the ability of roots to explore the soil, to take up nutrients and to use nutrients efficiently.

Nutrient profiles in the soil

Soil texture, organic matter concentration and pH have important affects on the concentration of available soil nutrients. In most soils these properties change with depth and subsoils are generally much different to those of the topsoil (Figure 3.3). The organic matter concentration of subsoils is inherently low and consequently the total nutrient pool and the availability of nutrients from mineralisation are low There can be a steep decline in nutrient concentrations and availability down the soil profile, especially for less mobile nutrients such as phosphorus (P) and zinc (Zn) (Figure 3.3). Mobile nutrients such as nitrate (NO_3^-) can be leached into the subsoil, however it is still commonly observed that NO_3^- concentrations are much lower in the subsoil than in the topsoil. Subsoils therefore have much lower concentrations of many nutrients than the surface layers.

The concentration of some nutrients increases with depth. In alkaline soils, for example, the high pH in the subsoil is associated with high concentrations of boron (B) and in sodic soils, the sodium (Na^+) concentration increases in the subsoil (Figure 3.4).

Subsoil nutrient deficiencies

Subsoil infertility is common in most parts of Australia (Graham *et al*. 1992) and may be a major limitation to yields of dryland crops where the nutrient-rich surface soil horizons are often dry for long periods during the growing season (Figure 3.2). Plant roots generally cannot take up nutrients from dry soil, so when the surface soil dries out the demand for nutrients needs to be met from the subsoil. Subsoil infertility can also reduce root growth and the ability of crops to utilise water from the subsoil. Strategies for amelioration of subsoil nutrient deficiencies are discussed in Chapter 9.

Table 3.1: The effect of surface soil drying on the concentration of Manganese (Mn) in the youngest open leaf of narrow leaf lupin. (Source: Crabtree et al. (1998)).

Surface soil treatment	Mn concentration in youngest open leaf (mg/kg)
Wet	71
Intermittent drying	40
Dry throughout the experiment	8

Subsoil nutrient toxicities

At high concentrations, nutrient elements can become toxic to plants, reducing root growth and yield and can result in the death of plants in extreme cases. The most common nutrient toxicities in subsoils of the medium and low rainfall areas of south-eastern Australian are B, Na^+, carbonate (CO_3^-) and bicarbonate (HCO_3^-) (Nuttall *et al*. 2003, Rathjen *et al*. 1999, Rengasamy *et al*. 2003). In the high rainfall regions, where high rates of leaching occur, subsoil acidity can develop. This causes specific nutrient toxicities, especially aluminium (Al) and manganese (Mn).

Typical profiles for B, electrical conductivity, exchangeable Na^+ and chloride (Cl^-) in alkaline soils are shown in Figure 3.4. High concentrations of B and salt occur in many alkaline soils throughout south-eastern Australia and can restrict root growth and water uptake. Under saline conditions, the presence of high concentrations of salts reduces growth by osmotic stress, in which the presence of high salt concentrations restricts water uptake, and by the direct toxic effect of Na^+ and Cl^- in the plant tissues.

How does soil pH affect nutrient availability and toxicity?

Several physical, chemical and biological properties of soil interact to determine the concentration of available nutrients in the soil. Soil pH is arguably the most important because it influences the chemical form of nutrients and their availability (Figure 3.5). The optimum pH for most nutrients is generally from 6.5 – 7.5. Outside this range the concentration of many nutrients in the soil solution declines and for some nutrients, such as Al, Mn and B, the availability can increase to concentrations toxic to plants. The pH of the soil is therefore a good indicator of some of the nutritional problems that are likely to occur.

Alkaline soils

Alkaline soils have a pH above 7.0, but nutritional problems are encountered when pH is greater than 7.5 – 8.0. In alkaline soils, [already defined above] CO_3^{2-} and HCO_3^- may be present at high concentrations. Excess HCO_3^- inhibits root growth in plants and the high pH reduces the availability of a number of nutrients (Figure 3.5). In soils with high exchangeable Na^+, sodium

