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Plantation Forest Nutrition

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EXECUTIVE SUMMARY

Forest Research Institute Bulletin 97 'Nutrient deficiencies and fertiliser use in New Zealand exotic forests' was published in 1985. It brought together information collected from over 30 years of research on forest nutrition, and was produced as a practical guide for the identification and correction of nutrient deficiencies. A substantial amount of research on forest nutrition has been undertaken in the more than 20 years since publication of Bulletin 97, much of which has been reported in various journals and reports that are dispersed and not always easily available.

A proposal was put to The Forest Site Management Cooperative that information gathered and presented in the various reports and publications since Bulletin 97 be bought together in a single publication, along with information presented in the original Bulletin, to make that information more readily accessible. This report is the outcome of that proposal.

The report is divided into 14 sections, each beginning with a short key-point summary. Following an Introduction, the occurrence of nutrient deficiencies in New Zealand is described, and the factors that influence their occurrence are outlined. In the following section, visual symptoms of deficiency for all nutrients are described for radiata pine, Douglas-fir and eucalypt species.

The use of foliar analysis in diagnosing deficiencies is described, and diagnostic criteria are given for radiata pine and Douglas-fir. Tentative criteria are also presented for some key nutrients for cypress species. Recognising that sustainable forest management requires that forest managers protect the soil as it is the key environmental attribute that underpins forest productivity, these first sections on occurrence, recognition and foliar diagnosis of nutrient deficiencies are followed by three sections on forest soils. These describe important plantation forest soils of New Zealand and their chemical and physical characteristics, along with information on soil sampling procedures and use of soil data for maintaining forest nutrition and forest sustainability. The effect of forest management practices, including site preparation, weed control and harvesting on forest nutrition and sustainability are then described. This section also includes information on effects of forest management practices on soil carbon.

A section on forest fertilisation includes information on fertiliser types and application rates, methods and timing of application, the importance of weed control when fertiliser is applied at establishment, and information on fertiliser response, use of nitrogen-fixers, and avoiding impacts of fertilisation on water quality. Sections on management of forest and nursery nutrition, genetic differences in nutrition, and mycorrhizae are also included. Recognising that the quality of wood is as important as the quantity of wood produced, the report concludes with a section on the effects of fertilisation on wood properties.

The report provides an up-to-date coverage of relevant information on nutrition management for plantation forests in New Zealand. This will allow members to revise and refine their nutrition management systems and increase their awareness of the importance of forest nutrition so as to increase productivity and profitability.

1. INTRODUCTION

Forest Research Institute Bulletin 97 – 'Nutrient deficiencies and fertiliser use in New Zealand exotic forests' (Will 1985) – brought together information collected from over 30 years of research on forest nutrition in New Zealand. It was produced as a practical guide to the identification and correction of nutrient deficiencies. Deficiency symptoms, mostly for the important plantation forest species radiata pine (*Pinus radiata*), their occurrence and methods of correction through fertiliser application were described and illustrated. The Bulletin concluded with a section on foliar sampling methods and the interpretation of foliar analyses. Bulletin 97 became a much-used reference for foresters and researchers alike.

A substantial amount of research on forest nutrition has been undertaken in the more than 20 years since publication of Bulletin 97, much of which has been reported in various journals and reports that are not always easily available. This report seeks to bring this information together, along with that presented in the original Bulletin, to make it more readily accessible to foresters.

Sustainable forest management requires that forest managers protect the soil as it is a key environmental attribute that underpins the capacity of a forest to produce timber, along with non-timber values, in perpetuity. This report characterises the important plantation forest soils of New Zealand and their chemical and physical properties. Sections on forest management effects on nutrition, fertiliser use, nutrition in forest nurseries and genetic differences in nutrition are also included. All forest trees develop symbioses with soil fungi to form mycorrhizas which play a key role in facilitating nutrient uptake by the host tree. A section is therefore devoted to the main types of mycorrhizas formed by our plantation forest species, and their influence on tree nutrition. Finally, recognising that the quality of wood is as important as the quantity produced, the report concludes with a section on the effects of fertilisation on wood properties.

Reference

Will G. 1985. Nutrient deficiencies and fertiliser use in New Zealand exotic forests. Forest Research Institute, New Zealand Forest Service, Rotorua, New Zealand. FRI Bulletin No. 97. 53 p.

2. OCCURRENCE OF NUTRIENT DEFICIENCIES IN NEW ZEALAND

Summary:

- *Deficiencies of four nutrient elements are common in New Zealand – nitrogen, phosphorus, magnesium and boron. Potassium deficiency occurs less frequently, while copper, manganese, iron and zinc deficiencies are rare.*
- *The regional occurrence of nutrient deficiencies is outlined and factors associated with nutrient deficiencies are discussed. These include soil (parent material, pH, depth, drainage and aeration) climate, stand age and management, occurrence of pests and diseases, and tree species and genotype.*

Eleven elements are required for tree growth, and one additional element, molybdenum, is required by nitrogen-fixing tree species to fix atmospheric nitrogen. Deficiencies of many of these elements occur in New Zealand, and most have been confirmed by fertiliser response trials. Deficiencies of only a few elements – nitrogen, phosphorus, magnesium and boron – are relatively common, and potassium deficiency occurs somewhat less frequently. Deficiencies of the remaining elements are uncommon. Our understanding of the occurrence of deficiencies in New Zealand (Table 2.1) is derived mainly from experience with radiata pine (Will, 1985) – different species may show some differences from the patterns described here. The original description of the occurrence of deficiencies by Will (1985) was augmented by maps of the occurrence of key deficiencies published by Hunter *et al*. (1991) in the ‘Atlas of radiata pine nutrition in New Zealand’. The Atlas linked foliar nutrition data held in the Forest Research Institute database to New Zealand’s major Soil Orders to provide maps of foliar nutrient concentrations that show the likely occurrence and severity of nutrient deficiencies.

Factors Influencing Occurrence of Nutrient Deficiencies

Soil, climate, pests and diseases, stand management practices and species or genotype are all factors that can influence forest nutrition, either on their own or through interaction with each other.

Soil Factors

Key soil factors influencing stand nutrition are the parent material from which the soil is derived, depth of the soil, soil drainage and organic matter content.

Parent material

Soils derived from particular parent materials have characteristic nutrient limitations for forest productivity.

- Limestone soils are commonly alkaline (have high pH) and trees growing on these soils may develop lime chlorosis, caused by iron and/or manganese deficiency. In addition, the availability of these elements is reduced as soil pH increases (see Fig. 2.5). Limestone soils can be acidified by applying elemental sulphur, but the cost is likely to be prohibitive. Application of manganese or iron to these soils is likely to be ineffective as any additions will be rapidly made unavailable by the high pH.
- Raw soils such as coastal sands, dredge tailings and eroded soils have low organic matter contents and are commonly deficient in nitrogen (Fig 2.1). Nitrogen deficiency may be corrected by applying nitrogen fertiliser, though this may be readily leached, and use of legumes such as lotus (Lotus pedunculatus) to fix nitrogen may be a better option.
- Ultramafic soils have high magnesium and iron content and may have high, even toxic, levels of heavy metals (e.g., nickel, chrome). Calcium may also be low in these soils. An option for these soils may be to select genotypes tolerant of these conditions.

Table 2.1. Occurrence of nutrient deficiencies in radiata pine (after Will 1985 and Hunter *et al*. 1991).

Element	Occurrence of deficiency
Nitrogen	Nitrogen is the key deficiency limiting forest productivity in New Zealand. Severe nitrogen deficiency occurs on coastal sands, eroded land, dredge tailings and other raw soils where soil organic matter levels are low. Severe deficiencies also occur on soils where organic matter levels are adequate, but decomposition is too slow to supply adequate nitrogen, as in peats and the gley-podzols in Westland and Northland. In these situations, improved aeration through drainage is often the key to increasing the rate of decomposition and nitrogen availability. Nitrogen deficiency may also limit forest productivity on gravel and granite soils in Nelson, pumice soils in central North Island, and hill and stony alluvial soils in the South Island. Most of the South Island was mapped as having marginal levels by Hunter *et al*. (1991), who noted for the South Island that "a currently unexploited opportunity to increase growth by nitrogen fertiliser application exists".
Phosphorus	Phosphorus is an important element limiting forest productivity on strongly weathered soils in the tropics and sub-tropics. The New Zealand representatives of these types of soils – the podzolised sands and clay soils in Northland, North Auckland and the Coromandel peninsula – were extremely phosphorus deficient in the past, but phosphorus fertilisation has alleviated the deficiency in many of the forests. Elsewhere, phosphorus deficiency may limit forest productivity on pakihi soils in Westland, granite and Moutere gravel soils in Nelson, and on hill soils in the Maramua, King Country and Rimutuka regions of the North Island, and on eastern and southern hills in the South Island.
Sulphur	Sulphur deficiency has not been reported for New Zealand forests. It would be most likely to occur in central South Island areas away from the coast where inputs from atmospheric deposition are low, where it is widely deficient for pastoral farming. As such it may develop in new hill and high country Douglas fir and pine plantations.
Potassium	Deficiency of potassium is restricted to podzolised, leached sandy soils in Northland, pakihi soils in Westland and small areas of ultramafic soils.
Magnesium	Severe deficiency occurs on coarse pumice soils in southern Kaingaroa. Slight to moderate symptoms are common throughout central North Island and in many South Island areas, away from the coast, especially in dry years and/or after pruning.
Calcium	Calcium deficiency has not been confirmed in New Zealand, but trees showing symptoms of calcium deficiency have been observed in some severely phosphorus deficient forests in North Auckland and the Coromandel Peninsula.
Boron	Severe deficiency occurs on granite and Moutere gravel soils in Nelson and on dredge tailings on the West Coast. Severe to moderate deficiency occurs in low rainfall inland hilly areas, free draining soils in the South Island, and coarse pumice soils in the North Island.
Iron	Occurs on small areas of limestone where the rock is at or near the soil surface. Iron deficiency has also been observed in nurseries.
Manganese	As for iron – deficiency occurs on small areas of limestone where the rock is at or near the soil surface.
Copper	Deficiency occurs on recent and older coastal sands in Northland. May be induced after N and P application in some podzolised soils in Northland
Zinc	Deficiency has been recorded only at Karikari Peninsular in Northland

Fig. 2.1. Radiata pine showing chronic nitrogen deficiency symptoms associated with the low organic matter content of the substrate - dredge tailings, Taramakau, Westland (Craig Ross).

Soil Depth

Nutrient availability is reduced in soils where the rooting depth is limited by factors such as shallow bedrock, compacted gravels or high water table. In some situations the effective soil depth can be increased, for example by ripping compacted gravels and draining soils with a high water table.

Soil pH

- Nitrogen availability for forest tree species is not greatly affected by soil pH over a relatively wide pH range (4 to 7).
- Phosphorus availability peaks between pH 6 and 7 and decreases at both low and high pH. Under acid conditions phosphorus can be precipitated and become insoluble or ‘fixed’ by iron and aluminium oxides or soil clay components, while under alkaline conditions it may form insoluble calcium phosphate.
- The levels of plant-available potassium, calcium, magnesium and molybdenum fall as soils become more acid and soil pH declines below 5.
- In contrast, the solubility and availability of the metallic micronutrients manganese, copper, iron and zinc increases as the soil pH falls below 6. In high pH soils (above 7) these nutrients may become deficient.
- Boron is most highly available under neutral conditions; it becomes soluble and can be leached under acid conditions, while under alkaline conditions it can be fixed by soil clays and made less available for plant uptake.
- There are no generally accepted ‘critical values’ for soil pH for forest species. For many agricultural plants, optimum growth occurs in the pH range 5.5-7.0, but most forest species tolerate more acid soils and the lower level for optimum growth is more likely to be around pH 4.0. Internationally, there have been very few instances where liming has produced improved growth of forest species.

Drainage and aeration

Most plant species require good drainage for optimum growth (Fig. 2.2). Once drainage is impeded and soil becomes waterlogged and anaerobic, oxygen, required by roots and soil microbes for respiration, becomes deficient and productivity is impeded. As root respiration declines root permeability to water is reduced and water uptake is restricted. Under anaerobic conditions nutrient uptake is reduced and nitrogen may be lost from the soil through nitrate leaching or loss of nitrous oxide or nitrogen to the atmosphere. In contrast, manganese and iron both increase in solubility and availability in anaerobic soils.

Climatic Factors

Deficiency of some nutrients may be exacerbated by specific climatic events associated with the season of the year. Boron deficiency develops in mid-summer, and is most severe under drought conditions. Magnesium deficiency develops in spring when it is withdrawn from older foliage and translocated to satisfy the requirements of new growth. Drought may also exacerbate magnesium deficiency as uptake from the soil is reduced under dry soil conditions. This has also been shown to occur with potassium deficiency – Smethurst *et al.* (2001) show a sequence of photographs of the same tree where yellowing due to potassium deficiency increased with drought at age 3.0 years, then decreased following rain (Fig. 2.3). As the authors noted, low soil moisture inhibits movement of potassium to the root and thus the amount available for uptake.

Fig 2.2. Improving drainage to lower the water table and increase aeration can increase nutrient availability. Craigieburn, Westland.

Fig 2.3. **Climatic factors can influence nutrient availability. Here symptoms of potassium deficiency in a radiata pine tree increased with drought from age 2.4 years (left photo) to 3.0 years (centre), then decreased following rain (right, 3.6 years), Tasmania. From Smethurst *et al*. (2001).**

Stand Age and Management

In forest stands, nutrient demand is greatest during periods of canopy expansion. This applies especially for nitrogen. Stands may be nitrogen deficient and respond strongly to nitrogen fertiliser after thinning (Fig 2.4), but may not be nitrogen deficient, or responsive to fertiliser, before the operation or after the canopy has fully expanded again.

Fig 2.4. Thinning opens up a canopy, providing space for the canopy to expand. Nutrient demand then increases, leading to temporarily greater fertiliser responses, Kaingaroa Forest.

Severe pruning may exacerbate deficiency of some nutrients as it reduces the resource within the tree from which those nutrients can be translocated to new foliage, placing greater demand on the remaining older foliage.

On limestone or other soils with naturally high pH in the subsoil, pruning and thinning may contribute to development of chlorosis (Fig. 2.5). As the canopy is reduced, rainfall interception and evapotranspiration are reduced, resulting in increased soil moisture. If this leads to elevation of the water table, high pH water from subsoil horizons can move into upper soil layers (where pH was initially lower), increasing the pH and reducing the availability of manganese and iron (Dick and Beets 2000).

Prior to canopy closure and suppression of weed growth, developing young stands compete with weeds for available nutrients and water. Deficiencies are therefore more likely to occur in stands with strong weed growth than in stands where weed growth has been controlled.

Pests and Diseases

Stands that have lost a proportion of foliage because of pest or disease attack may respond to fertiliser, especially nitrogen, in much the same way as thinned and pruned stands.

Fig. 2.5. Chlorosis, on a limestone soil, developed following pruning, thinning and high rainfall. The chlorosis is thought to be caused by manganese and/or iron deficiency – see text for explanation. This stand recovered after the photograph was taken.

Tree Species and Genotype

Some tree species and genotypes are better able to obtain access to nutrients than others. For example species with ectotrophic mycorrhizae such as pines and Douglas-fir are able to access nitrogen from soil organic matter more readily than species with arbuscular mycorrhizae such as cypresses and redwoods. The latter species are commonly referred to as 'site demanding' species. Genotypic differences in nutrition have also been found to occur within species, a good example being magnesium deficiency in radiata pine (Fig. 2.6) – some clones or families are much more prone to exhibit deficiency symptoms than others (Beets *et al*., 2004).

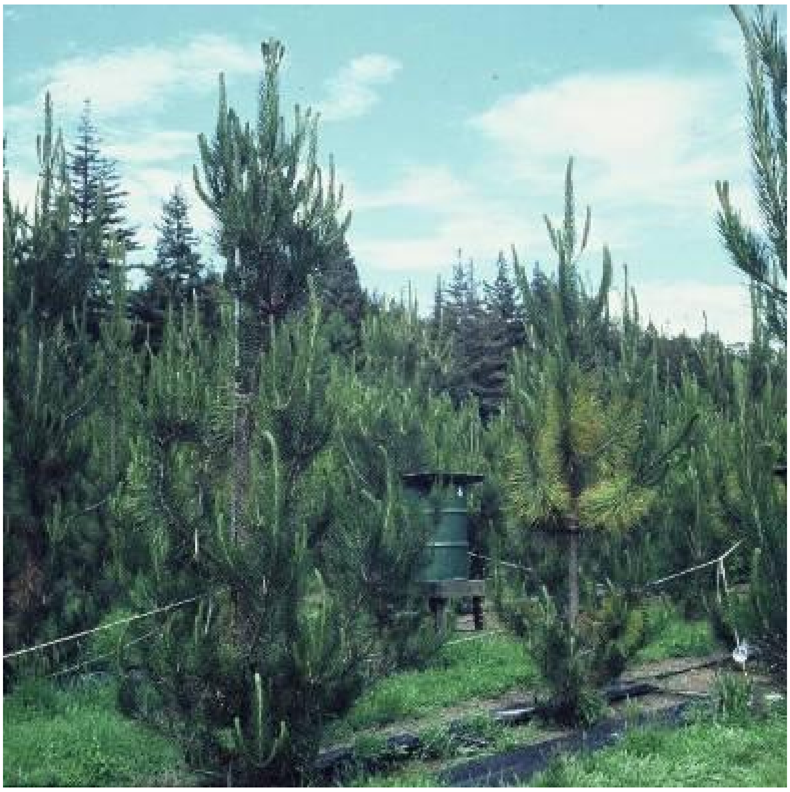

Fig. 2.6. An example of genetic variation in susceptibility to nutrient deficiency – a tree in a trial plot showing symptoms of magnesium deficiency amongst others without deficiency symptoms.

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3. VISUAL SYMPTOMS OF NUTRIENT DEFICIENCY

Summary

- *Nutrient deficiency symptoms can take many forms including needle chlorosis, necrosis or fusion, stem distortion, bud or shoot death, abnormal pigmentation or simply slow growth.*
- *These are briefly described, and the effect of nutrient element mobility within the tree on symptom expression is discussed. Nutrient deficiency symptoms are described for radiata pine, Douglas-fir and Eucalyptus species.*

Field observations of needle, leaf and stem abnormalities and canopy condition allow an initial assessment of nutrient deficiency. The occurrence of symptoms can help identify stands likely to give good response to fertilisers. The absence of symptoms does not mean that stand productivity is not nutrient-limited or that a fertiliser response will not be obtained. Symptoms are an expression of a relatively severe deficiency and may become apparent only after the deficiency has already resulted in a growth reduction.

Leaves and needles can be sensitive indicators of nutrient deficiency, though not all deficiencies show distinctive symptoms. For example, chlorosis (see below) can be caused by deficiencies of several nutrients that interfere with chlorophyll synthesis, and may vary with severity of deficiency, the extent to which young and old tissues are affected as well as environmental or other biotic conditions (moisture, temperature, disease) which may produce similar symptoms.

Additionally, fungal disease, insect attack, drought, frost, direct application or drift of herbicides and pesticides, or animal damage are all factors that can cause foliage or stem abnormalities. These factors must be considered when ascertaining whether or not an abnormality is due to nutrient deficiency. Initial diagnosis from visual symptoms may need to be confirmed by foliar chemical analysis.

Deficiency Symptoms

Nutrient deficiency in forest trees is commonly expressed as one or more of the following symptoms.

Chlorosis

Chlorosis results from partial to complete loss of chlorophyll, making needles pale green, yellow-green or yellow (Fig 3.1). Several nutrient deficiencies (nitrogen, phosphorus, sulphur, potassium, magnesium, boron, manganese) as well as other factors can cause chlorosis. A key to chlorosis prepared by Will (1985) given in Table 3.1 can be used to distinguish causes of chlorosis in radiata pine, and may be used as a guide for other needle-leafed conifers.

Necrosis

Necrosis is death of tissue resulting in brown or tan colours. Commonly, needle or branchlet tips become necrotic, but in extreme conditions the entire needle or branchlet may become necrotic and is usually shed from the plant. A number of nutrient deficiencies will cause necrosis in severe or later stages of the deficiency (Fig. 3.1)

Table 3.1. Key to chlorosis in radiata pine (from Will 1985, supplement)

On an individual tree, and often on most trees in a group:			
1	**A**	Needles of the same age on shoots in a similar position in the crown affected to a similar degree	Refer to 2
	B	Different degrees of chlorosis on adjacent fascicles and/or individual needles in a fasicle	Non-nutrient cause, may be needle cast fungus
	C	Sharp boundary between chlorotic and green tissue, sometimes chlorotic band across part of the needle.	Non-nutrient cause, may be herbicide damage
2	**A**	Degree of chlorosis similar over whole length of needles and all ages of needles	Refer to 3
	B	Chlorosis restricted to needle tips	Refer to 4
3	**A**	Chlorosis most marked (very pale yellow) in most recent flush of leader growth (limestone soils)	Manganese
	B	Chlorosis even over whole tree with tendency for greener tuft on leader	Nitrogen
4	**A**	Chlorosis associated with bud or leader dieback	Boron
	B	Chlorosis not associated with dieback	Refer to 5
5	**A**	Chlorosis affects current season's needles on ends of branches from mid-summer	Phosphorus
	B	Chlorosis affects previous season's foliage	Refer to 6
6	**A**	Yellowing of needle tips in mid to lower crown in late winter	Potassium
	B	Golden yellowing of needle tips in mid to upper crown in early summer	Magnesium

Stem Distortion

Stem distortion may occur with boron, copper or calcium deficiency (Fig. 3.2). Sometimes a number of distorted needles are clustered at the stem tip forming a rosette, as in zinc deficiency in radiata pine. Wind and frost damage are also major causes of stem distortion (Fig 3.3).

Fig 3.1 Needle tip chlorosis caused by magnesium deficiency, with older needles showing necrosis.

Fig. 3.2 Stem distortion caused by boron deficiency in radiata pine at Crater Block, Rerewhakaaitu, Kaingaroa Forest

Fig. 3.3. Stem distortion caused by climatic damage (wind or frost) in Douglas-fir near Lake Coleridge, Canterbury.

Bud or Shoot Death

Bud or shoot death, especially of terminal buds, may be caused by boron, or less commonly, calcium deficiency. Drought or frost during the growing season can also cause bud death (Fig 3.4), which can subsequently result in stem distortion (Fig 3.3).

Fig 3.4. Dead buds in Douglas-fir caused by a November frost, Kaingaroa forest.

Needle Fusion

Needle fusion occurs where individual needles in a fascicle fail to separate; in severe cases the fused fascicles are stunted and distorted. Phosphorus and copper deficiency can cause needle fusion in radiata pine.

Pigmentation

Red and purple pigments develop from accumulation of anthocyanins, and may occur in leaves and stems of some species as a result of nutrient deficiencies. Reddish pigments in eucalypts are indicative of nitrogen deficiency, purplish pigments are associated with phosphorus deficiency.

Slow Growth

Slow growth is a non-specific symptom of all severe deficiencies, and of less severe deficiencies where visual symptoms are not apparent. In such cases foliar analysis may be required to distinguish between potential nutrient deficiency and other possible causes of reduced growth.

Element Mobility and Expression of Deficiency Symptoms

An understanding of nutrient element mobility aids diagnosis of nutrient deficiencies. Nitrogen, phosphorus and potassium are known as mobile elements as they can move from older tissues in which they were initially incorporated into young tissues where nutrient demand is high. Magnesium is also mobile in some species, but moves only slowly in others, including pines and Douglas-fir. Calcium, iron, boron, manganese, copper, zinc and molybdenum are considered immobile as they do not move readily. Sulphur tends to be intermediate between the two groups.

Deficiency symptoms of mobile elements show up first or most strongly in the lower part of the plant, or in the older foliage, as the elements migrate to younger tissues (Fig 3.5a). In contrast deficiency symptoms of immobile elements show up first and most strongly in youngest foliage, while older foliage appears normal (Fig 3.5b).

Fig 3.5. Chlorosis in old and young foliage caused respectively by a (left), the mobile element nitrogen and b (right), the immobile element boron.

Recognition of Nutrient Deficiency Symptoms

Nutrient deficiency symptoms can be recognized from published written descriptions and photographic images. One of the most comprehensive sets of descriptions was provided by Will (1985) for radiata pine; these are summarised in Table 3.2. Deficiency symptoms described for Douglas-fir by Binns *et al*. (1980) and Walker and Gessel (1991) are reproduced in Table 3.3, and symptoms for eucalyptus species described by Dell (1996) are reproduced in Table 3.4. For eucalypts, experience of Australian workers is that visual symptoms (and foliar analysis) of the major nutrients is only useful for about the first year of growth (P. Smethurst pers. comm.). Thereafter, at least for *E. globulus* and *E. nitens*, eucalypts seem to respond to nutrient and other stresses by regulating leaf area – by dropping leaves – so that leaf symptoms become less useful for diagnostic purposes. Photographs of deficiency symptoms in a range of eucalypt species can be found in Dell *et al.* (1995). Descriptions of deficiency symptoms have not been reported for *Cupressus* species.

Table 3.2. Visual symptoms of nutrient deficiencies in radiata pine (from Will 1985)

N	The crowns of nitrogen-deficient trees are characteristically a uniform yellowish green, becoming yellow under severe conditions (Fig 3.6), and the needles are shorter than normal (Fig. 3.7). Unlike the chlorosis caused by phosphorus, potassium, and magnesium deficiency, each needle is a uniform colour along its whole length. Needles in all parts of the crown tend to be a similar light green, yellowish green, or yellow, but older needles are more affected than younger needles. There may be a tuft of greener foliage on the leader just below the terminal bud, particularly in young trees.
P	In *young* trees the most characteristic feature is short yellow-tipped needles on the ends of branches, giving a flat end to shoots when seen in profile (Fig. 3.8). In *mature* trees phosphorus deficiency is characterized by narrow, thin crowns caused by restricted diameter and branch growth (Fig. 3.8), short needles and needle loss. In severely deficient trees, foliage colour is a dull to greyish green, giving phosphorus-deficient stands a grey appearance. Leader dieback may be evident in extreme cases. Although not specific to phosphorus deficiency (see copper), needle fusion is common in a small proportion of trees in moderately phosphorus-deficient stands, and in severe cases the fused fascicles are stunted and distorted.
K	Potassium deficiency is characterized by yellow tips in previous season needles initially in the mid-lower crown area, but symptoms may subsequently develop throughout the crown (Fig 3.9). The symptoms intensify in late winter, and this is probably associated with the expansion of pollen cones, which have a high potassium content. Potassium deficiency can be confused with magnesium deficiency, but the two symptoms can be distinguished by needle colour only - magnesium deficient needles are more golden, and location within the crown - magnesium deficiency symptoms are evident in the upper-mid crown. Both deficiencies must be distinguished from chlorosis caused by needle-cast fungi. Needle-cast fungi rarely attack tree crowns and individual needles in the uniform pattern characteristic of nutrient deficiencies.
Ca	Calcium deficiency causes resin exudation around buds and on stems, ultimately resulting in shoot death.
Mg	Golden yellow needle-tip chlorosis (Fig 3.10), subsequently turning brown with a yellow region between the brown tip and the green basal region; eventually the whole needle turns brown. Initially restricted to the upper crown giving rise to the condition ‘upper mid-crown yellowing’ and to previous season foliage, especially during the period of rapid foliage expansion in spring. In severe cases, chlorosis extends to a third or more of the needle length, and needle tip chlorosis can occur on current season needles.

Table 3.2. cont.

B	Boron deficiency causes the death of buds and shoots. Symptoms become apparent in mid-summer or later, and are most apparent in drought years. Usually the main leader is first affected, followed by the shoots on the ends of upper branches (Fig. 3.11). Where a tree has been affected for several years, it develops a bushy appearance. The apical portion of shoots may die before needle fascicles elongate. The unopened fasicles are usually shed and the unlignified stem may crook or curl into a U- or J-shape. The pith becomes brown within the dead portion of the stem, and discoloration and dark brown spots may occur below the dead zone. Tip or bud dieback, in the absence of stem distortion, may result from less acute deficiency. The dead bud is usually surrounded by dead needles, and infiltrated or coated with resin.
Mn and Fe	Older foliage becomes a pale yellowish-green, particularly at the tips (Fig. 3.12). Current season immature foliage becomes very pale yellow. See also Section 3 and Figure 3.5.
Zn	Growth of young trees is stunted, producing a rosette of buds around the terminal bud leading to formation of multiple leaders (Fig. 3.13). Needles are short and have dead tips.
Cu	Copper deficiency is characterized by twisting of branches and the main leader (Fig. 3.14). Both the branches and the leader may grow horizontally. Fused needles and needle-tip burn may be apparent

Fig 3.6 Nitrogen deficiency in radiata pine – crowns are a uniform yellowish green, yellow when deficiency is severe, Santoft Forest.

Fig. 3.7 Nitrogen deficient needles are shorter than normal and are uniformly light green or yellowish green along the whole length.

Fig. 3.8 In young trees, phosphorus deficiency is characterised by short, yellow-tipped needles on branch ends, while in mature trees it is characterised by narrow, thin crowns, Riverhead Forest.

Fig. 3.9 Potassium deficiency is characterised by yellow tipping of previous season needles developing first in the lower crown (left), possibly spreading over the whole crown (right), Tasmania. (Philip Smethurst).

Fig. 3.10 In magnesium deficiency needle tips are golden yellow (above left), and symptoms are seen in the upper-mid crown area, Puruki Forest (above right) and Dalethorpe Forest (below left, Euan Mason), rather than initially in the lower crown as in potassium deficiency. Needle tips subsequently become necrotic, thus needles grade from brown at the tips, through yellow, to green at the base (below right).

Fig. 3.11 Boron deficiency causes bud and shoot death of the leader and upper branches, particularly on free draining soils and in drought years (upper left). The stem may curl into a ‘J’ or ‘U’ shape (upper right). Repeated occurrences result in the tree developing a bushy appearance (below), Crater Block, Rerewhakaaitu, Kaingaroa Forest

Fig. 3.12 In manganese deficiency older foliage develops a pale yellow green colour at the tips (left, Mt Gambier, South Australia). Current immature foliage becomes very pale yellow (right, young tree on limestone soil, Hawkes Bay). On limestone soils iron deficiency may contribute to these symptoms.

Fig. 3.13 Zinc deficiency is characterised by stunting of young trees and the formation of a rosette of buds around the leader which causes multi-leadering (Cape Karikari).

Fig. 3.14 Copper deficiency is characterised by twisting of branches and the main leader, Mangawhai Forest, North Auckland

Table 3.3. Visual symptoms of nutrient deficiencies in Douglas-fir. The symptoms are from Binns *et al.* (1980) who described symptoms for young field-grown plants. Asterisks note symptoms from Walker and Gessel (1991), who described symptoms for plants grown in sand or solution culture for periods of about six months. See Section 11 for further description of deficiencies in young plants.

N	Light green foliage, needles shorter than normal; in severe deficiency needles are yellow-green or yellow, The leader may become thin and spindly. Discoloration is uniform over the whole length of the needle and symptoms are apparent over the whole live crown rather than specific areas (Fig. 3.15).
P	Needles dull green and reduced in length, loss of older foliage as deficiency increases. Tree form usually remains good, though a loss of apical dominance may develop.
S*	Upper (younger) needles yellowish, older needles green
K	Needle chlorosis, with the effect being greater at lower temperatures, thus discoloration is more pronounced in winter. In severe deficiency, death of the apical bud and upper side branches may occur, leading to stunted growth and development of a bushy habit.
Ca*	Death of terminal and some lateral buds
Mg	Deficiency shows up in late autumn as a yellowing of the needles of the current year at the base of the shoot. Individual needles yellow from the tip and the yellowing gradually extends up the shoot towards the bud. *Beginning with older needles, the tips turn brown and there is a yellow region between the brown tip and green basal portion; this progresses until the entire needle is brown.
B*	Death of terminal buds, foliage exceptionally dark green. Boron deficiency must be distinguished from frosting which can also cause bud death (Fig 3.3) subsequently leading to stem malformation (Fig. 3.4).
Fe*	Upper (younger) foliage bright yellow, older foliage remains green
Cu	Little effect on needle colour or size. Branches tend to droop and the leader may be sinuous or point downwards.

Fig 3.15 Above: nitrogen deficiency symptoms in Douglas-fir are similar to those in radiata pine – needles are light-green to yellow, over the whole length of the needle (above and below left) and whole length of the crown. Needles are shorter than normal. Below: Nitrogen deficient (left) and healthy (right) Douglas-fir needles, Port Underwood.

Table 3.4 Visual symptoms of nutrient deficiencies in Eucalyptus species (from Dell 1996).

N	Early stages: mature leaves uniformly pale green or with mild interveinal chlorosis, symptoms then spread to young leaves and intensify. Advanced stages: all leaves uniformly chlorotic, anthocyanin accumulates as small reddish spots in mature leaves of some species, old leaves abscise prematurely.
P	Early stages: mature leaves with small interveinal reddish spots or patches or with necrotic margins or dark, bluish green; symptoms then spread to young leaves. Advanced stages: whole plant pale red, new leaves small, plants stunted, old leaves abscise prematurely.
S	Early stages: interveinal areas of young leaves pale green or young leaves uniformly pale green. Advanced stages: chlorosis extends to mature leaves, leaves uniformly yellow, leaf tips bronzed then necrotic.
K	Early stages: necrotic areas form apically, marginally or within the lamina of old leaves, interveinal chiorosis of old leaves. Advanced stages: necrosis progresses into young leaves, leaves dry and scorched, increased lateral branching, new leaves small, plants stunted, old leaves abscise prematurely.
Ca	Early stages: impaired expansion at margins of young leaves causing leaves to reflex and leaf margins to turn over or under or become undulate. Advanced stages: young leaves severely distorted and with tip-burn, leaf margins chlorotic then necrotic, death of shoot apex, multiple axillary shoots.
Mg	Early stages: marginal and interveinal chlorosis of mature leaves, necrotic spots in old leaves. Advanced stages: mature leaves chlorotic except for the midrib and major lateral veins which remain green; chlorotic areas may become necrotic, white or brown, symptoms spread to young leaves, old leaves abscise prematurely.
B	Early stages: expanding leaves keeled upwards or curled, sectors of leaf blade missing, or marginal and interveinal chlorosis, or margins reddish purple. Advanced stages: Dieback of young shoots, plants prostrate or with pendulous branches.
Mn	Early stages: expanding and recently mature leaves with marginal chlorosis or interveinal chlorosis in young leaves. Advanced stages: small brown or white necrotic spots appear in chlorotic marginal or interveinal areas, leaf tips and margins withered. Old leaves abscise prematurely, bark may show bleeding.
Fe	Early stages: interveinal areas of expanding leaves pale green. Advanced stages: young leaves yellow with narrow green veins, symptoms spread from young to old leaves.
Zn	Early stages: symptoms vary with species – expanding and recently mature leaves turn bluish green and leaf margins turn pale yellow, or adaxial surface of young leaves bronzed, or interveinal areas of young leaves pale green. Advanced stages: symptoms spread to old leaves, plants dwarfed, internodes short, leaves small, often with reddish and necrotic tips.
Cu	Early stages: expanding leaves with undulate or deformed margins, stem bleeding at nodes. Advanced stages: death of lateral buds, enlarged nodes, dieback of shoot apex, necrosis of young leaves.