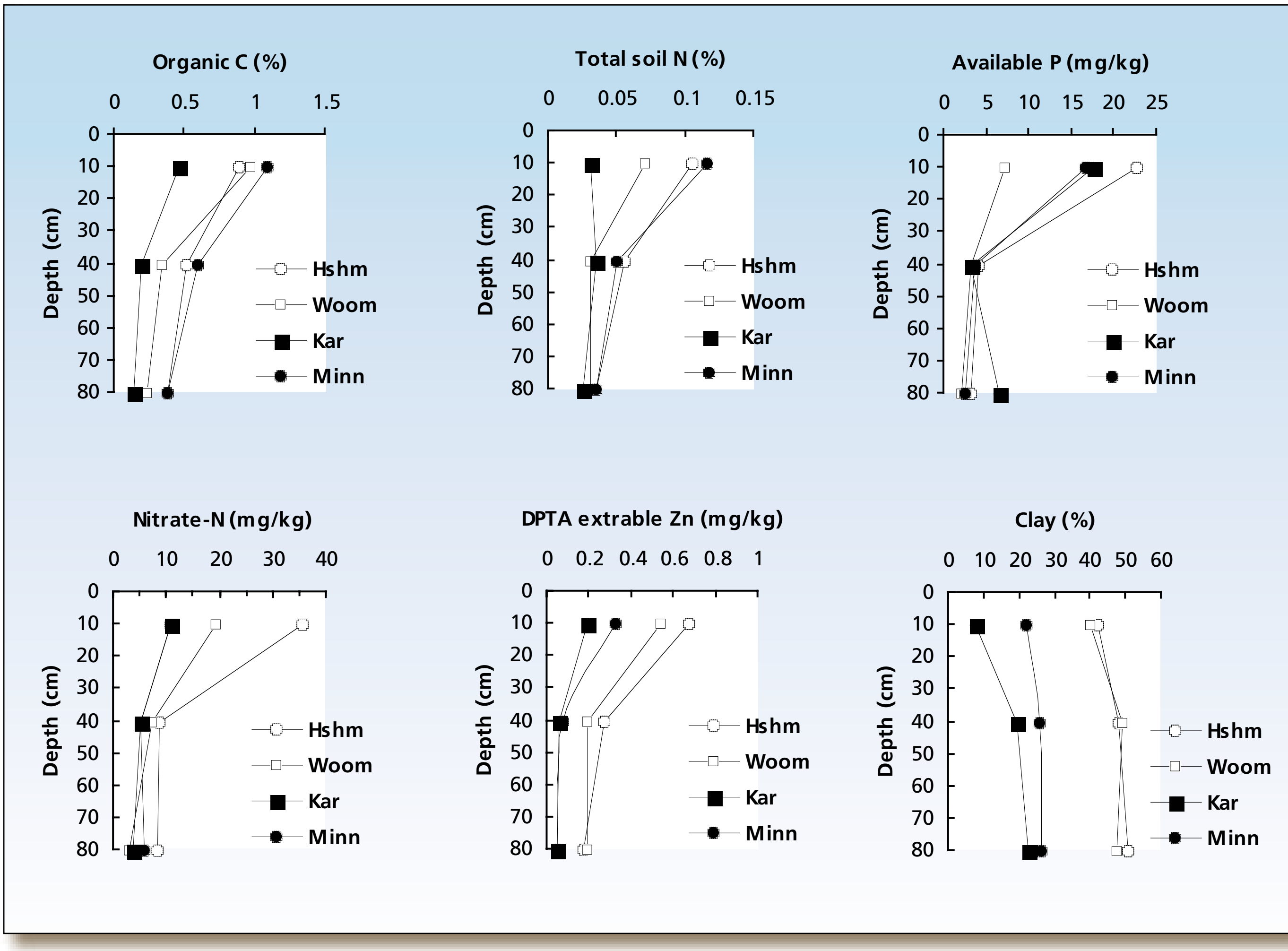


Figure 3.3: Changes in the organic C, total N, Colwell P, nitrate-N, DPTA-extractable Zn and the percentage clay in soil profiles at Horsham and Woomelang, Victoria and Karoonda and Minnipa, South Australia. As a general guide, for wheat, low levels are <15-25 mg P/kg, <20 mg NO_3^- - N/kg and <0.3-0.8 mgZn/kg (Peverill et al. 2001).