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4. FOLIAGE ANALYSIS AND INTERPRETATION

Summary
- *Foliage analysis is based on the concept that the concentrations or contents or ratios of nutrients in foliage reflect the nutritional status of a plant, and thus its growth potential.*
- *Foliar nutrient concentrations are influenced by genetic differences, seasonal and annual variation, and foliage age and position within the crown, and these factors need to be considered in the design of a sampling strategy.*
- *Sampling procedures for needle-leaved conifers, eucalypts and cypress species are described to ensure representative samples are collected that will produce analytical results that can be reliably related to diagnostic criteria.*
- *Diagnostic criteria are presented for radiata pine and Douglas-fir. Some diagnostic guidelines are also suggested for cypress species.*

The rationale behind foliage analysis is that the concentrations or contents or ratios of nutrients in foliage reflect the nutritional status of a plant, and thus its growth potential. Foliage analysis is a better measure of nutrient availability than soil analysis, as the tree integrates nutrient availability over the whole soil volume occupied by the tree roots, as well as over time. For these reasons foliage analysis is more commonly used than soil analysis to determine forest nutrient status and for assessing fertiliser requirements. Other plant parts may be analysed to assess nutrient status, but foliage is generally used because it is convenient to sample, and foliage often shows the first signs of nutrient disorder.

The value of foliage analysis for diagnosing or monitoring nutritional status relies largely on the care that is taken in collecting, handling and analysing the samples. Unreliable and misleading interpretation will happen unless proper steps are taken to minimize errors in each of these tasks. Procedures for collecting and handling samples need to be standardised to ensure that the tests can be interpreted with confidence.

Purpose and Principles of Foliage Analysis

Application of Foliage Analysis

Foliage analysis is undertaken to determine the nutrient status in the plant at the time of sampling with the objective of identifying the cause of a disorder or poor vigour of a crop, or confirming a preliminary diagnosis made on the basis of plant symptoms. Foliage analysis can be used to predict the need for fertiliser and assess the effectiveness and longevity of past fertiliser applications. It can also be a convenient method for assessing the nutrient status of forest sites. Monitoring crop nutrient status over time can provide an early indication of declining nutrient status, and can be used to verify that nutritional management practices are satisfactory, or alternatively, that practices should be modified.

Derivation of Diagnostic Nutrient Concentrations

Assessment of plant nutrient status requires an understanding of relationships between plant nutrient concentration and crop vigour, growth or yield. Diagnostic nutrient concentrations associated with optimum or below optimum performance have been derived for numerous crop species. Ideally, standard nutrient concentrations are derived from well-defined relationships established experimentally between nutrient concentration in a plant part and plant growth or yield as a result of response to nutrient supply (Fig. 4.1). This is more difficult for long lived forest species than for many crops, and diagnostic concentrations for forest species may be obtained indirectly. This may be done, for example, by analysing foliage from trees showing deficiency symptoms or growing below optimum levels, then comparing the concentrations of various elements with those found in healthy or vigorously growing plants.

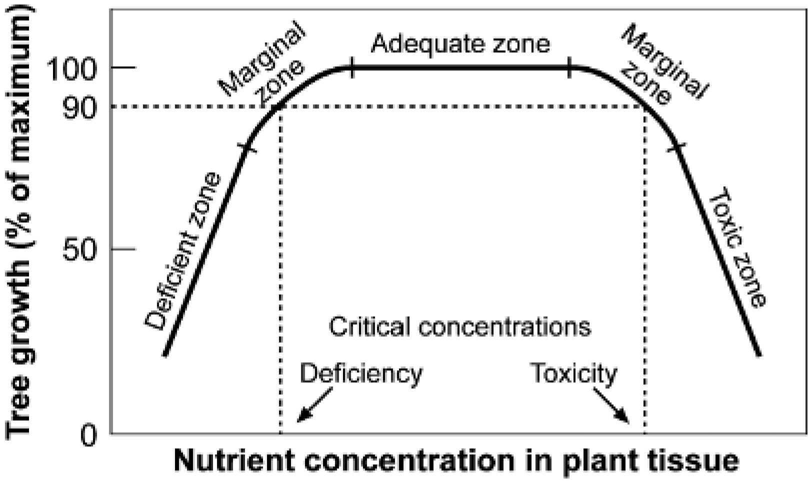

Fig. 4.1 Nutrient concentration zones for diagnosing nutrient deficiency and toxicity in plants (after Smith and Loneragan, 1997).

Zone definitions are:

- Deficient (or low) zone: The range of concentrations in the specified plant part at which visible deficiency symptoms and/or severely reduced growth or yield occur.
- Marginal zone: The range of concentrations at which there are no visible deficiency symptoms, but a reduction in growth or yield occurs. Similarly, another marginal zone for nutrient toxicity is located at higher concentrations, between the adequate and toxic zones.
- Critical concentration (deficiency or toxicity): The concentration at which 90% maximum growth or yield of the plant is found. Plant nutrient status should normally be kept above this critical concentration (deficiency) or below it (toxicity).
- Adequate zone: The range of concentrations at which the growth or yield of the plant doesn’t change with increasing nutrient concentration.
- Toxic zone: The range of concentrations at which the growth or yield of the plant decreases with increasing nutrient concentration.

Factors Affecting Foliar Nutrient Concentrations

In practice, the values of nutrient concentrations determined vary widely due to a number of biotic and abiotic factors, and these should be taken into account when interpreting plant analysis data. In tree crops, foliage analysis has been shown to be reasonably sensitive for diagnosing tree nutrient status, but the following factors can influence nutrient concentrations and the sensitivity of foliage analysis (Mead, 1984).

Between-tree and Genotypic Variation

Measurement of between-tree variation has enabled estimation of the number of trees that need to be sampled in order to determine means within given limits or to detect differences of given sizes. The usual recommendation for diagnostic purposes is to bulk together samples collected from about 20 dominant and co-dominant trees (Mead 1984, Will 1985, Ballard and Carter 1986), though analyses indicate a minimum sample number of 25 trees is necessary to achieve analytical results within 10 % of the true stand mean for most key nutrients deficient in plantation forestry in New Zealand for radiata pine and Douglas-fir (Table 4.1). Boron in radiata pine appears an exception, requiring a sample of 50 trees to obtain accuracy within 10% of the mean (Table 4.1). For more precise determination of the level of deficiency the sample number should be increased accordingly.

Table 4.1. The number of sample trees of radiata pine and Douglas-fir required to achieve analytical results within 5 and 10% of the true stand mean, determined from three studies.

Species	Accuracy required	Nitrogen	Phosphorus	Potassium	Magnesium	Boron	Copper
Radiata pine	5 %[1]	27	46	63	121	209	44
	10 %[1]	7	12	16	30	52	11
	10 %[2]	4	11	14	24	-	-
Douglas-fir	5 %[3]	19	54	55	73	98	78
	10 %[3]	5	13	14	18	25	22

[1]From Knight (1978)
[2]From Mead and Will (1976)
[3]From Graham and Kimberley (2003)

Large genotypic variation in nutrient concentrations has been found among clones. Knight (1978) reported that clonal differences in radiata pine could vary from as little as 2% for copper to 48% for boron. Clonal differences tend to be consistent with time. However, differences among clones in diagnostic nutrient concentration have yet to be assessed.

Seasonal and Annual Variation

Marked seasonal changes in nutrient concentrations occur. For most species, seasonal trends differ between nutrients, with the more mobile elements tending to show low levels in mid-summer or autumn while less mobile elements tend to accumulate throughout the growing season. Generally, nutrient levels tend to be most stable in autumn or winter, and therefore this has often been chosen as the sampling period for temperate and cool climates. To get the maximum sensitivity, however, it is better to sample foliage immediately after most reserves of a nutrient have been mobilised for growth. Thus, late summer or early autumn (i.e., from mid-February to the end of March) has been recommended for foliage sampling of radiata pine because this is a period of maximum stress, yet over which the nutrient concentrations are relatively stable (Mead and Will, 1976). For Douglas-fir in North America Heilman (1971) (in Walker and Gessel 1991) recommended sampling in the dormant season (northern hemisphere mid-September-mid December), and foliar interpretative data have been developed using foliage collected during this period (Ballard and Carter 1986). From a study of seasonal variation of six nutrients in four New Zealand Douglas-fir stands Graham and Kimberley (2003) recommended that Douglas-fir should be sampled during June and July when concentrations were most stable. Since these months are in the middle of the dormant season, the interpretative data developed for North American use should be appropriate for New Zealand samples collected at this time. Preferred sampling times do not appear to have been recommended for eucalypt or cypress species. For diagnosing or confirming deficiencies where nutrient deficiency is sufficiently severe for symptoms to be apparent, foliage samples can be taken at any time of year.

Annual variations of foliar nutrient levels on the same site may be so large (commonly from 15 to 40% of the highest level measured) that at some stages the stand could be interpreted as being distinctly deficient and at other times healthy. The year-to-year variation in a stand may be largely explained by rainfall patterns. In a study by Lambert and Turner (1988) rainfall in the pre-sampling period accounted for 68%, 65% and 56% of variance of annual phosphorus, calcium and nitrogen concentrations respectively in radiata pine.

Foliage Age and Crown Position

Foliage of different ages in evergreen trees is often distinctly different in nutrient concentration. Current year foliage usually has lower variability between trees and is generally accepted as the most useful for diagnostic and monitoring purposes. Vertical gradients of nutrients are found for the different crown positions, and it is usually accepted that foliage from the upper crown is the best indicator of nutrient status in a tree.

For pine, Douglas-fir and cypress species it is recommended that samples be collected from at least two branches per tree exposed to full sunlight in the top third of the crown. For eucalypts, Dell *et al*. (1995) recommended sampling the first fully expanded leaves of an actively growing branch in the mid-upper canopy of young plantations.

Guidelines for Foliar Sample Collection and Handling

Sampling Strategy

A sampling strategy is required to ensure that the data obtained from foliage analysis adequately represent the stand in question. The sampling strategy will depend on the purpose for which the samples are required.

Where samples are being collected to determine possible fertiliser requirements, they should be taken from about 25 trees at approximately evenly spaced distances along transects located to cover the whole of the area being sampled. An alternative strategy is to take composite samples from fewer locations within the stand (but still covering and being representative of the whole stand), with each composite consisting of samples taken from a cluster of five trees. However single sampling provides better representation of the stand than cluster sampling. Similar amounts of foliage should be collected from each tree sampled. In total, a good handful should be collected.

If sampling is being undertaken to determine the cause of visual symptoms or of slow growth of a patch of trees, then samples from about 10 trees may be collected from trees showing the symptoms. The results can be compared with standards, or, using a paired sample approach, with those of samples from healthy trees collected from the same general area. Where symptoms or plant growth vary substantially (e.g., severely affected, mildly affected and healthy), then samples can be taken to characterise this variability. The paired sample approach overcomes some of the difficulties related to seasonal, climatic or annual variation (Mead, 1984). Nutrient deficiency may be inferred where there is a substantially lower concentration of a specific nutrient in tissues of plants exhibiting depressed growth or deficiency symptoms than in normal trees.

Where the area contains different soil types or topographies or is otherwise heterogeneous, stratified sampling may be appropriate, with the number of samples collected from each soil type or other variable being in proportion to its area within the stand. Where it is practical to fertilise such areas separately, consideration should be given to treating them as separate sampling units.

Further points to note are:

- Samples should be collected from dominant or co-dominant trees
- Trees with heavy cone production should be avoided because of diversion of nutrients from foliage to cones
- Edge trees and trees near localised pollution sources (for example unpaved roads, limeworks or recent nearby aerial topdressing) should be avoided.

Sampling Procedures

Standard sampling procedures must be adopted to minimise variation in nutrient concentrations associated with foliage age and crown position. Recommended sampling procedures for needle-leaved conifers, eucalypts and cypress species are as follows:

Needle-leaved conifers
For radiata pine, Will (1985) recommended that samples should be taken from current-season fully-grown foliage on the most recent second order branches in the top third of the crown (see Fig. 4.2). Graham and Kimberley (2003) also recommended sampling from second order branches in Douglas-fir, because there was a little less year-to-year variation than in needles from first order branches.

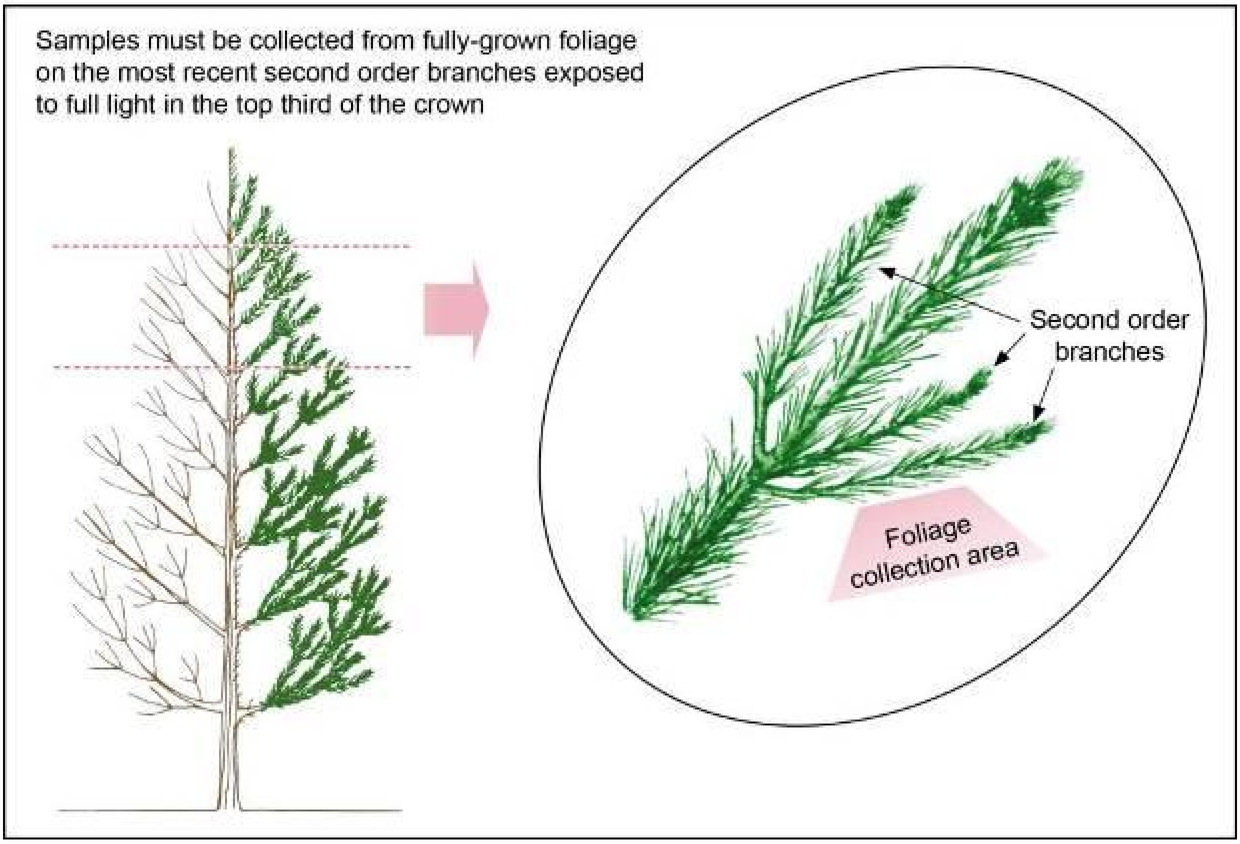

Fig. 4.2: For radiata pine and other needle-leaved conifers, collect mature length needles on the youngest second-order branches.

Eucalypts
Dell *et al*. (1995) recommend sampling the first fully expanded leaves of an actively growing branch in the mid to upper canopy. The leaves should be undamaged and exposed to full sunlight. For species that have juvenile and adult foliage, the latter is preferred.

Cypress species
No studies have been undertaken of positional or seasonal effects on foliage nutrient concentration in cypress species. The foliage of cypress species varies continuously in age along individual

branches and branchlets, so discrete foliage age classes cannot readily be distinguished. The following procedure is recommended. Samples should consist of branchlets ('b' in Fig. 4.3) taken from first-order branches ('a' in Fig. 4.3) from the upper third of the crown (see also Fig. 4.4). Current branch stems may be distinguished from previous branch stems by a change in the colour of the stem from green (current) to brown (previous). Sample branchlets should preferably be taken from current branch stem material, and should only include green material. There is a gradation of age class of branchlets along the current 1st order branch from mostly currently expanding (lighter green) at the tip ('c' in Fig. 4.3), to mostly fully expanded (darker green) at the base. Avoid sampling 'c' foliage. Where tips of selected branchlets have reproductive structures present, these should be removed. Where branchlets further subdivide to sub-branchlets of sufficient size for sampling, the sub-branchlets may be sampled following the above protocols, treating the branchlet as a first order branch.

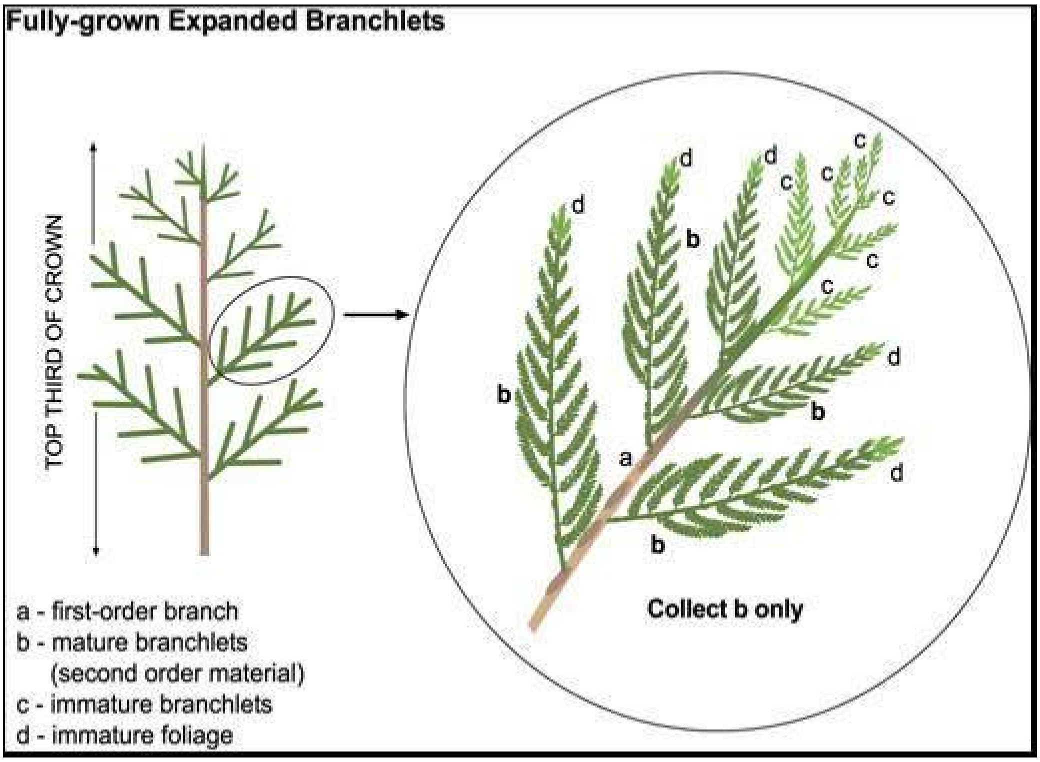

Fig. 4.3 Identification of sample branchlets in cypress species. Sample 'b' material only.