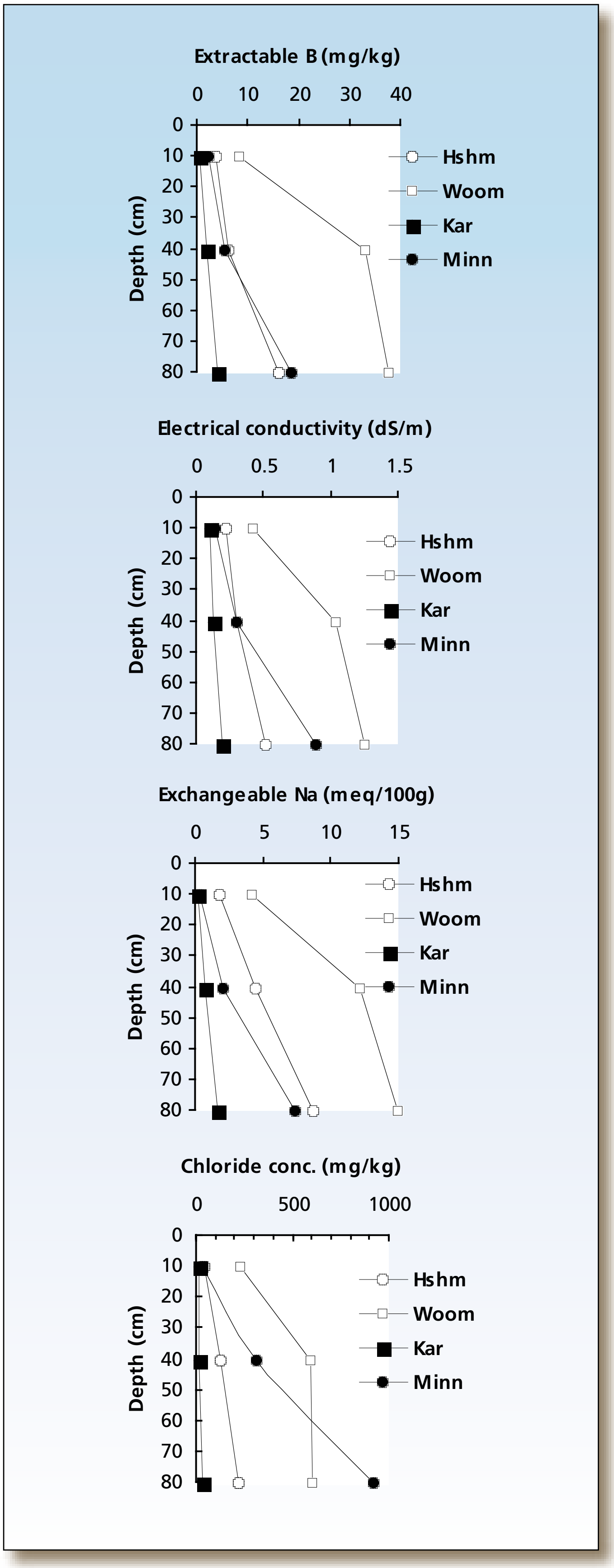


Figure 3.4: Changes in hot-water extractable B, EC (1:5 soil water extract), exchangeable Na^{+} and Cl^{-} in soils at Horsham and Woomelang, Victoria and Karoonda and Minnipa, South Australia. B toxicity occurs with B concentrations >20 – 50 mg/kg. As a general guide, EC values >0.4 – 1.0 dS/m indicates high soil salinity for soils with 20 – 60% clay.

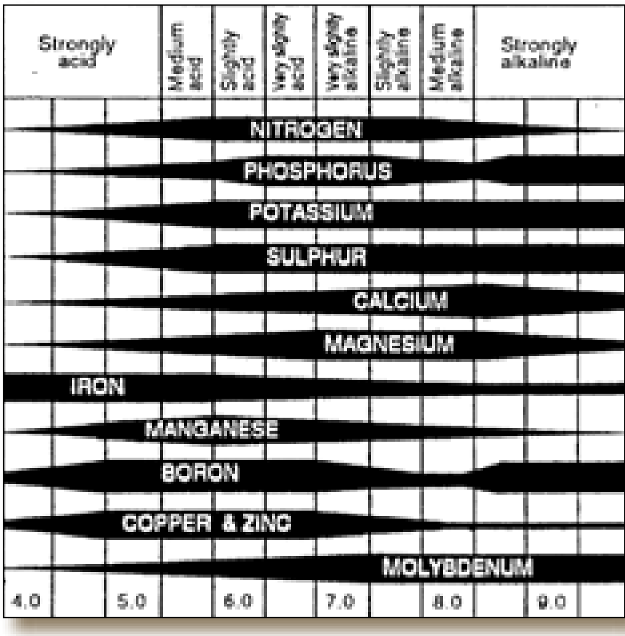


Figure 3.5: The affect of pH on the availability of nutrients. The width of each bar indicates the relative availability of the nutrient.

carbonate and sodium bicarbonate raise the pH above 9.0. Plant growth can be affected directly by this high pH as well as being reduced by a number of nutrient toxicities and deficiencies (Table 3.2). Some of the commonly observed nutritional problems of highly alkaline soils include:

- decreased solubility of Fe and Mn with increasing pH
- low availability of Zn at high pH resulting from the adsorption of Zn to $CaCO_3$ and HCO_3^-
- low availability of P due to adsorption to clay particles and the formation of complexes with Ca^{2+} and H^+
- phytotoxic B concentrations (Figure 3.6)
- increases in phytotoxic $Al(OH)_4^-$ in soils with pH>9.

Alkaline soils and calcareous soils have a high capacity to 'fix' P. This reduces the availability of P to plants and limits their response to P fertiliser. The effects of pH and the amount of calcium carbonate in the soil on the response to P fertiliser are illustrated in Figure 3.7. There was no response to granular P fertilizer in the alkaline calcareous soil and the response was lower in the non-calcareous alkaline soil. The fact that there was a response to liquid P indicates that the plants were deficient in P, but the availability of P in granular fertilizer was low.

Acid soils

Acidic soils have a pH less than 7.0, but soils that are only slightly acidic (pH 6.5-7.0) have few nutritional problems. Aluminium toxicity is generally regarded to be the most important nutritional problem of acid soils. Aluminium toxicity severely impairs the growth of the root tip and reduces the development of lateral roots and root hairs. This results in a small root system with very little fine root development that is unable to absorb nutrients and water efficiently. The concentration of Al^{3+} in solution begins

Table 3.2: The major constraints to plant growth associated with alkaline and sodic soils (adapted from Marschner 1995).

	Soil pH (water)	
	7.5-8.5	**>8.0**
Major nutritional problems	Deficiencies of Iron, Zinc, Phosphorus and sometimes Manganese	Toxicities of Sodium and Boron Deficiencies of Zinc, Iron, Phosphorus and sometimes Calcium, Potassium and Magnesium
Other problems	High Bicarbonate Mechanical impedance Water deficit	Poor soil aeration High Bicarbonate Mechanical impedance Water deficit

to increase at soil pH(water) less than 6.0 (Fig. 3.8). Below a pH of 5.0 the Al^{3+} concentration increases to be high enough to inhibit root growth of many crops. Mn^{2+} toxicity can also develop below pH 6.0 – 5.5, but high concentrations of Mn^{2+} are only to be expected in soils with large amounts of reducible manganese.

A number of nutrient deficiencies can also develop under low pH. Uptake of the cations Mg^{2+}, Ca^{2+} and K^{+} are reduced by low pH and by competition from high concentrations of Al^{3+} and Mn^{2+}. Where the supply of Mg^{2+}, Ca^{2+} and K^{+} is low, deficiencies can be induced in highly acidic soils.

Crop tolerance to soil pH

Significant variation in response to soil pH exists among different crop species. The optimum pH for different crops is given in Table 3.3, but the extent of variation among the cultivars of different crops commonly grown in the southern region has not specifically been studied. Tolerance to acid and alkaline soil conditions may reflect the ability of the crop to cope with the nutrient deficiencies and toxicities associated with extremes in pH, as well as the direct affects of pH on plant growth.

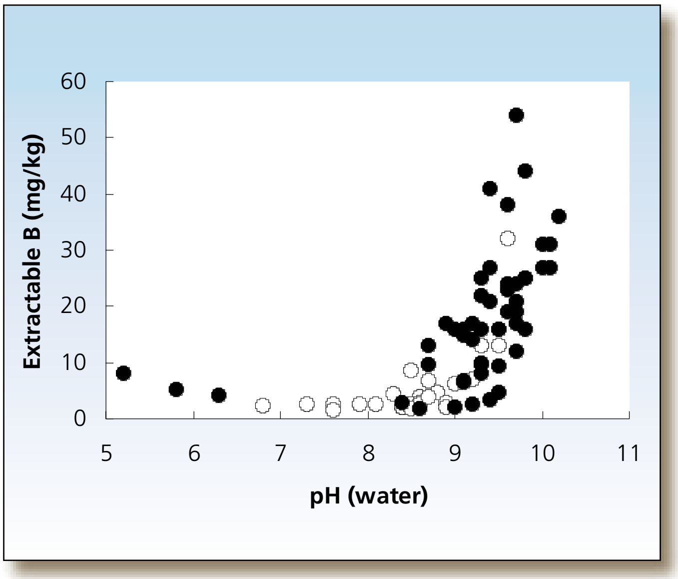


Figure 3.6: The relationship between soil pH and the concentration of extractable B in the topsoil (0-35 cm; ❍) and subsoil (>35cm; ●) at Birchip. Both B and pH increase down the soil profile. .