Fig. 4.4 Foliage (branchlets) on a 1st order branch.

Sampling Tall Trees

The method used to collect foliage samples is determined by tree height. For trees:

- up to 6 metres in height, the samples are generally picked directly from the tree by hand. A shepherd's crook may be useful to bring branches within reach.
- between 6 and 11 metres in height, pole-mounted cutters can be used to remove small branches. Different lengths of poles can be used for stands of different heights.
- between 11 and 30 metres, a shotgun can be used to collect samples. Use a 28 to 36 gram load of No. 5 or No. 6 shot, or, for smaller trees No. 7 shot. Ear muffs and protective glasses are essential, and for safe operation it is advisable to insert only one round.
- over 30 metres in height samples can be collected by climbing. Trees of this height are beyond the range of a shotgun. A safety belt is essential, and will allow use of both hands for removing samples.
- in dense undergrowth, or in tall stands, samples can be collected using a helicopter. This method can be used for trees of any height, but specifically designed equipment subject to Civil Aviation and Department of Labour approvals is required.

Sample Handling and Preparation

To reduce errors arising from sample spoilage during handling and transport, the guidelines modified from Reuter *et al.* (1997) are recommended:

- Wash hands before collection or use disposable gloves.
- Excess moisture should be removed from samples before packing.
- Place samples in paper bags or polythene bags. Do not seal samples in polythene or grease-proof bags (including white food bags), unless they can be refrigerated within 24 hours (samples stored in sealed bags in non-refrigerated conditions may decompose rapidly).

- Avoid storing samples unprotected in crushed ice which melts and can contaminate samples or leach out soluble fractions.
- Do not store samples for prolonged periods under ambient conditions during warm weather.
- Store samples in a refrigerator - samples can be stored at 5°C for up to 14 days. If possible, dry samples in a forced draft oven at 65°C to minimise respiratory losses.
- Label samples and dispatch to the laboratory as soon as possible. Aim to have the laboratory receive fresh (undried) samples within 24 hr of collection or removal from a refrigerator. Completely dried samples can be sent by ordinary mail.

In the laboratory, the samples are dried in a forced-air oven at 70°C for about two days to prevent carbon loss by respiration or decomposition. Samples collected from dusty areas should be washed to remove soil and dust before drying, especially if iron, zinc and boron analyses are desired. The oven-dried needles are ground to a fine powder using a laboratory mill. Ground samples may be analysed by a variety of procedures. In the current procedures used by the Veritec Laboratory in Rotorua, samples are digested in a mixture of nitric acid and hydrogen peroxide and analysed by inductively coupled plasma optical emission spectroscopy for phosphorus, potassium, calcium, magnesium, iron, boron, manganese, zinc, copper, aluminium and sulphur. Carbon and nitrogen are measured after dry combustion using a LECO CNS-2000 analyzer. Results of analyses (i.e., nutrient concentrations) are generally expressed as % dry matter for macronutrients and mg/kg of dry matter for micronutrients.

Interpretation of Foliage Analysis Data

Use of Nutrient Concentrations

For nutritional management purposes, the method of interpretation based on known deficient and adequate nutrient concentrations is the most widely used. However, such standards for interpreting analytical data must be used cautiously. The current growth performance of the stand, preceding climatic conditions such as drought or unusually moist conditions, and factors such as insect or disease attack, should be considered when interpreting foliar nutrient data.

Conifers
Table 4.2 provides a guide for interpreting foliage analysis results for two needle-leaf conifer species, radiata pine and Douglas-fir, and cypress species.

Two sets of values are given for radiata pine. The Will (1985) values are derived from analyses of healthy trees in comparison with those affected to varying degrees by nutrient deficiency. The values for nitrogen, phosphorus and magnesium have been updated since original publication. The Boardman *et al*. (1997) values for radiata pine are generally derived from verified foliar nutrient concentrations by statistical analysis of growth rate and/or visual symptoms in fertiliser trials. Note that the Boardman *et al*. (1997) values are valid for samples collected later in the season than recommended for New Zealand. The main differences in the concentrations specified as deficient and adequate for radiata pine between the criteria given by Will (1985) and Boardman *et al*. (1997) are for nitrogen, calcium and boron; the former gives somewhat higher deficiency levels for nitrogen and calcium, but lower levels for adequate concentrations for boron (Table 5.2). The Boardman *et al*. (1997) data require verification under New Zealand conditions before these standards are applied in operational management of plantation forests in New Zealand.

The analyses are appropriate for foliage collected over the following periods:

Radiata pine (Will, 1985): mid-February to end of March
Radiata pine (Boardman *et al*., 1997): late May to late June (no later than the end of July)
Douglas-fir (Ballard and Carter, 1986): late March to mid-June
Cypress (Moorhead, 1996): dormant season, equivalent to June-August.
Cypress LTSP trial mean data: February-March

Table 4.2 Deficient and adequate foliar nutrient concentrations for radiata pine and Douglas-fir, and adequate and trial mean data for cypress species. (Deficient concentrations have not been derived for cypress species).

	Radiata pine [a]		Radiata pine [b]		Douglas-fir [c]		Cypress	
	Deficient <	Adequate >	Deficient	Adequate	Deficient <	Adequate >	Adequate[d]	LTSP Trial mean[e]
				%				
N	1.20	1.45	<1.0	1.2	1.2	1.45	1.5	1.21
P	0.10	0.13	<0.10	0.14	0.08	0.15	0.2	0.17
K	0.30	0.50	<0.35	>0.50	0.35	0.80	0.6	1.19
Ca	0.10	0.10	<0.06	0.08	0.10	0.25	0.6	1.07
Mg	0.06	0.10	<0.05	0.10	0.06	0.12	0.1	0.19
S	-	-	-	>0.13	0.12	0.14	0.08	0.11
[f]SO_4-	-	-	<0.008	0.02	0.008	0.012	-	-
				mg/kg				
B	8	12	5-12	16	12	15	18	24
Cu	2	4	<2	2.4	1	4	5	7
Zn	10	20	<11	14	9	15	20	17
Mn	10	20	<10	25	4	25	75	42
Fe	-	-	<35	70	25	50	50	35

[a]New Zealand data (updated from Will, 1985).
[b]Australian data (Boardman *et al*., 1997). For most nutrients, Boardman *et al* (1997) give a range of values for 'Adequate'; only the lowest values of the ranges are presented here.
[c]USA data (Ballard and Carter, 1986; Boardman *et al*., 1997).
[d]From Table 2 at: http://www.bugwood.org/christmas/98003.html (Adapted from North Carolina State University for adequate ranges of foliar nutrients in *Cupressus* × *leylandii* (Leyland Cypress). Only the lowest value of the range is given here
[e]Mean value for *C. lusitanica* grown at 26 New Zealand sites representative of the national forest estate. Samples were from 3.6-year-old unfertilised trees. The value for N is likely to be deficient.
[f]Interpretation for SO_4-S applies only to unfertilised foliage and not to analytical procedures that use an inductively coupled plasma spectrophotometer (Brockley 2001)

For the ranges given by Will (1985) for radiata pine, for most nutrients (calcium, zinc and manganese are exceptions) a fertiliser response would be expected from trees where nutrient concentrations are in the deficient zone. Responses are less likely where concentrations lie in the marginal (between deficient and adequate) zone for nitrogen, potassium, magnesium, boron and copper. For phosphorus, response is likely where concentrations are in the marginal zone.

Values for cypress species indicating deficiency have not yet been published, but some information is available from unpublished studies. From a study of *Cupressus lusitanica* foliar nutrient concentrations in relation to tree size in Tairua Forest, Knight (1985) suggested that concentrations of at least 1.2% N and 0.12% S are desirable for satisfactory growth. A Columbian study quoted by Knight (*loc cit*) reported that critical levels for *C. Lusitanica* on ash soils in that country were 1.3 % and 0.13% for N and P respectively. From a study of foliar nutrient concentrations in relation to diameter growth rates of three cypress species in Westland (*C. lusitanica, C. macrocarpa* and *Chamaecyparis lawsoniana*) Davis (1994) found that minimum foliar concentrations for greatest growth rates of the stands studied were 1.3%, 0.15%, and 0.12% for N, P, and S respectively. Recent unpublished data from a nationwide trial series in New Zealand that included *Cupressus lusitanica,* with and without fertiliser treatment, indicate that fertiliser response was unlikely where foliar nitrogen concentrations exceeded 1.41% and that the likelihood of a response increased as concentrations fell below this. Taken together, these studies suggest that minimum levels for close to optimum growth for cypress species might be N, 1.4%; P, 0.14%; and S, 0.12%. Foliage of cypress species contains higher concentrations of K, Ca and Mg than radiata pine (Knight 1986, Davis *et al.* 2007), but it is not known if the required concentrations of these elements for optimum growth are also higher.

The concentration of sulphate in foliage has been used to predict whether or not stands will respond to nitrogen fertiliser in a number of conifers including Douglas-fir and radiata pine (Turner *et al*. 1977, 1979). This analysis is based on the understanding that sulphur in excess of that used to balance nitrogen in protein synthesis in conifer foliage accumulates as sulphate. Stands with low pre-fertilisation foliar sulphate (indicating sulphur deficiency) are unlikely to respond to nitrogen additions, even if foliar nitrogen levels are low enough to indicate deficiency. In New Zealand, there have been no recorded instances of sulphur deficiency in conifers, and sulphate analysis has not been used to predict the likelihood of nitrogen response.

Eucalyptus

It is recognised that eucalypts often respond to deficiencies in soil nutrient availability by regulating leaf area rather than foliar nutrient concentration or colour (Philip Smethurst, personal communication). Due to this reason as well as the distinct variation among different eucalypt species, diagnostic nutrient concentrations for eucalypts are not included here. For more information, refer to Boardman *et al.* (1997) and Dell *et al*. (1995).

Use of Optimum Nutrient Ratios

An approach that may aid diagnosis of nutrient deficiencies is the examination of nutrient ratios within the plant. The interpretation of nutrient ratios is based on the concept of nutrient balance, which recognises that plant growth is dependent on proper proportions as well as amounts of nutrients present in plants. Thus, maximum growth or yield can only be realised when an optimum level and optimum balance of all essential nutrients is maintained. The nutrient ratios not only reflect nutrient balance, but are often less affected by growth dilution and aging processes than nutrient concentrations. However, nutritional interpretations based on nutrient ratios have not yet been widely developed. Interpretation of several nutrient ratios is presented in Table 4.3. The ratios involving nitrogen were proposed for lodgepole pine by Brockley (2001). The K/Mg ratio proposed for radiata pine by Olykan *et al*. (2001) is included. This ratio is now used routinely in aiding diagnosis of Mg deficiency in radiata pine in New Zealand. Although it is not known to what extent the ratios in Table 4.3 are applicable to species other than those for which they were proposed, those for lodgepole pine should be applicable to other pine species.

Other Methods of Interpreting Foliage Analyses

Two other methods have been developed for interpretation of foliage nutrient data, but are not in routine use. The Diagnosis and Recommendation Integrated System (DRIS) method is a more comprehensive diagnostic approach of nutrient balance. By calculating multiple two-way nutrient ratios and comparing them to standard norms, this system can be used to obtain directly comparable indices for nutrients influencing yield so that it would be possible to determine the relative adequacy or deficiency of each nutrient. DRIS has been demonstrated with several forest tree species including *Populus, Eucalyptus, and Pinus radiata.* However, this system has not been adopted in New Zealand. More information on use of DRIS for diagnosis of nutrient deficiency in radiata pine in New Zealand is available in a paper by Svenson and Kimberley (1988).

Vector analysis uses a graphical approach (Timmer and Armstrong, 1987). Its development recognises the weakness of diagnosis based on the nutrient concentration alone, particularly for detecting dilution effects and nutrient balance. More information about this method can be found in a paper by Haase and Rose (1995).

Table 4.3. Interpretation of foliar nutrient ratios.

Ratio	Threshold value	Interpretation
N/P[1]	< 9 > 13	No P deficiency (possible N deficiency) Moderate to severe P deficiency
N/S[1]	<14 >20	No S deficiency Moderate to severe S deficiency
N/K[1]	<2.5 >4.5	No K deficiency Moderate to severe K deficiency
N/Mg[1]	<15 >30	No Mg deficiency Moderate to severe Mg deficiency
P/Al[2]	< 3	Possible P deficiency, unless P > 0.13%
K/Ca[2]	< 0.5	Possible K deficiency
K/Mg[3]	< 10 > 15	No Mg deficiency Mg deficiency

[1] Values for current year foliage of *Pinus contorta*, abbreviated from Brockley (2001).
[2] Values from Ballard and Carter (1985), the P/Al value is from radiata pine, the K/Ca value is from Norway spruce.
[3] Lower value proposed by Olykan *et al*. (2001) for radiata pine, upper value derived from the foliage analysis database of radiata pine by the Veritec Analysis Laboratory at Scion, New Zealand.

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5. PLANTATION FOREST SOILS

Summary

- *The type of soil that develops on a site depends on the parent material, climate, topography, the vegetation and the length of time the soil has had to develop.*
- *Soils develop characteristic and recognisable organic and mineral horizons – these are used for describing and classifying soils.*
- *The area, distribution, parent materials, properties, erosion potential, drainage, restrictions to root growth and susceptibility to damage of the important soils for plantation forests in New Zealand are described, and representative profiles are illustrated.*
- *For radiata pine, tree growth rates in trial plots located on different Soil Orders declined in the order Pumice > Brown > Pallic > Allophanic > Recent > Raw > Ultic > Podzol. With some exceptions, productivity of Cupressus lusitanica followed a similar order.*

The Soil Profile

Soils develop in “parent material” which may be bedrock or material that was transported and deposited by gravity (colluvial deposits on or at the base of slopes) water (alluvial deposits from rivers) ice (till deposits from glacial activity) or wind (loessial deposits of fine particles, sand dunes, and airfall tephra from volcanic activity). With the passage of time the parent material is subject to various physical and chemical weathering processes, and plants establish and provide organic matter inputs to the developing soil. The type of soil that ultimately develops depends on the parent material they form in, the climate, the topography of the site, the vegetation and other organisms present and the length of time the soil has had to develop. Good descriptions of the processes influencing soil development can be found in McLaren and Cameron (1996) and Molloy (1998). As soils develop, recognizable layers called horizons form that differ in structure, colour, texture, and other physical and chemical properties – these are used to classify the soil.

Organic Horizons

Forest soils commonly have an upper layer of organic material in which three separate horizons can be recognized; designated the L (fresh litter), F (partly decomposed litter with still recognizable plant remains) and H (decomposed humic material) horizons (Fig. 5.1). These horizons are formed from biomass (leaves, cones, branches and stems) shed from the growing crop or remaining from a previous crop. Together these horizons are sometimes called the forest floor. Under warm, moist and fertile conditions that promote rapid organic matter decomposition the L, F, and H horizons may be quite thin – thickness increases in colder, dry and infertile environments.

Mineral Horizons

The organic horizons overlie the topsoil, designated the A horizon which is the uppermost mineral soil horizon. It is usually darkened in colour because of incorporation of organic material. A horizons are present in most forest soils, but are absent or weakly developed in coastal sands. The A horizon may overlie a pale coloured E horizon with residual quartz evident as organic matter, clays and iron and aluminium oxides are leached to lower horizons. E horizons are a feature of podzol soils found in wet, high leaching environments in Northland, on the West Coast and in the high country. The A and E horizon (if present) normally overlie a subsoil or B horizon which may have clays, humus, iron and aluminium oxides, or carbonates present from weathering of rock or leaching from above horizons. The B horizon in turn overlies the soil ‘parent material’ which is called an R horizon if hard rock, or a C horizon if unconsolidated rock.

Fig. 5.1. L, F and H organic horizons from a pine forest. Arrows indicate base of horizons. (John Adams)

Transitional Horizons

Horizon boundaries may be sharp, or there may be a gradation between two horizons, in which case a transitional horizon may be recognized, for example an AB or BC horizon.

Subordinate Horizons

The 'master' horizons described above are designated using upper case letters. Additional soil properties may be shown by adding lower case letters, for example Ah, Bg. Definitions for these can be found in McLaren and Cameron (1996); a reduced list is given in Table 5.1. These can be helpful for indicating whether site preparation may be required to allow root penetration (fm, m), or improve drainage (g, r)

Table 5.1. Definitions for some letter suffixes applied to soil master horizons (from McLaren and Cameron 1996).