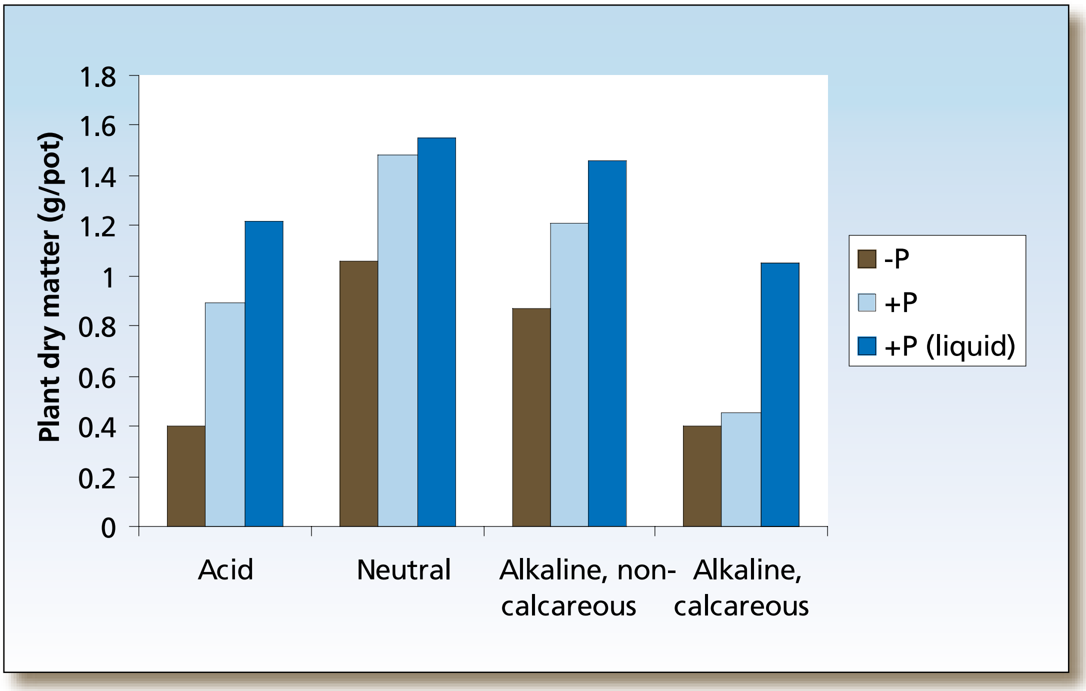


Figure 3.7: The response to P in soils with a range in pH values. The soils were collected from Victoria, South Australia and Western Australia and there are a number of soils in each group. Phosphorus was applied either as triple superphosphate (granular) or as ammonium polyphosphate (liquid). The average pH's were 5.36 (acid), 6.58 (neutral), 8.14 (alkaline, non-calcareous) and 8.24 (alkaline, calcareous) (Adapted from McBeath et al. 2005).

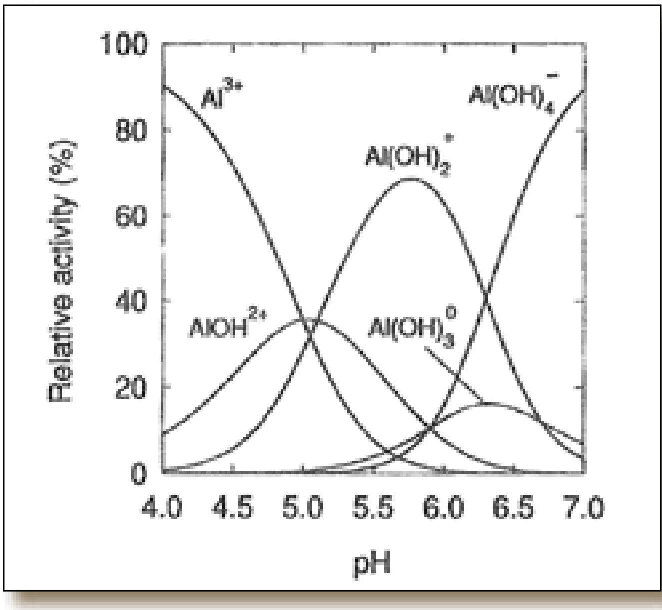


Figure 3.8. The effect of solution pH on the relative activities of different species of Al. The activity is a measure of the concentration of an ionic species in solution. As pH declines from pH 7 to 4 there is a large decline in $Al(OH)_4^-$ and a marked increase in Al^{3+} (Kinraide 1991).

Table 3.3: Optimum pH (water) ranges for selected crops and pastures

Crop	Optimum soil pH range
Lucerne	5.5–8.5
White clover	5.5–7.5
Strawberry clover	6.0–8.0
Medic	6.5–8.5
Barley	6.0–8.0
Wheat, oats	5.5–8.0
Canola	6.0–7.5
Chickpea	5.5–7.0
Lupin	5.0–7.0
Phalaris	6.0–8.5
Rye	5.5–8.0
Vetch	5.5–7.0
Mustard	5.5–6.5

Waterlogging, nutrient deficiencies and toxicities.