Suffix	Definition
fm	Black to red-brown brittle or cemented horizon less than 10 mm thick enriched in iron and organic compounds (iron pan)
g	Mottled colours present because of periodic saturation
h	Accumulation of humus in a mineral horizon
m	Continuously cemented horizon sufficient to resist root penetration
r	Strongly gleyed horizon with predominantly greyish colours due to prolonged saturation
s	Brightly coloured yellow-brown B horizon containing iron and aluminium minerals translocated from horizons above
t	Horizon containing clay translocated from above horizons
x	Compact massive horizons rich in silt and low in clay, not cemented

Soil Classification

Up until the mid-1980s New Zealand soils were classified using a system called The New Zealand Genetic Soil Classification System. The system was extensively revised and a new classification with more precise definitions of classes, called the New Zealand Soil Classification, was introduced (Hewitt 1992). Much of the soil resource information (maps, bulletins) currently available in New Zealand conforms to the original system so familiarity with both systems is necessary. The new system has four levels of hierarchy, the soils being divided into orders, groups, sub-groups and series. The majority (94%) of plantation forests in New Zealand fall within the seven (of a total of fifteen) soil orders listed in Table 5.2. The table shows how the main soil groups of the “old” system fit into these soil orders, and main diagnostic features of the orders.

Characteristics of the major soil orders used for plantation forests, including potential for erosion, key physical and chemical properties, drainage characteristics, restrictions to root growth and susceptibility to compaction are summarized in Table 5.3. Examples of the soil orders are shown in Figures 5.2 to 5.8.

Table 5.2. The main soil orders of plantation forests, proportional areas, their main diagnostic features and the corresponding soil groups of the old Genetic Soil Classification System with which they correlate. Compiled from Hewitt (1992, 1998), areas are from Payn (2005).

Soil order NZ Soil Classification	% of NZ	% of forest estate	Main diagnostic features	Distribution	Soil group NZ Genetic Soil Classification
Allophanic	5	2	Soils dominated by allophane minerals	Central NI, small areas in SI high country	Yellow-brown loams, weakly weathered red loams and brown loams, some upland and high-country yellow-brown earths
Brown	43	33	Aerobic soils with brown colours due to iron oxide coatings	Widespread	Moderate and weakly weathered yellow brown earths, yellow-brown sands, southern brown-granular loams and clays
Pallic	12	7	Soils with pale coloured subsoils with high density	Seasonally dry eastern areas in both Islands, and Manawatu	Yellow-grey earths
Podzol	13	7	Strongly leached acid soils with bleached E horizons beneath topsoil, underlain by dark, organic horizon	Northland, high country of both Islands, West Coast of SI	Podzols, gley podzols, podzolized yellow-brown earths
Pumice	7	32	Soils dominated by pumice or pumice sand with a high content of natural glass	Central NI, mainly, Volcanic Plateau	Yellow-brown pumice soils
Recent	6	9	Weakly developed soils showing minimum horizon development, but with distinct topsoil	Throughout in young landscapes	Recent soils
Ultic	3	4	Strongly weathered soils with clay enriched subsoils	Northern NI, Wellington, Marlborough, Nelson	Northern yellow-brown earths, podzolised northern yellow-brown earths, central yellow-brown earths

Table 5.3. Characteristics of important soil orders used in New Zealand forestry. Compiled mainly from Hewitt (1992, 1998) and MacLaren and Cameron (1996).

Soil Order	Parent materials	Physical and chemical properties	Erosion potential	Drainage	Restrictions to root growth	Susceptibility to damage
Allo-phanic	Volcanic ash and rock, also greywacke and schist weathering products	Low BD[1], high P retention, low natural fertility	Low except on steep slopes or exposed sites	Mostly free draining	Generally none, minor areas have a hard layer that restricts root growth	Topsoils stable and resist machinery impact.
Brown	Mostly greywacke, schist, rhyolite or granite, some basalt	Medium BD, lower in uplands. Mod-high P retention, low-mod BS	Induced erosion in upland soils	Good	Generally none	Topsoils relatively stable
Pallic	Loess from Schist or greywacke	Med-high BD. Mod-high BS, med-high nutrient content	Susceptible to erosion	Slow permeability	Subsoil horizons with high BD restrict root growth	Topsoils may break down under heavy machinery impact
Podzol	Material from silica rich rocks-granite, greywacke, schist, rhyolite	Strongly acid, low BS and fertility	Susceptible to erosion	Slow permeability	Cemented or compacted subsoil horizons limit root penetration	Susceptible to compaction
Pumice	Pumice	Low reserves of major nutrients	High erosion potential	Rapid, but capable of high water storage	None	Susceptible to compaction
Recent	Various	High BS & natural fertility, except N, low P retention	Susceptible to erosion	Good	Generally none	
Ultic	Clay or sandy clay materials from silica rich sediments (greywacke) or acid igneous rocks (granite)	Acid, strongly leached, with low basic cation and P levels. P retention low in topsoil but moderate in subsoils	Susceptible to erosion	Mostly imperfectly to poorly drained	Root growth can be severely restricted	Susceptible to compaction when wet

[1] BD = bulk density (see Section 7), P = phosphorus, N = nitrogen, BS = base saturation (see Section 6)

Fig 5.2 Allophanic Soil. Pokaka sandy loam, Karioi Forest. Developed in andesitic and rhyolitic tephra.

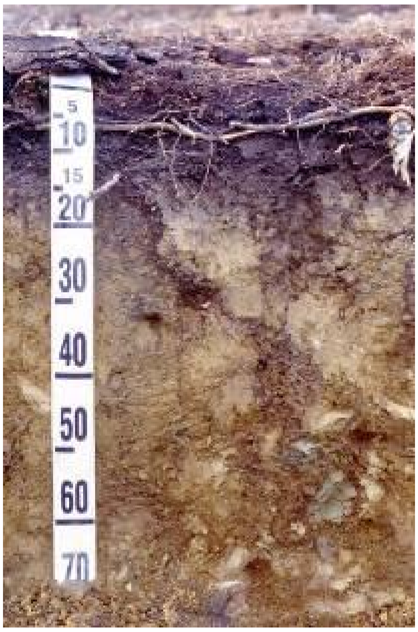

Fig 5.3 Brown Soil. Kaitangata hill stoney silt loam, Otago Coast Forest. Developed in breccia and conglomerate gravels.

Fig 5.4 Pallic Soil. Glendhu clay loam, Ashley Forest, Canterbury. Developed in siltstone, sandstone and greywacke gravels.

Fig 5.5 Podzol Soil. Maimai humic silt loam, Hochstetter Forest, Westland. Developed in greywacke and granite alluvial gravels.

Fig. 5.6 Pumice Soil. Rotoiti sandy loam, Tikitere Forest Rotorua. Developed in tephra.

Fig. 5.7 Recent Soil. Pinaki sand, Woodhill Forest, Auckland. Developed in quartzo-feldspathic and basaltic sand.

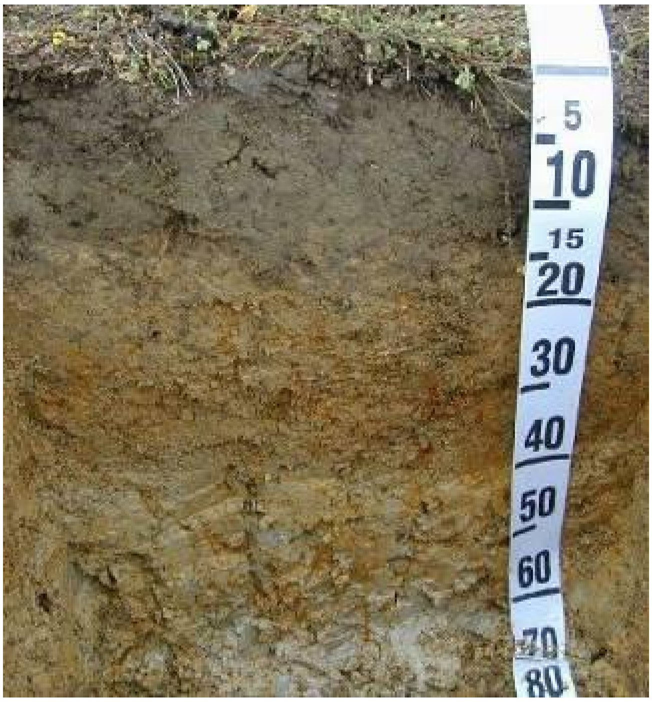

Fig. 5.8 Left - Ultic Soil. Puhoi clay loam, Riverhead Forest. Developed in strongly weathered mudstone.

Forest Soils and Forest Productivity

Forest productivity varies substantially between the major soil orders as illustrated in Fig 5.9. The data shown are derived from densely planted 'mini-plots' of radiata pine and *Cupressus lusitanica,* measured at age 4 years (Ross *et al*. 2009). The plots were located across a range of sites throughout New Zealand to sample all the major forest growing environments. The sites were planted with similar genetic material, had similar weed control treatment, and were unfertilized (though some sites would have received fertiliser in earlier times). Climatic variables accounted for 36% and 30% of variation in volume increment of the two species respectively. The data in Fig 5.9 have been corrected for climatic effects. The number of sites representing each soil order varied reflecting their predominance in the plantation forest estate, but all orders except one (Raw Soils) were represented by at least three sites. For radiata pine, tree growth rates declined in the order Pumice > Brown > Pallic > Allophanic > Recent > Raw > Ultic > Podzol. Productivity followed a similar order for *C. lusitanica*, except that Brown and Recent Soils were ranked lower in the order than for radiata pine.

The rankings generally followed expectations, with some exceptions. The high ranking of Pallic Soils was unexpected, as these soils have rooting limitations and poor drainage in the subsoils, and are subject to summer water deficits. It was expected that Allophanic Soils would rank more highly, as these soils, when developed in Volcanic tephra, are regarded as high quality soils for agricultural production, once phosphorus deficiencies have been corrected. The soil at one of the sites was developed in greywacke parent material however, and this may have contributed to the lower than expected ranking. The poor growth rates of Podzols and Ultic Soils are predictable, as these soils have significant chemical and physical limitations.

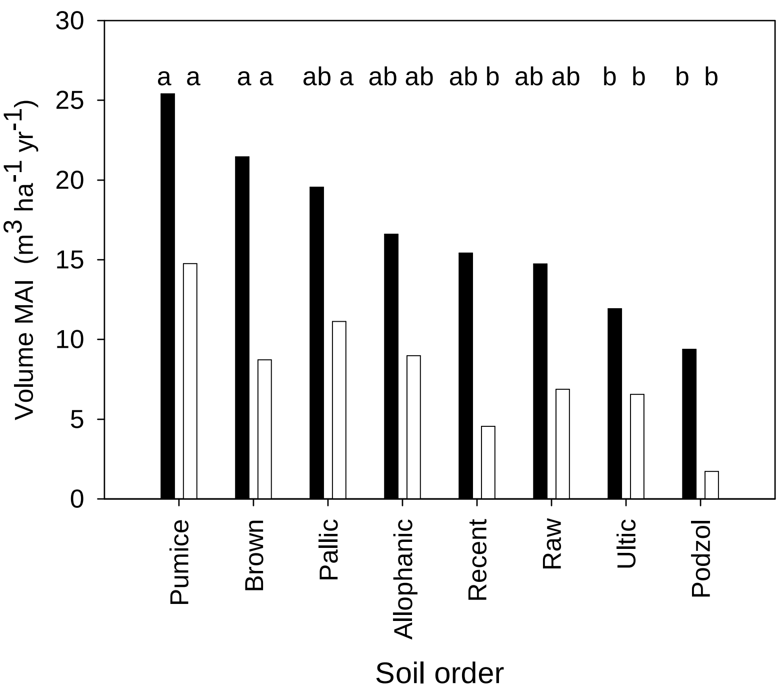

Fig 5.9 Volume mean annual increment (MAI) of radiata pine (filled bars) and *Cupressus lusitanica* (open bars) after four years in densely planted mini-plots located across the major soil orders used in forestry in New Zealand. The values are means for unfertilized plots and have been corrected for climatic effects. Within each species, MAI significantly differs between Soil Orders that have a different letter above the bar (Ross *et al*. 2009).

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6. SOIL SAMPLING AND CHEMICAL PROPERTIES

Summary

- *Soil analysis is not commonly used for diagnosing nutritional problems in forestry, but will be increasingly used for long term monitoring of forest sustainability.*
- *Soils vary greatly across the landscape and sampling schemes need to take this into account.*
- *For radiata pine, fertiliser guidelines are available only for soil phosphorus and magnesium. Even for these tests, the guidelines are limited.*
- *Measurement of carbon, nitrogen and phosphorus are generally considered to be of greatest importance for monitoring long term forest sustainability*

Unlike pastoral agriculture, soil testing is not commonly practised in New Zealand forestry, with the possible exception of establishing new forests, or in nurseries (Section 11). Testing is only occasionally used for nutrient deficiency diagnosis – most nutritional diagnosis for forestry is via foliar testing because it generally provides a better indicator of tree nutrient status than soil tests. Soil sampling and analysis can be time-consuming and costly. However, soil analysis is becoming more widely used overseas for predicting late rotation nitrogen and phosphorus response. Soil analysis can help in defining possible reasons for nutrient deficiency, for example in nitrogen deficiency when this is due to immobilisation of nitrogen because of high carbon:nitrogen ratio, or pH-related nutrient availability problems. Because soils are quite variable across the landscape, considerable replication to provide a reasonable standard of precision is required. As trees are deep rooting there are also difficulties associated with the selection of the depth of soil to sample. Nevertheless, soil testing is likely to become more widely used in forestry as the need for information on the influence of forestry and forestry practices on the soil resource increases.

Soil Sampling for Diagnosis of Nutrient Deficiency

Sampling Pattern

Soils vary considerably across the landscape and the soil sampling pattern needs to take account of this variability for correct interpretation of results. For example, in hill country separate samples should be taken from ridges, side-slopes and valley bottoms. Apart from position in the landscape, factors to consider that might require sampling stratification include fertiliser history, especially of phosphorus, and differences in mechanical site preparation. For diagnosis of nutrient deficiency where symptoms are visible, a comparison of the area or areas showing the deficiency or inferior growth with an area or areas of healthy growth would be useful.

Once the sampling area has been defined, soil samples should be collected from the whole of the area of concern. The sampling points should be chosen either randomly, using pairs of random numbers to locate points on a grid, or systematically, by locating points at pre-defined intervals along one or more transects. Systematic sampling is likely to be easier.

Number and Depth of Samples

To sample for nutrient diagnostic purposes it is typical, to cover the natural variability of soils, to collect from each area of interest, a minimum of 50 cores of mineral soil to a depth of 10 cm. Overlying organic soil layers (litter, ferment and humus layers) need to be removed before collection of the mineral soil. The cores are bulked into one sample. After thorough mixing, a subsample (about 500 g) can be taken, placed in a clean plastic bag and then sent to the laboratory for analysis. Cores can be collected using a “Hoffer” sampler or equivalent (Fig. 6.1). Hoffer samplers take a 17 mm diameter core. Spade sampling is not recommended because of a tendency to over sample upper soil layers at the expense of lower layers. If a spade is used it is important that the sample hole is made perpendicular to the soil surface. With spade sampling care is also needed to ensure similar soil volumes are collected from each sampling point.

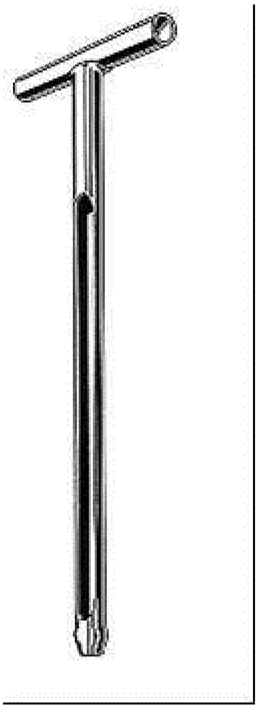

Fig 6.1 A Hoffer soil sampler.

Sampling to Monitor the Soil Resource

Sampling to a depth of 10 cm is insufficient for monitoring changes in soil properties over time to determine the influence of forest practices on the soil resource. Where such information is required, sampling to greater depths, for example to 30 cm or greater, may be necessary because forest operations can disrupt the upper layer through displacement or burial. Soil organic layers should also be sampled as these can contain large quantities of nutrients.

To properly assess changes in soil nutrient reserves over time it is necessary to measure both nutrient concentration and nutrient content – for the latter it is necessary to measure soil mass per unit volume (known as fine earth bulk density). This allows for the determination of the mass of nutrients per unit area to the depth of sampling. Measurement of bulk density in forest soils is difficult and time-consuming, especially if rocks or coarse woody debris preclude the use of a core sampler[1]. It is necessary to undertake measurements within permanently marked plots or at marked points, either along a transect or randomly located, to allow the sample points to be revisited for future measurement.

Plots may be located next to existing permanent sample plots for monitoring tree growth, or randomly located within a forest, or within some stratification of interest (e.g., topographic unit, management history unit). No real guidance can be given on the numbers of sample plots or points

[1] See Section 7 for further information on soil bulk density.

required, however a minimum of 10 plots or 20 sampling points is suggested (per forest or stratification unit) for initial sampling. Results from these analyses will allow calculation of the number of sample plots or points needed to obtain values within a specified accuracy (e.g., within 10% of the true mean). Where it is desired to calculate the total amount of nutrients on an areal basis, it is necessary to measure slope of the ground so that the area can be corrected for slope. See Gordon (2005) for a description of different sampling methods.

A plot-based method for soil sampling to monitor temporal changes in soil properties is given in Davis *et al.* (2004). The method involves taking eight bulked Hoffer samples at each of four sample points per plot for chemical analysis, and one bulk density core at the four sample points. If sampling is point-based, rather than plot-based, it is recommended that a single bulk density sample is taken, and a composite sample of eight cores is taken for measurement of soil chemical properties as these are more variable. The soil samples should be taken for three depths, 0-10 cm, 10-20 cm and 20-30 cm (Davis *et al.* 2004).

As stands develop, nutrients are absorbed from the organic layer and mineral soil and stored in plant biomass. A proportion of these nutrients is subsequently returned to the soil surface via litterfall and as thinnings or prunings. At harvest all except those nutrients stored in harvested products are returned to the soil surface. After decomposition of litter and slash, nutrients may be transferred to the mineral soil. These processes will lead to changes in nutrient contents in the mineral soil as well as in the organic layer, and this needs to be taken into consideration when designing a program to monitor the soil resource over time. Monitoring must be undertaken at a similar time in the different rotations, for example at the rotation mid-point, or just prior to harvest. Harvest and site preparation are likely to increase soil variation, so sampling during the early part of a rotation is not recommended.