Under very wet conditions, or where drainage is impeded, the pores in the soil fill with water and reduce the concentration of oxygen in the soils. This alters soil chemistry and availability of plant nutrients, and also affects plant growth by reducing the supply of oxygen to roots. Roots need a continual supply of oxygen for growth. Root elongation is reduced in waterlogged soils and this may limit the ability of the plant to utilise nutrients in the soil once the soil drains.

The changes in soil nutrients under waterlogging occur in a specific sequence. Nitrate is the first to decline and thus plants may become N deficient. Under prolonged waterlogging there is an increase in Mn^{2+} and finally Fe^{3+}, both of which can become toxic to plants. Waterlogging can also make plants more sensitive to salinity. This may be an important consideration in saline-sodic soils where the poor drainage associated with sodicity can cause periods of transient waterlogging.

Nutrient imbalances

A nutrient imbalance occurs when the availability of one nutrient induces a deficiency or toxicity in another. It can result from a natural imbalance of available nutrients in the soil caused by sodicity, salinity or extremes in soil pH. A nutrient imbalance can also be caused by fertiliser practices that apply a nutrient at a high enough rate to interfere with the uptake of other nutrients.

Many subsoils have more than one potential nutritional problem and this can sometimes lead to nutrient imbalances. For example, the increase in pH in alkaline soils causes an increase in the availability of B and a reduction in the availability of Zn. On a calcareous soil at Minnipa, genotypes of barley that accumulated less B tended to have high concentrations of Na, while high B accumulation tended to reduce Zn uptake and exacerbate Zn deficiency (Figure 3.9). Overcoming one nutritional problem may not lead to improved yields if other nutritional problems persist.

Soil imbalances

The dominant exchangeable cation in agricultural soils is usually Ca^{2+}, followed by Mg^{2+}, Na^+ and K^+, with variable amounts of NH_4^+. Cation ratios vary considerably between soils as well as with depth. An example of the changes that occur with depth in soils in the Birchip region is shown in Figure 3.10.

This soil also becomes more alkaline and sodic with depth. There is little change in the percentage of exchangeable K^+ or Mg^{2+} down the profile. The major change is the replacement of Ca^{2+} with Na^+, which occurs in the top 50 cm; below this the percentage of Ca^{2+} remains low and the percentage of Na^+ remains high. These variations in cation ratios may affect plant nutrition or soil structure at the extremes. Some cation ratios have been proposed as indicators of soil chemical and physical fertility. Some of the common nutrient imbalances that have been shown to be of practical importance include:

Exchangeable Sodium Percentage (ESP)

High Na^+ in relation to the other exchangeable cations, as assessed by ESP, affect plant nutrition and soil structure. See Chapter 5 for details.