Soil Analysis and Interpretation

Only a small proportion of the total amount of nutrients present in soils is available for immediate plant uptake. The greater proportion is held in one form or another within the soil organic and mineral matrix, some of which will become available for plant use over time as a result of biological and chemical processes. Soil analyses are used to determine the total amounts of nutrients present or to assess the amount of nutrients expected to be available for uptake over the coming growing season. Information on total nutrient quantities is most useful for monitoring changes in soil properties over time, while information on the available nutrient fraction is useful for both diagnostic and monitoring purposes.

Analysis for Nutrient Availability

The tests that assess nutrient availability are empirical and need to be calibrated with results of trials designed to examine productivity response to different rates of the particular nutrient(s) in question. These calibrations tend to have a high degree of specificity with regard to soil type, climate and other factors, and have not been undertaken widely for forestry in New Zealand. For radiata pine, fertiliser guidelines are available for only phosphorus and magnesium, and even for these tests the guidelines are somewhat limited (Table 6.1). Results of a recent study using plots located on a wide range of soils showed volume growth of *Cupressus lusitanica* (but not radiata pine) increased exponentially with Olsen phosphorus, allowing an upper threshold value for volume growth for *C. lusitanica* to be derived. The value is expected to be applicable to other species that form arbuscular mycorrhizae (see Section 13).

Table 6.1. Soil tests and interpretation, based on 0-10 cm sampling depth

Analysis	Interpretation
Bray-2 phosphorus This test uses a sequential extraction procedure to provide information on immediately available phosphorus and the ability of the soil to replenish phosphorus absorbed by plants. (Skinner *et al.,* 1989).	Where phosphorus is low in the first extract (e.g., 5 mg/kg) but declines only slowly in the 2nd and 3rd extracts (e.g., to 4 mg/kg), fertiliser is not required Where phosphorus is low (e.g., 5 mg/kg) in the first extract, and declines rapidly in the 2nd and 3rd extracts (e.g., to 2 mg/kg), fertiliser is required Where phosphorus is high (>12 mg/kg) initially, and declines rapidly in the 2nd and 3rd extracts (e.g., to 4 mg/kg), fertiliser is required.
Bray-2 magnesium Interpretation is based on the first extract. (Payn *et al*., 1996)	Magnesium at less than 0.75 me/100 g of soil shows there is a probability of deficiency of 20%. Foliar monitoring at age 4 is suggested to confirm deficiency.
Olsen phosphorus Interpretation for *Cupressus lusitanica* (and likely other cypress and arbuscular mycorrhizal species – see section 13) (Watt *et al.,* 2008)	A fertiliser response is unlikely where Olsen P exceeds 25 mg/kg; response is increasingly likely as the value declines below this threshold

Analysis for Soil Resource Monitoring

A range of soil analyses that may be used for assessing temporal changes in soil chemical properties are listed in Table 6.2 along with concentrations found in the 0-10 cm layer of mineral soil of the major soil orders used for forestry in New Zealand. The analyses include the macronutrients carbon, nitrogen, phosphorus, calcium and magnesium, but not sulphur or the micronutrients. Measurement of carbon, nitrogen and phosphorus are generally considered to be of greatest importance for monitoring of long term sustainability.

Carbon and nitrogen occur mainly in organic forms in the soil, and the concentration of total carbon and nitrogen is measured. The carbon to nitrogen ratio is also a useful parameter; in highly developed agricultural soils the ratio can be as low as 10:1, but in forest soils the ratio is more likely to be around 20:1. As the soil C:N ratio increases, nitrogen becomes progressively more limiting for plant growth.

Phosphorus occurs in both inorganic and organic forms and both can be determined as well as the total phosphorus concentration. Additionally there are several tests that measure available phosphorus; in New Zealand the Olsen test is universally used in agriculture while the Bray-2 test has been used in forestry. Both tests provide an index of the availability of inorganic phosphorus only.

Potassium, calcium and magnesium occur in the soil in mineral forms that are largely unavailable or only slowly available to plants. They also occur as positively charged cations that are held on to the surface of negatively charged inorganic and organic soil particles. These cations are in equilibrium with, and can exchange with, cations in the soil solution; as such they are known as exchangeable cations. Exchangeable forms rather than total amounts of potassium, calcium and magnesium are normally measured as these forms are considered to provide the major pools for plant uptake.

Other parameters listed in Table 6.2 that are of less importance for monitoring changes in the soil resource include:

- CEC (cation exchange capacity), a measure of the soil's ability to hold cations,
- TEB (total exchangeable bases), the sum of exchangeable potassium, calcium, magnesium and sodium ions,
- BS (base saturation), the proportion of the CEC that is occupied by the exchangeable bases. Exchange sites not occupied by bases are normally occupied by hydrogen and aluminium ions; these ions are dominant in soils of pH 5 or less, and are hence dominant in most forest soils.
- Soil pH, a measure of soil acidity.

The units for exchangeable cations, CEC, TEB and Sum of bases are me % (or meq/100g of soil – millequivalents per 100 g of soil).

Table 6.2. Soil chemical properties in the 0-10 cm layer of mineral soil of the major soil orders used for forestry in New Zealand. Data are from Scion 'Long Long Term Site Productivity' Series 2 trials.

Soil Order	Value[1]	pH (H_2O)	Carbon (%)	Nitrogen (%)	C:N	P Olsen available (ug/g)	P Bray available (ug/g)	P inorganic (mg%)	P organic (mg%)	P total (mg%)	P retention (%)	CEC (me %)	Sum bases (me %)	Base saturation (%)	Exchange Ca (me %)	Exchange Mg (me %)	Exchange K (me %)	Exchange Na (me %)
Brown	mean (13)	5.11	5.78	0.31	20	9.8	18.1	141	387	529	42	25	7.9	34	4.61	2.56	0.51	0.19
	Min	4.04	3.68	0.17	11	3.7	4.8	30	182	212	16	16	2.5	10	1.30	0.74	0.11	0.03
	Max	5.79	8.91	0.67	27	29.1	44.7	271	675	777	63	39	23.6	95	11.02	12.02	1.07	0.43
Allophanic	mean (5)	5.47	10.40	0.45	23	4.0	11.6	175	388	564	87	38	9.1	26	5.76	2.39	0.74	0.23
	Min	4.49	7.31	0.33	14	2.8	7.1	87	225	391	81	26	5.8	15	3.25	1.39	0.32	0.10
	Max	5.95	21.56	0.58	37	7.2	23.7	329	662	991	96	72	12.5	44	9.72	4.67	1.15	0.54
Pumice	mean (3)	5.44	5.97	0.28	21	10.5	45.5	200	326	525	55	21	4.6	23	2.90	0.74	0.79	0.20
	Min	5.38	3.89	0.25	14	2.5	11.8	91	192	282	39	14	2.6	11	1.58	0.29	0.64	0.11
	Max	5.48	7.55	0.31	26	17.4	81.5	314	419	733	66	25	6.9	31	4.27	1.30	1.09	0.27
Pallic	mean (3)	5.14	3.42	0.19	20	4.3	9.4	102	247	348	24	18	8.4	39	6.93	1.07	0.26	0.10
	Min	4.72	2.64	0.14	14	2.3	2.6	22	68	95	17	11	1.8	11	1.02	0.50	0.17	0.05
	Max	5.81	3.95	0.29	26	7.7	21.5	256	546	802	37	25	20.8	83	18.67	1.66	0.34	0.15
Recent	mean (3)	5.61	2.66	0.13	20	10.6	31.0	182	162	343	22	13	6.3	54	3.94	1.80	0.40	0.16
	Min	5.12	1.29	0.08	17	5.0	12.3	109	81	215	5	7	4.8	40	2.62	1.29	0.20	0.12
	Max	5.96	3.43	0.19	26	17.2	50.5	302	219	486	40	23	9.0	72	6.06	2.30	0.58	0.22
Ultic	mean (3)	4.88	3.76	0.19	24	9.2	22.9	121	172	293	28	16	4.3	26	2.85	1.06	0.21	0.17
	Min	4.36	2.52	0.09	15	5.2	8.4	15	58	73	11	10	2.0	20	1.11	0.63	0.11	0.12
	Max	5.35	5.32	0.35	28	12.5	36.4	232	376	608	38	23	7.1	30	5.35	1.32	0.31	0.20
Podzol	mean (3)	4.45	6.11	0.27	25	10.0	8.8	39	154	193	14	19	2.9	13	1.83	0.72	0.20	0.12
	Min	3.75	1.02	0.03	18	4.4	4.7	18	33	51	6	3	0.4	9	0.15	0.21	0.01	0.00
	Max	5.22	13.96	0.53	36	20.5	14.6	70	261	307	36	45	6.8	17	4.38	1.79	0.34	0.31
Raw	mean (1)	5.62	1.53	0.03	47	7.1	14.4	198	44	242	0	4	1.6	39	0.89	0.47	0.16	0.06

[1]The value in parenthesis shows the number of trial sites

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7. SOIL PHYSICAL PROPERTIES

Summary
- *Soil structure can be damaged by disturbance, most commonly by machinery compaction. Soils are most vulnerable to compaction when wet. In compacted soils, drainage and air exchange is reduced and root growth is restricted.*
- *The soil texture is indicated in the soil name, and gives an indication of properties such as water storage. Sands or sandy loam soils have good drainage and aeration, but may have poor water storage and nutrient supply characteristics, while clays and clay loams may be poorly drained but provide good nutrient supply. Clay soils are most vulnerable to damage by compaction.*
- *Soil bulk density, total porosity, and penetration resistance are the key indicators of soil physical properties likely to be affected by management practices.*

Soil Structure and Texture

Soil physical condition is commonly referred to as soil structure. The structure of a soil determines its porosity, strength and stability. These properties influence the movement and storage of water in the soil, the ability of roots to penetrate the soil and how readily the soil will erode. A well structured soil has many stable aggregates with a wide range in aggregate size, and contains many pores which maintain a good balance of air and water, and allows easy root penetration. A poorly structured soil either does not have many aggregates or the aggregates are packed together tightly and there are few pores. An aggregate size range of 2 – 5 mm is considered optimal.

Soil structure can be damaged by disturbance, most commonly by compaction by machinery, which reduces the number of pores and increases soil density. Soils are most vulnerable to compaction when wet. As a soil is compacted, the proportion of fine pores is increased which causes a decrease in drainage and air exchange. Root growth is also restricted, causing a decline in the plant’s ability to absorb water and nutrients.

Soil that passes through a 2 mm sieve (i.e., excluding the coarser gravel, stone, and root components) contains organic matter and mineral material, the latter being composed of sand, silt and clay fractions. These particles differ in size – sand particles range from 2-0.02 mm, silt particles range from 0.02-0.002 mm and clay particles are less than 0.002 mm. Soil texture is determined by the proportion of sand, silt and clay fractions, and this proportion is indicated in the soil name, for example Pinaki sand (Fig 5.7) which consists dominantly of sand-sized particles. Soils with a relatively uniform proportion of sand, silt and clay materials are called loams, for example Puhoi clay loam (Fig 5.8), the name in this case indicating a higher proportion of clay than sand and silt particles. An understanding of soil texture is important as it gives an indication of other properties such as water storage, drainage and nutrient supply. Sands or sandy loams, for example, have good drainage and aeration, but may have poor water storage and nutrient supply characteristics, while clays and clay loams may be poorly drained but provide good nutrient supply.

Key Soil Physical Properties

Measurement of physical properties of forest soils can be difficult because of high field variability, the occurrence of stony soils, and the presence of coarse woody roots. Soil sampling protocols for monitoring changes in soil properties over time have been discussed in Section 6. Measurement of soil physical properties has generally been restricted to the A-horizon or the 0-10 cm depth range, but these are insufficient for forestry, and a minimum sampling depth range of 0-20 cm is recommended.

In their review of environmental indicators of sustainable forestry, Jones *et al*. (in prep) recommend that soil compaction and strength-related indicators (bulk density, total or macro-porosity, and penetration resistance) should be measured to monitor changes in these characteristics over time. Soil bulk density (Table 7.1) can provide an indicator of soil compaction. Bulk density is inversely related to soil porosity and consequently water holding capacity, drainage properties and root penetration. Soil density is measured on samples taken with a soil corer of known volume (preferably thin walled, and 50 mm or greater in diameter) which is pushed or driven into the soil to a specified depth (Fig. 7.1). The weight of the soil is measured after oven drying at 105^{o}C. If roots or stones inhibit the use of a corer then it is necessary to dig a pit and extract, dry and weigh the contents, and determine the pit dimensions to calculate the pit volume. Volume is determined by lining the pit with thin plastic sheeting or similar material, filling with sand to the soil surface, then extracting and measuring the volume of the sand.

Fig. 7.1. Taking a bulk density core. Measurement of bulk density is necessary to express soil nutrient mass on an areal (kg/ha) basis.

Fine earth bulk density is determined by weighing the material that passes through a 2 mm sieve. The soil weight is determined after drying at 105^{o}C. Knowledge of fine earth bulk density allows calculation of nutrient masses to a given depth once nutrient concentrations of the material are known (Section 6).

Definitions of density and other useful soil physical properties related to compaction (porosity) and soil strength (penetration resistance), and methods of measurement are summarized in Table 7.1. Further information on these properties can be found in McLaren and Cameron (1996).

Table 7.1. Definition, uses and methods of measurement of some soil physical properties.

Property (and unit of measurement)	Definition	Use	Method of measurement
Bulk density (g/cm^3)	The ratio of the mass of total dry soil to the total volume of soil	Indicator of compaction	Soil extracted from a pit or by using a corer is oven dried (105°C) and weighed. The volume of the pit or corer is also measured.
Fine earth bulk density (g/m^3)	The ratio of the mass of < 2 mm dry soil to the total volume of soil	Calculation of mass of soil nutrients to a given soil depth	As above, but the mass of soil passing through a 2 mm sieve is measured
Particle density (g/cm^3)	The ratio of the total mass of solids to the volume of solids	For determining porosity	A value is of 2.65 g/cm^3 is assumed for most mineral soils
Porosity (% v/v)	The ratio of the volume of pores to the total volume of soil	For determining air filled porosity	Calculated from P_t=1-(BD/2.65)
Air capacity (%)	The ratio of the volume of air to the total volume of soil	Indicator of soil aeration status	Calculated from $P_a=P_t-W_v$ Depends on soil water content and is normally determined when soil is at field capacity[1]
Penetration resistance (MPa)	The force required to push the penetrometer tip into the soil	For estimating soil resistance to root growth	Penetrometer instrument

BD = bulk density
P_t = total porosity
P_a = air capacity (also called air filled porosity)
W_v = volumetric water content
[1] Field capacity occurs when rapid drainage of the soil has ceased

Physical Properties of New Zealand Plantation Forest Soils

Physical properties have been measured at 35 sites covering the main soil orders found in the New Zealand plantation forest estate as part of an experimental study to determine productivity drivers and sustainability indicators. Values for the upper soil layer (0 – 10 cm) are presented in Table 7.2. Standout soil groups are the Ultic Soils which have high bulk density and penetration resistance and low air capacity, and the Raw Soil (a sand) which also has high bulk density, but very low penetration resistance (i.e., little impediment to root growth). As soil organic matter declines with increasing depth, bulk density and penetration resistance normally increase in lower soil horizons, while porosity and air capacity decrease.

Table 7.2. Physical properties of the main soil orders of New Zealand plantation forests, 0 – 10 cm layer. Values are averages of the number of sites shown and are for the undisturbed treatment (see below).

Soil Order	Number of sites	Bulk density (g/cm^3)	Porosity (%)	Air capacity (%)	Penetration resistance (MPa)
Allophanic	5	0.66	72	29	0.72
Brown	13	1.00	61	23	0.75
Pallic	3	1.10	58	20	0.74
Podzol	4	0.82	67	25	0.47
Pumice	3	0.77	66	26	1.75
Raw	1	1.38	48	28	0.29
Recent	3	0.91	66	38	0.47
Ultic	3	1.22	52	9	1.38

Influence of Disturbance on Physical Properties of Plantation Soils

Disturbance during harvest is probably the most important management practice affecting soil physical properties of plantation soils. The influence of disturbance, mostly by compaction, on a range of soil physical properties was assessed in 31 of the trial plots spanning the range of plantation soils in New Zealand noted above (Watt *et al*., 2008). Plots were either disturbed by previous harvesting operations or not disturbed. Disturbance increased bulk density and penetration resistance, and decreased total porosity and air capacity (Table 7.3).

Table 7.3. Physical properties of mineral soil measured to 200 mm depth for disturbed and undisturbed plots sampled at 31 New Zealand forest plantation sites. The effect of disturbance was statistically significant for all properties except particle density.

Property (and unit of measurement)	Undisturbed plots		Disturbed plots	
	Mean	Range	Mean	Range
Bulk density (g/cm^3)	1.01	0.42 – 1.45	1.1	0.50 – 1.59
Particle density (g/cm^3)	2.55	2.23 – 2.96	2.56	2.23 – 2.96
Penetration resistance (MPa)	0.93	0.30 – 2.48	1.16	0.32 – 2.36
Total porosity (% v/v)	61	44 – 84	57	45 – 79
Air capacity (%)	23.6	4.1 – 61.5	18.1	6.3 – 35.9

Well structured and well drained soils are less at risk than poorly drained soils that have a high clay content. Soils are most vulnerable to compaction when they are wet, so the best way to avoid compaction damage is to avoid machinery traffic when the land is too wet. Using larger tyres or dual wheels reduces the contact pressure and hence compaction (McLaren and Cameron 1996).

Influence of Physical Properties and Disturbance on Tree Productivity

The trial plots mentioned above were planted in radiata pine or Mexican cypress. For both species soil physical properties were less strongly related to volume MAI (mean annual increment) than soil chemical properties (Watt *et al*. 2008). Of the physical properties, total porosity and bulk density showed the strongest relationships with productivity. For both tree species soil porosity was optimal at 63 to 64% and volume MAI declined at lower or higher porosities. The relationship between bulk density and volume MAI was predominantly due to a decline in volume MAI above bulk densities of 1.25 g/cm^3, which is consistent with results of work with white spruce (Gale *et al*. 1991). Growth reductions at high bulk densities are likely to be due to a reduction in water and oxygen supply. High bulk densities measured in these soils are unlikely to limit root extension as penetration resistance did not exceed 2.5 MPa, which is the threshold thought to limit root growth (Greacen and Sands 1980), and penetration resistance was not significantly related to volume MAI. There was a strong linear correlation between bulk density and total porosity ($r^2 = 0.96$; $P < 0.01$), and the reductions in growth at low porosities mirrored the effects of high bulk density on growth. At tree age four years, soil disturbance reduced total tree volume by an average of 9%. Mexican cypress appeared more sensitive to disturbance than radiata pine, with disturbance reducing the volume of four-year-old trees by 14% and 6% respectively, but the species by disturbance interaction was not statistically significant.

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8. FOREST MANAGEMENT PRACTICES, NUTRITION AND SUSTAINABILITY

Summary

- *Forest management practices, other than fertiliser application, that influence crop nutrition include site preparation, weed management, thinning, pruning and harvesting operations.*
- *Burning can result in the loss of large amounts of organically-bound nutrients from the site through volatilisation, wind-blow or water-wash of ash into streams, but is now rarely practised.*
- *Harvesting operations that remove and compact soil have the potential to reduce yields of the following crop. The past practice of root-raking using bulldozers caused substantial soil loss. Modern practices using excavators causes less soil disturbance.*
- *Nutrients are removed in harvest products. A Scion 'Long term site productivity' trial indicates that sites with youthful soils that are low in organic matter and total nitrogen are likely to be more vulnerable to nutrient removal than crops on soils with higher organic matter levels.*
- *By leaving the site bare of vegetation, harvesting disrupts nutrient cycling processes, allowing nutrient leaching to occur. Amounts of nutrients leached are generally small, but may be greater if site revegetation is prevented, or if the soil is high in nitrogen, as on ex-pasture sites.*
- *Rapid revegetation reduces potential loss of nutrients after harvest, and nutrient enrichment of streamwaters, where leaching potential is high.*
- *Weeds compete with the crop for moisture, light and nutrients, reducing potential tree growth, and it is important to control weeds, particularly where fertiliser is applied, as fertiliser stimulates weed growth. However the surface area affected by weed control should be kept to a minimum, so that the beneficial effects of 'weeds' are not lost.*
- *Removal of slash and the forest floor organic material at harvest can have long term impacts on soil C pools. Retention of both harvest residues and forest floor materials for maintenance of soil C stocks is recommended.*
- *Spot mounding can reduce soil carbon stocks, whereas fertilisation can increase stocks, although this does not always occur. 'Weeds' may also increase soil carbon stocks.*

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Forest management practices, other than fertiliser application or the introduction of nitrogen-fixing species (Section 9), that have potential to greatly influence crop nutrition include: site preparation operations, weed management, and thinning, pruning and harvesting. Site preparation and harvesting practices also have the potential to influence long term sustainability of forests.

Site Preparation

Site preparation activities are undertaken to improve soil drainage and aeration or tree root penetration, provide frost protection or to prepare sites to facilitate planting. Such activities include burning, ripping, discing, rolling, bladeing, windrowing, root-raking, and mounding. Activities such as bladeing and windrowing that displace soil from the planting spot are likely to have a detrimental affect on soil nutrient supply and possibly on long term sustainability. In contrast, activities that locally increase soil thickness (spot mounding) or effective soil thickness (ripping) may increase nutrient supply.

Burning

Burning was used frequently in the past to clear sites for planting, but is now rarely practiced. Burning has become more costly due to requirements for safety controls, and slash loadings are lower because indigenous forest with high slash loading is now rarely converted to plantation forest. There are also limited areas of minor species, which, in comparison with well managed radiata pine, can also create high slash loadings (Maclaren 1996).

Fig 8.1 Burning converts organically bound nutrients, especially nitrogen, into mineral forms that may be easily lost from the site though volatilization.

Burning can result in loss of nutrients from the site through loss to the atmosphere (by volatilization and particulate loss), surface wash or wind-blow, and leaching (Fig 8.1). Most of the nitrogen contained in fuel when combusted is lost to the atmosphere as gas as it has a low volatilization temperature (200^{o}C). Transfer of other elements to the atmosphere may also be large where fire intensity is high. In an Australian study where logging slash of radiata pine was burnt in a high intensity fire, 84% of the fuel load (79 t/ha) was consumed, resulting in the following losses (kg/ha); nitrogen, 220 (72%); phosphorus, 8 (27%); potassium, 21 (21%); calcium, 123 (31%), magnesium 13 (16%); and sulphur, 50(30%) (Flinn *et al*.1979). The total amounts of nutrients lost to the atmosphere can be compounded where soil organic layers in addition to slash are burnt. As an example Feller and Kimmins (1984) report the loss of nutrients from the slash and forest floor for a site in British Columbia to be (kg/ha) nitrogen, 982; phosphorus, 16; potassium, 37; calcium, 154; and magnesium, 29. Additional volatilization losses of carbon, nitrogen and sulphur can occur from the upper mineral soil where temperatures exceed 200^{o}C as would occur in a low intensity burn (Raison *et al*. 1990).

Nutrients in ash remaining on the soil surface after fire are subject to re-distribution or loss to streams by wind or surface wash. Alternatively ash may be leached into the soil where nutrients may be held on exchange surfaces, or subsequently lost through leaching. Burning may result in a quick flush of nutrients into streams, although the long-term loss may be no greater than where slash is left to decay, as was found for burning indigenous forest slash in the high rainfall Maimai catchment in Westland (Rowe and Fahey 1991). Compared to unlogged indigenous forest, over an eight year period logging increased nitrate and potassium loss to streams by around 3-6 fold and 5-6 fold respectively, while logging followed by burning increased nitrate loss by a similar amount, and potash loss by a slightly reduced 4-5 fold.

Nutrient availability to plants normally increases following a burn even though the total site capital of nutrients is reduced, and tree growth is usually greater after burning as a result of the increase in nutrient availability (Raison *et al*. 1990). However repeated low-intensity burning is likely to ultimately lead to reduced tree growth (Raison *et al*. 1990).

A side effect of burning is stimulation of seed germination of the leguminous shrub-weeds gorse and broom, which may then need to be controlled.

Mechanical Site Preparation

Root-raking into windrows is often used to prepare harvested sites for replanting. On flat terrain root-raking is likely to create little soil displacement, but on steep slopes root-raking can displace woody debris and soil downslope. On infertile Moutere gravel soils in Golden Downs Forest, Nelson, operational root-raking by bulldozing was estimated to have displaced between 3 and 18 cm of soil containing 600-2800 kg N/ha, depending on whether the soil had been heavily or lightly scraped (Table 8.1). Prior to the early 1990s, bulldozers were used for windrowing, but current practice uses excavators (Fig. 8.2) which cause much reduced soil displacement.

Surface soil stripping can have serious long term effects on productivity, where lower productivity may be due to both reduced moisture and reduced nutrient availability. Windrowing, resulting in an estimated removal of 2.5 cm depth of soil into windrows, resulted in a 40% loss of productivity, after 7 years, of inter-windrow planted radiata pine on a pumice soil in central North Island (Ballard 1978). Growth of trees planted in the windrows was greater than in un-stripped sites, but overall productivity was down by 20%, projecting to a 50 m^3/ha volume reduction at maturity. Thus, in addition to productivity loss, such soil disturbance increases crop variability. Similarly, Dyck *et al.* (1989) reported that windrowing and heaping of logging slash prior to planting significantly reduced radiata pine growth on a central North Island pumice soil and on two droughty stony silt loam soils in Canterbury by 40-50% at mid-rotation. The reductions on the pumice soil were attributed to reduced nutrient supply, those on the droughty soils to reduced moisture availability.

Fig 8.2. Windrowing on steep slopes using an excavator causes less soil disturbance than bulldozing (Brendon Whitley)

In contrast to activities that result in soil loss, ripping effectively increases soil depth by allowing roots to grow through impenetrable layers and access otherwise inaccessible moisture and nutrients. In the example of Mead (1990) given in Table 8.1, both ripping and discing increased nitrogen availability, probably through cultivation increasing nitrogen mineralization. Generally, the beneficial effects of ripping are a result of improved drainage and aeration or, in drier environments, to greater access to soil moisture stored below impenetrable layers.

Table 8.1. Impacts of some mechanical site preparation practices on soils and productivity.

Activity	Environment	Impact	Reference
Root raking	Moutere gravel soils, Golden Downs, Nelson	Down-slope displacement of 3-18cm of soil and 0.6-2.8 t N/ha, depending on whether soil had been lightly or heavily scraped	Sims *et al*. 1998.
Windrowing	Pumice soil, Kaingaroa, central North Island	Displacement of upper 2.5 cm of soil into windrows, productivity loss of 20%, projecting to 50 m^3/ha volume reduction at maturity	Ballard 1978
Windrowing and heaping of logging slash	Pumice soil, Kaingaroa, central North Island, and gravel soils, Canterbury	40-50% growth reduction at mid-rotation (8-17 years)	Dyck *et al*. 1989
Ripping and discing	Rosedale Hill soil, Motueka, Nelson	Ripping increased volume at age 11 by 25 m^3/ha (39%) and interacted positively with fertiliser. Nitrogen availability seemed to be increased. Discing had no effect	Mead 1990

Harvesting

Machinery Impacts

Heavy machinery used in harvesting has the potential to remove litter and topsoil, mix soil horizons and compact the soil, which may all affect crop growth. The impact of simulated logging damage of increasing severity on subsequent tree growth, in terms of litter and topsoil removal and compaction, was investigated on a low fertility shallow clay loam Ultic soil susceptible to compaction at Maramarua Forest in the Waikato (Fig. 18. 3) (Murphy *et al.* 2004).

Relative to control plots, average tree volume at 21 years was reduced by 8% in plots where the litter had been removed and the topsoil had been compacted, and by up to 42% in plots where the topsoil had been removed and the subsoil compacted (Table 8.2). The degree of compaction did not have a significant effect on average tree volume in plots where litter had been removed, but did have a significant effect where the topsoil had been removed. Per tree economic potential was reduced to a greater extent (up to 60% loss in value) than average tree volume was reduced. This was largely due to changes in log product yield distribution (Murphy *et al.* 2004).

Fig 8.3. An early view of the soil disturbance trial, Maramarua Forest.

Table 8.2. Soil and litter removal and compaction effects on tree growth and economic return of radiata pine at Maramarua Forest. Within columns, values without a letter in common are significantly different at the P < 0.05 level. From Murphy *et al*. (2004).

Treatment[1]	Diameter breast height (cm)	Height (m)	Stand volume (m^3 ha^{-1})	Stand economic potential (% of control)
TR-HC	39.2a	28.7a	324a	35a
TR-LC	42.4b	30.2b	414b	53a
LR-LC	48.8c	31.1bc	550c	71b
LR-NC	50.0c	31.8c	582c	91c
Control	50.7c	31.6c	586c	100c

[1] TR = topsoil removed, LR = litter removed, HC = high compaction, LC = low compaction, NC = no compaction

Skinner *et al.* (1989) reported that tree growth reduction due to treatment was evident during the first five years of the Maramarua trial. They attributed growth losses to a combination of factors including nutrient loss, which was reflected in low foliar nitrogen and phosphorus levels in treatments where topsoil was removed. Increased topsoil penetration resistance was also considered to reduce growth, especially in summer, as was an 8-10^{o}C increase in summer soil temperatures leading to greater moisture loss where litter was removed.

The impact of soil disturbance (mainly compaction) by machinery on tree growth when harvesting has been shown recently in a trial series covering all major soil groups across New Zealand for radiata pine and Mexican cypress. Disturbance affected a number of physical soil properties – bulk density and penetration resistance were increased, while total porosity, macroporosity, air capacity and void ratio were all decreased by disturbance. Disturbance reduced radiata pine and cypress productivity by an average of 9% when the plots were harvested at age four (see Section 7).

Nutrient Removals at Harvest

Harvesting removes nutrients from the site through biomass removal, and additional loss will occur if the forest floor organic layer or mineral soil is locally displaced. The quantities of nutrients that might be removed in stems, branches and the forest floor of radiata pine are shown for a range of sites in Fig 8.4. The amounts of nutrients contained in the tree components and forest floor relative to that in the upper soil (0-0.2 m) vary greatly between sites. In some cases, for example for nitrogen and phosphorus at Woodhill and calcium and magnesium at Kinleith, the amounts contained in the biomass and forest floor are large relative to the amounts in the soil, indicating that those sites may be especially sensitive to nutrient removals in harvest materials and disruption of the forest floor.

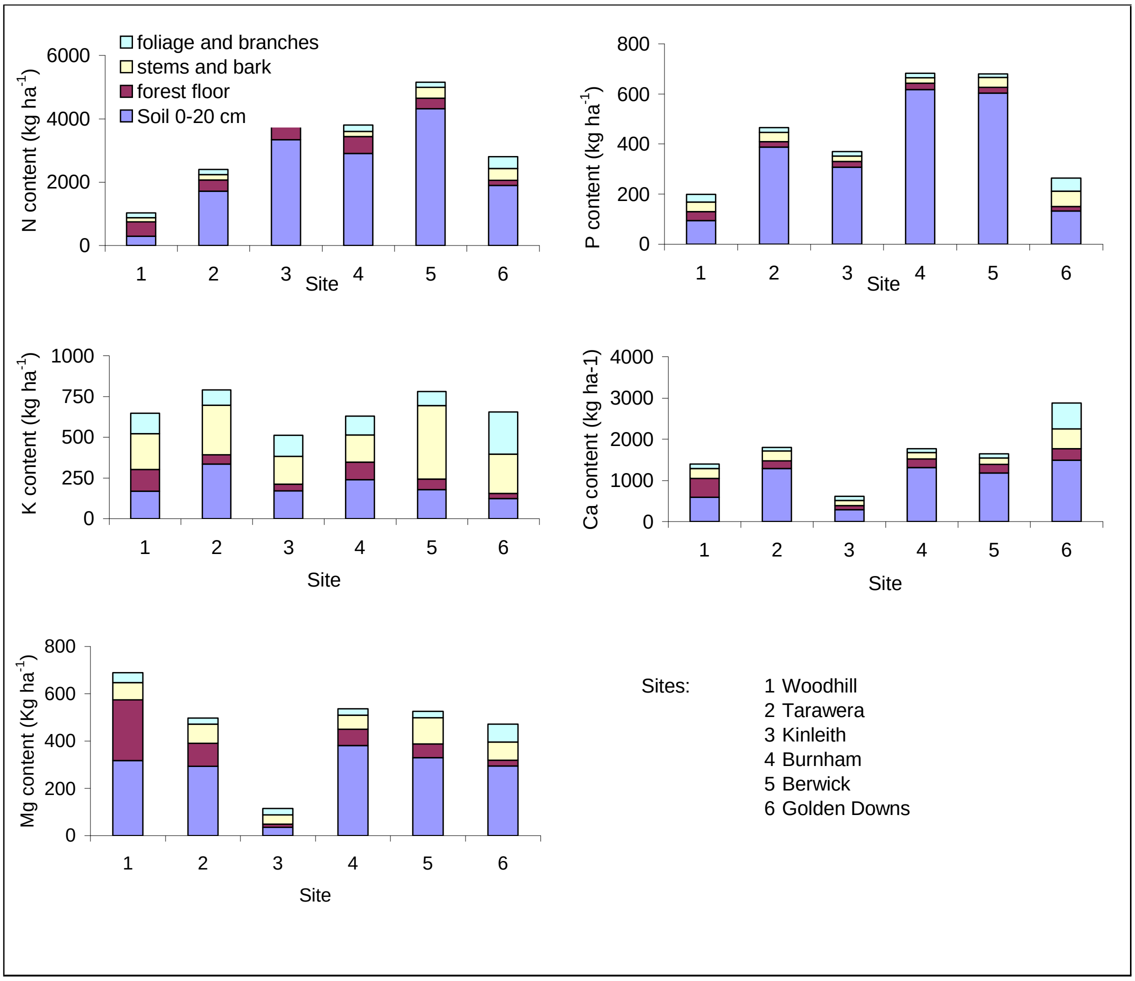

Fig 8.4. Nutrient contents in components of radiata pine forests at six locations. Soil values for nitrogen and phosphorus are totals, those for potassium, calcium and magnesium are for amounts of exchangeable nutrients. Data are from Scion 'Long Term Site Productivity' trials.

The impact of harvest operations with increasing intensity of biomass removal on soil properties and long term site productivity is currently being examined at the six sites shown in Fig. 8.4. The treatments applied were stem-only removal, whole tree (i.e., including branches and foliage) removal, and whole tree plus forest floor removal. No effects on productivity were seen initially, but measurements made at the mid-rotation stage showed that in the oldest of the trials (Tarawera and Woodhill) the greatest intensity of removal of biomass resulted in significant reductions in productivity of the new crop (Table 8.3). Treatment effects had not then shown up in the younger trial instillations. Where both whole tree and the forest floor were removed, tree growth reductions in the new crop amounted to 9% at Tarawera Forest and 16% at Woodhill Forest (Table 8.3). The trial to date indicates that sites with youthful soils that are low in organic matter and total nitrogen are more likely to be vulnerable to nutrient removal than crops on soils with higher organic matter levels.

Table 8.3. Impact of increasing intensity of biomass removal on basal area growth. Data are from Scion 'Long Term Site Productivity' trials.