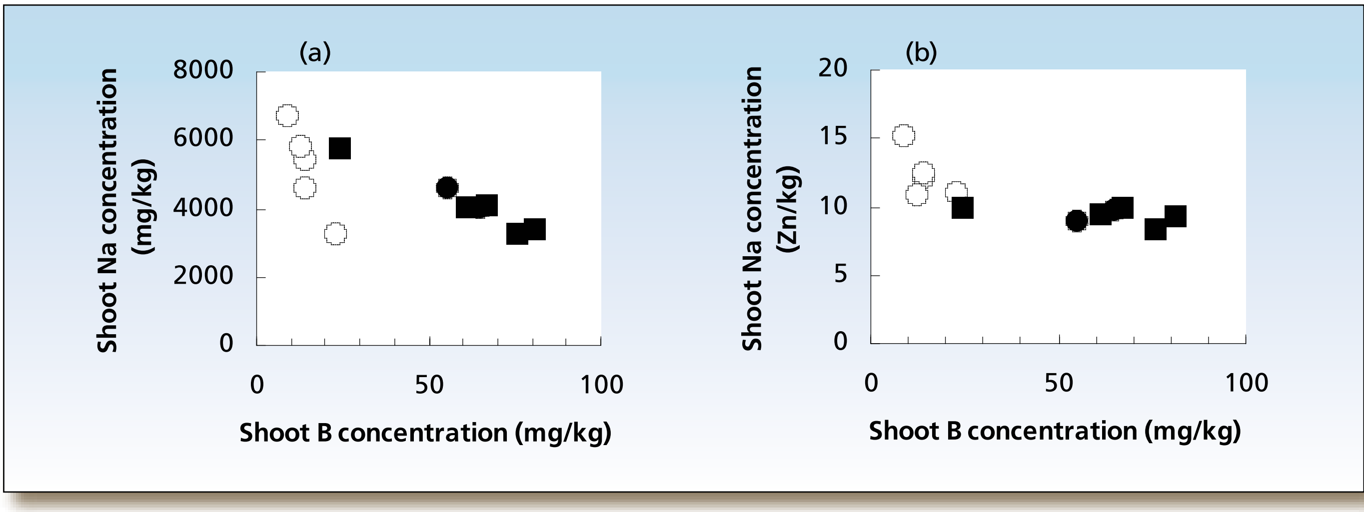


Figure 3.9: : The relationship between (a) whole-shoot Na concentration and whole-shoot B concentration and (b) whole-shoot B concentration and whole-shoot Zn concentration at ear emergence in different barley varieties at Minnipa in 2000 (●), 2001 (❍) and 2002 (■). The varieties were Gairdner, Keel, Mundah, Sahara and Sloop. (McDonald, unpublished data)

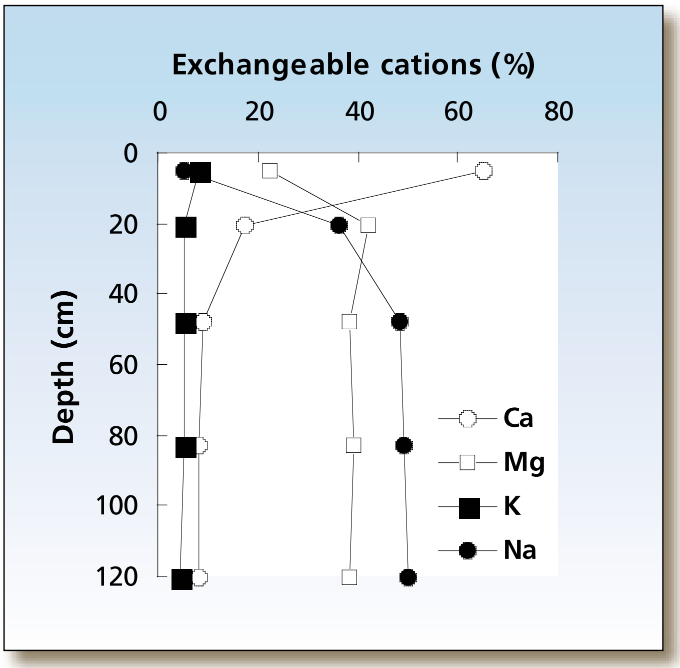


Figure 3.10: Changes in exchangeable cations in a Calcarosol at Birchip. The mean total amount of exchangeable cations was 32 meq/100g, which did not change down the profile.

Ca:Mg ratio

The importance of imbalances between Ca^{2+} and Mg^{2+} on the soil exchange complex have been considered and debated for both plant nutritional and soil structural reasons, but there are no clear guidelines on the importance of this nutrient balance for soils of south-eastern Australia. Ions of the same electrical charge compete for the limited number of binding sites for transport into plant roots. In some instances, ratios of Ca:Mg in excess of 4 – 5 have resulted in Mg deficiency (when both cations are present in low concentrations). However, the alkaline soils of South Australia and Victoria have Ca:Mg ratios that are generally lower than 5 (for example, Figure 3.5) and the ratio declines with depth in the soil profile.

Some early work suggested an ideal Ca:Mg ratio for plant growth of between 2 and 7 and that Mg deficiency may occur if Mg was less than 6% of the exchangeable cations. However more recent surveys in Australia and overseas have indicated that Ca:Mg ratios in soils can vary widely with little effect on the growth of a range of crops and pastures (McLean *et al*. 1983, Aitken and Scott 2001). To maximise crop yields, the current view that appears is that sufficient, but non-excessive levels of each basic cation should be provided rather than attempting to attain a 'favourable' cation saturation ratio. Rengasamy *et al*. (2003) concluded that deficiencies of Mg or Ca are of much less importance than deficiencies in N, P, S and K and the micronutrients Zn, Fe, Cu and Mn on the highly weathered soils of the semi arid regions. Magnesium deficiency is rarely reported in agricultural plants.

Structural stability of soil aggregates has been shown to be linked with Ca:Mg ratio. This is because high Mg^{2+} has been shown to enhance the dispersion of some soils that also contain high ESP (Rengasamy 2002, Sumner 1993). Both Ca^{2+} and Mg^{2+} have a double positive charge, but the hydration shell of the Mg^{2+} ion is bigger than that of the Ca^{2+} ion, so it is not bonded as closely to the soil surface as Ca^{2+}. However, Mg^{2+} does not have the same degree of influence over dispersive behaviour as Na^{+} and needs to occupy ten times more of the cation-exchange sites than Na^{+} to have an equivalent effect on soil dispersion (Rengasamy & Olsson 1991). Poor soil structure can decrease the plant available water of a soil by increasing the bulk density and decreasing the porosity of subsoil horizons. This limits root penetration into, and water extraction from, underlying soil layers.

Ca:Na ratio

Sodium and Ca^{2+} ions can compete with one another during uptake by plant roots. High concentrations of Na^+ inhibit the uptake of Ca^{2+} which may lead to the development of Ca^{2+} deficiency. Adding Ca^{2+} eg. gypsum or lime to plants growing in saline substrates can increase salt tolerance. However, foliar symptoms of Ca deficiency of broadacre field crops are rarely observed. Monocotyledons (cereals and other grasses) have a lower requirement for Ca than dicotyledons (broadleaf plants such as canola and legumes) and so Ca deficiency will tend to show up first in broadleaf plants.

Anion imbalances

Anion imbalances are less common, although interactions between Cl^-, SO_4^{2-} and $H_2PO_4^-$ uptake can occur. In the most common anion imbalance, high concentrations of Cl^- around the roots can depress NO_3^- uptake.

Plant genotype and nutritional problems

Soil properties are not the only determinant of the nutrient status of crops and pastures. There is considerable variation in the ability of plants to cope with different nutrient deficiencies and toxicities. The occurrence of a nutritional problem may reflect the sensitivity of a plant species or variety to a nutrient deficiency or toxicity as well as the specific properties of the soil. For example, current genotypes of durum wheat are more sensitive to salt and a number of micronutrient deficiencies than bread wheat. Table 3.4 provides a summary of the tolerance of some wheat genotypes to B, high pH and salt encountered on alkaline soils.

How do you diagnose nutrient deficiencies, toxicities and imbalances?

Nutrient deficiencies, toxicities and imbalances can be diagnosed from plant appearance and soil and/or plant tests. Plant tissue tests are generally the best way of quantifying the nutritional status of the crop or pasture because they measure what the plant has taken up from the soil, whereas soil tests will indicate the amount of the nutrient in the soil and what is potentially available to the plant.

Visual symptoms

Many symptoms are sufficiently characteristic to identify the disorder, but others are less characteristic and might indicate one of several possible stresses. The advantage of using visual symptoms to diagnose nutrient disorders is that they can be applied in the field, independent of laboratory support. The major disadvantage is that a disorder will only be diagnosed after severe stress has occurred and it may be too late to correct the problem in the growing season. Common symptoms of nutrient deficiencies and toxicities are given in Appendix 1. Detailed information is obtainable from colour photographs showing typical symptoms of deficiency or toxicity (Grains Research and Development Corporation 1999, Grundon 1987, Weir & Cresswell 1994).

Table 3.4: The tolerance of some wheat genotypes to high levels of boron, pH and salt.

	Boron	High pH	Salinity
Tolerant	BT Schomburgk Frame Halberd Krichauff Yitpi	Krichauff Carnamah	Krichauff Westonia
Intermediate	Carnamah Stylet Westonia	BT Schomburgk Stylet	BT Schomburgk Carnamah Diamondbird Excalibur Frame Halberd Schomburgk Yitpi
Sensitive	Chara Diamondbird Excalibur H45 Janz Schomburgk	Chara Diamondbird Excalibur Frame H45 Halberd Janz Schomburgk Westonia Yitpi	Janz Frame Stylet

Soil and plant tests

Soil tests do not identify plant nutrient deficiencies or imbalances directly, but they give a measure of the amount and the potential availability of nutrients to plants. This can guide fertiliser strategies and also highlight potential problems in the soil.

Plant tests are useful to confirm a diagnosis, to quantify the nutrient concentration in plant tissue or grain and to monitor variation across a paddock or over time. Some skill and experience is required in interpreting the results of soil and plant tests because the critical level of nutrients in soils and plants for deficiency or toxicity varies with crop and crop age, variety and soil type. Nutrient deficiencies and toxicities also may alter the nutrient balance in plants and in severe cases more than one nutritional problem may be evident (Figure 3.9).

Critical nutrient concentrations for different crop species or plant tissues can be found in Reuter & Robinson (1997) and for soils in Peverill *et al*. (1999). Always use a National Association of Testing (NATA)-certified laboratory for soil and plant analysis

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