	Location					
	Golden Downs	**Burnham**	**Kinleith**	**Berwick**	**Tarawera**	**Woodhill**
	Trial characteristics					
Age	10	11	12	13	15.5	18
Soil	Brown hill soil	Brown stony silt loam	Pumice sandy to silty loam	Pallic silt loam	Recent pumice gravel	Recent sand
Soil properties	Low total P		Low exch. Ca, Mg		Low OM, total N, P, organic P, exch. K	Very low OM, total N
Soil organic matter (t/ha)	90	167	166	154	64	25
	Treatment effects on plot basal area (m^2/ha)					
Stem only	19.1	12.8	22.1	36.2	39.2	40.8
Whole tree	19.8	12.8	25.3	36.9	37.3	38.4
Whole tree + FF[1]	19.0	-	22.6	-	35.4	34.2
Statistical significance[2]	ns	ns	ns	ns	*	**

[1]Forest Floor
[2]ns not significant, * significant at 5% probability level, ** significant at 1% probability level

A similar study in Oregon highlighted the effects of biomass removal on tree growth. In a 55-year-old Douglas-fir forest, removal of the whole tree, understorey and forest floor layer resulted in growth reductions at age 10 of more than 40% relative to stem-only removal (Compton and Cole 1991). The reduction occurred at both low and high productivity sites. In general, the greater the amount of biomass removed, the more pronounced the reduction in growth of the regenerating forest. Growth differences became evident at age 4 and increased with time.

Thinning to waste, pruning and production thinning, if waste material is left close to the stump, should have little long term effect on crop productivity. However, where branches are concentrated at a point well away from the stump, "whole-tree" harvesting may effectively occur. Hunter *et al*. (1989) measured the amount of nitrogen removed by thinning on a youthful sandy soil at Woodhill Forest (Auckland) and on young and old pumiceous soils in the central North Island. They estimated whole tree thinning removed 105-204 kg/ha (depending on site) of nitrogen. While this represented a high proportion of the total nitrogen on site, they found no immediate effect on crop growth.

Harvesting and Nutrient Leaching

By leaving the site bare of vegetation, clear-fell harvesting disrupts nutrient cycling processes. Mineralisation of organic matter in both the organic layer and mineral soil beneath is an ongoing process resulting in more or less continuous release of nutrients at a rate dependent on moisture supply, temperature and the soil properties. These nutrients are available for plant or microbial uptake. On some sites the rate of nutrient release from organic layers may increase at harvest because of increased moisture availability and temperature. At harvest, plant uptake is taken out of the equation, so mobile nutrients can become available for leaching if the supply exceeds microbial demand. One year after harvesting operations on a volcanic ash soil in Kaingaroa Forest, concentrations of nitrate in leachate collected in suction cups at soil depths of 1 m increased nine-fold from 0.07 to 0.60 mg/l Dyck *et al.* (1981). Assuming a 1500 mm rainfall and 450 mm drainage, these values would translate to an increase in leaching from 0.3 to 2.7 kg/ha/yr. The elevated levels persisted for three years after logging.

Where leaching losses occur after harvest they are usually small, as in the above example, (compared to losses from agriculture) and short lived since revegetation of cutovers by weeds, which take up nutrients that might be otherwise leached, is rapid (Fig. 8.5). Losses can be higher if revegetation is prevented. Increased concentrations of nitrate were measured in suction cups after above ground vegetation was removed from trenched treeless plots (simulating harvesting) in Kaingaroa Forest (Dyck *et al.* 1983). After 21 months soil-water nitrate concentrations had risen to a maximum of 9.4 mg/l (equivalent to 42 kg/ha/yr) compared to 2.0 mg/l in an adjacent logged but unweeded area. Concentrations in unlogged controls were 0.002 mg/l. Concentrations in trenched and weeded plots declined to 4 mg/l at the close of the study (24 months after treatment).

Fig. 8.5. Rapid site revegetation after harvest by grasses and other species inhibits nutrient loss by leaching, but reduces tree growth as shown by the better growth of trees in plots (centre right) treated with herbicide. Grass and ‘weed’ growth over the re-establishment phase also builds soil carbon levels. Kaniere Forest, Westland.

Some insight into the pattern of nitrate leaching from a high nitrogen (fertilized former pasture) site over a rotation has been given by Quinn (2003, 2005) for Puruki, a radiata pine forest in the Purukohukohu experimental basin between Lakes Taupo and Rotorua. Nitrate concentrations in stream-water showed a gradual decline over the first five years after conversion from pasture to pine (Fig. 8.6). The average nitrate concentration was almost an order of magnitude lower in the young forest phase (age 6-13 years), but levels then increased, indicating that the forest, at this high-N site, started to leak nitrate as it matured. When harvested, nitrate yields increased to be similar to those in an adjoining catchment in pasture, but then declined rapidly to be similar to yields in the young forest phase. Parfitt *et al*. (2002) had found a similar pattern in a sub-catchment of the Puruki catchment; they also found large decreases in soil nitrogen after harvest which they attributed to increased uptake by weeds and soil microbial biomass, both of which increased after logging. The results indicate that nitrate retention of pine forest is greatest when the crop has established and is growing vigorously, but is reduced as the crop approaches maturity and is harvested.

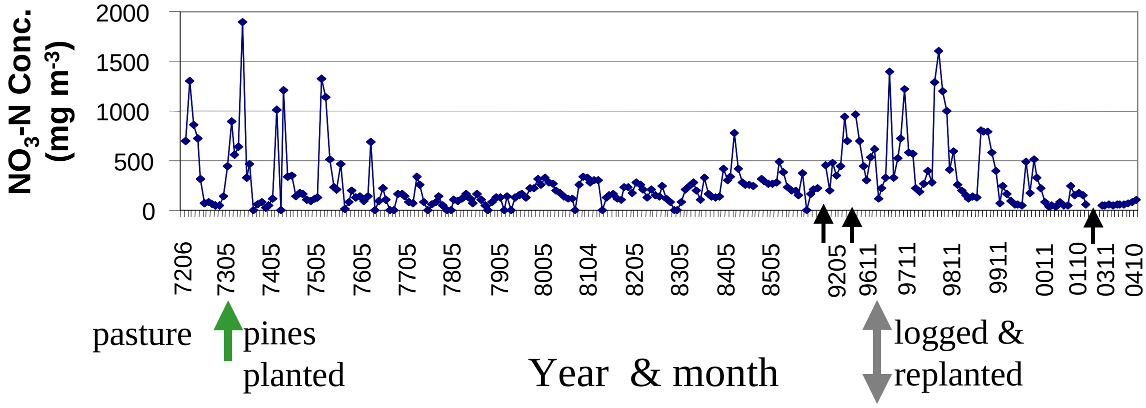

Figure 8.6. Long term variation in nitrate concentrations in stream flow in the Puruki catchment from before pine planting of pasture (1973) through to logging and replanting (1997), and regrowth of the second pine crop. Short arrows indicate gaps when data were not collected (after Quinn 2005).

While harvesting can lead to a short term increase in nutrient leaching, it is not clear how common or widespread the phenomenon is. A large (345 ha) catchment (Pakuratahi) study located in the coastal hill country of Hawke's Bay showed no increase in nitrogen or phosphorus levels in streamwater for a period of six years following harvest, despite the harvest being concentrated over a two-year period (Fahey and Stansfield 2006). Increases in nutrient leaching following harvest might be restricted to areas of high fertility or where revegetation has been suppressed, as in the above examples.

Where nutrient leaching at harvest is likely, steps can be taken to reduce leaching to retain nutrients on the site and also reduce potential nutrient enrichment of receiving waters. Sites are most vulnerable to leaching loss through winter and early spring months when soil moisture levels are high, so a vegetation cover should be well established before the first winter after logging. If natural vegetation development of 'weed' species is slow, sites can be oversown in autumn with pasture grass (not legume) species to speed vegetation development.

Weed Management

Weeds compete with the crop for moisture, light and nutrients, reducing potential tree growth. Because there is often simultaneous competition for all three resources it can be difficult to establish if competition for nutrients is limiting crop growth. This is illustrated by the studies summarized in Table 8.4. The first four studies showed no clear effect of weed control on nutrition – foliar nutrient concentrations were increased marginally, inconsistently or not at all. The Mamaku Forest trial (Skinner *et al*. 2002), is at a high-rainfall (2000 mm) phosphorus deficient (foliar phosphorus < 0.10%) site. Treatments were applied at tree age 7 after thinning and pruning; weeds included hardwood shrubs and toetoe (*Cortaderia* sp.). Weed control increased basal area growth by 22% and phosphorus application (50 or 100 kg P ha^{-1}) increased basal area growth by 27%. When applied together, these treatments increased basal area growth by 39%. Although foliar phosphorus was increased to non-deficient levels by fertiliser application, foliar phosphorus levels were not affected by weed control, so it is not possible to conclude that the growth response to weed control was due to increased phosphorus availability. However at this high rainfall site the growth response to herbicide is more likely to be a result of alleviation of phosphorus deficiency than increased water availability.

An example illustrating that weed control can increase nutrient availability is given by Smethurst (2001) in a Tasmanian study with radiata pine where weed control markedly increased foliar potassium, calcium and magnesium concentrations. Because the foliar potassium concentration in plants with weeds present was severely deficient (0.16%) and approximately doubled by weed control (to 0.33%), it is likely that alleviation of potassium deficiency contributed strongly to the growth response to herbicide application. An increased growth response to potassium fertiliser in addition to weed control confirmed this.

Table 8.4. Weed control effects on tree nutrition.

Location and Environment	**Impact of weed control on crop growth**	**Impact of weed control on foliar nutrient concentration**	**Reference**
Mariri Forest Nelson. Mapua Hill soil. Weed control tested only in presence of P fertiliser	No response to weed control, strong basal area response to P	Weed control increased foliar P by 0.01-0.03%	Skinner *et al.* 1995
Tairua Forest Coromandel Peninsula. Central Yellow-Brown Loam soil.	No effect of weed control alone, response to P and increased response with weed control	P increased marginally but significantly by 0.01%	Skinner *et al.* 1995
Rerewhakaaitu Forest Central North Island. B deficiency symptoms evident	Growth not measured	Initial weed control had no effect on foliar B.	Skinner *et al.* 2000
Hunua Forest, Auckland. Moderately P deficient Te Rango clay loam. Treatments applied at age 5 after thinning/pruning	Response to weed control in presence of P, no response to P alone	Weed control did not consistently improve foliar P levels	Skinner *et al.* 2001
Mamaku Forest, Central North Island. P deficient Mangowera/Otanewainuku soils	Weed control, P, and weed control + P increased basal area growth by 22%, 27% & 39% respectively.	Weed control increased foliar N for 3 years, but had no effect on P or B	Skinner *et al*. 2002

Importance of Controlling Weeds when Fertiliser is Applied

Weed competition can limit the ability of the crop to respond to fertiliser, and fertiliser addition can increase weed growth and competition at the expense of tree growth. The effects of weed competition from grasses, herbaceous legumes, voluntary weeds and the legume shrub-weeds gorse and broom on growth of radiata pine to age seven were studied at Eyrewell Forest in Canterbury (Figure 8.7) (Kimberley and Clinton 2000). Growth loss due to competition was generally greater in fertilized than unfertilized plots. This was particularly true for grass, voluntary weeds and herbaceous legumes (dominantly Maku lotus). The results indicate that weed control, especially for herbaceous species, is likely to be most beneficial on fertile sites or where fertiliser is being applied at establishment. The trial also demonstrated that competition persisted longer in more fertile conditions. In fertilized plots competition from all weed types remained intense at age 7, with 2-4 years growth lost to competition. In unfertilized plots there was generally only 1-2 years' growth lost at age 7.

Figure 8.7. Examining the effects of grass (left) and legume (right) competition on tree growth, Eyrewell Forest.

In the first year of the trial at Eyrewell Forest, foliar nitrogen levels in radiata pine were reduced from 1.75% in weed free plots to about 1.25% where weeds, including nitrogen fixing species, were present (Sun *et al.,* 1997). This indicates that even nitrogen-fixing species may compete for nitrogen. It was also found that where fertiliser was added, weeds reduced foliar phosphorus, potassium and magnesium concentrations. In years two and three, foliar potassium levels were markedly reduced by the herbaceous legumes, which were dominated by Maku lotus.

Weed Control, Nutrient Leaching and Nitrogen Fixing Species

As noted in the section on thinning, pruning and harvesting above, the presence of weeds can have a beneficial effect on bare sites by minimizing nutrient leaching, especially of nitrogen, and this needs to be considered when weed control operations are undertaken to aid tree establishment. The ground area affected by weed control should be no larger than that required for acceptable crop establishment – 'blanket' weed control should be avoided.

The nitrogen fertility of sites can be considered when determining vegetation management strategies. On high nitrogen sites (sites where a response to nitrogen fertiliser would not be expected), although a vegetative cover should be maintained to reduce possible nutrient leaching, it is desirable that the vegetation is not dominated by nitrogen fixing species, which may increase nitrate leaching. For example Dyck *et al.* (1983) found soil nitrate-nitrogen concentrations under gorse averaged 5.1 g/m^3 whereas nitrate under radiata pine forest averaged 0.006 g/m^3. With a rainfall of 1500 mm/year and assuming drainage of 450 mm, the concentration of 5.1 g/m^3 gives a nitrogen leaching rate of 23 kg/ha/yr. Higher leaching rates from gorse (40-60 kg/ha/yr) have been measured recently in the Bay of Plenty area (Figure 8.8). On high-nitrogen sites where it is anticipated that nitrogen fixing species (shrubweeds or herbaceous legumes) may invade naturally after harvesting, oversowing with grasses may be undertaken to attempt to reduce establishment of the nitrogen-fixers. Conversely, on low nitrogen sites establishment of nitrogen-fixers should be beneficial and result in little nitrogen loss through leaching. On low nitrogen sites oversowing with a pasture legume, in conjunction with application of phosphate fertiliser and weed control around tree seedlings, is an option to increase site nitrogen fertility.

Fig 8.8. Gorse inhibits forest establishment and can leach considerable amounts of nitrate – on sites like this leaching may amount to 40-60 kg/ha/yr. Galatea, central North Island.

Impacts of Forest Management Practices on Soil Carbon

The soil is a major reservoir of carbon in terrestrial ecosystems, and it is important to understand how management practices affect the amount of carbon stored in the soil. Soil carbon is a major constituent of soil organic matter, which strongly influences soil structure, water storage and nutrient supply to plants. Some recent studies in New Zealand have examined how forest harvesting and site preparation practices can affect the amount of carbon stored in the soil. These effects are summarised in Table 8.5

Harvesting

The impacts of two contrasting forest harvesting methods (hauler- and ground-based) on soil carbon concentrations and stocks were investigated at the Puruki experimental catchment, central

North Island, by Oliver *et al*. (2004). They measured mean soil carbon stocks in the 0-10 cm of mineral soil before and after harvesting and found that hauler-based harvesting did not significantly alter soil carbon stocks. In contrast, ground-based harvesting, involving the dragging of felled logs across the ground surface using tracked machinery, was shown to cause a significant 5 Mg/ha reduction in soil carbon stocks in the 0-10 cm depth. However, measurements to 1.0 m depth showed no difference in soil carbon stocks as a result of harvesting. Ground-based harvesting caused mixing of topsoil and subsoil material, resulting in reduced carbon in the 0-10 cm layer.

Residue Handling

Removal of slash and the forest floor organic material can have long term impacts on soil carbon pools. The effects of harvest residue management practices on carbon stocks in the forest floor material and mineral soil to 30 cm depth at Tarawera Forest in the Bay of Plenty were studied by Jones *et al*. (2008). Treatments investigated were residue retention (stem-only harvesting), residue removal (whole-tree harvesting), and residue plus forest floor removal (forest floor disturbance). They found that, 16-17 years after application of the residue management treatments, the removal of harvest residues and harvest residues plus forest floor material resulted in reductions of about 6 and 10 Mg/ha in total carbon stocks respectively when compared to stem-only harvesting. It was recommended both harvest residues and forest floor materials be retained for maintenance of soil carbon stocks. A further study examined the residue management effects on carbon stocks in the FH layer of six of the Scion Long Term Site Productivity sites, 8-16 years after the treatments were applied (Smaill *et al.,* 2008a). It was found that the FH layer in the residue removal and residue plus forest floor removal treatments had 4.4 and 8.4 Mg/ha less carbon respectively than where residues were retained. Harvest residue management may also involve the burning of residues prior to re-planting. Robertson (1998) investigated the effect of burning on soil carbon stocks at four sites in New Zealand and found that L and FH layer carbon was reduced by 8.4 Mg/ha, but there was little or no effect on carbon stocks in the top 10 cm of mineral soil.

Table 8.5. Effect of some management practices on soil carbon stocks.

Activity	Method	n[1]	Effect on soil carbon	Reference
Harvesting	Ground-based logging	1	C reduced by 5 Mg/ha in upper 0-10 cm soil, but no change if soil sampled to 100 cm	Oliver *et al*. (2004)
	Hauler logging	1	No change in soil C	Oliver *et al*. (2004)
Residue management	Residue removal	4	FH layer C reduced by 4.4 Mg/ha after 8-16 years	Smaill *et al*. (2008a)
	Residue + forest floor removal	4	FH layer C reduced by 8.4 Mg/ha after 8-16 years	Smaill *et al*. (2008a)
	Residue removal	1	Whole soil C (L+FH+0-30 cm mineral soil) reduced by 6.9 Mg/ha after 16 years	Jones *et al*. (2008)
	Residue + forest floor removal	1	Whole soil (L+FH+0-30 cm mineral soil) reduced by 10.2 Mg/ha after 16 years	Jones *et al*. (2008)
	Residue burning	4	L and FH layer C reduced by 8.4 Mg/ha	Robertson (1998)
Site preparation	Spot mounding	1	Soil C reduced by 4 Mg/ha in 0-30 cm layer	Jones (2007)
	Line ripping	1	No effect	Jones (2007)
Site improvement	Repeated N fertilisation	6	FH layer C increased by 5.8 Mg/ha after 8-16 years	Smaill *et al*. (2008b)
	Ground-cover vegetation retention	1	C in 0-10 cm layer increased by 10 Mg/ha after 2 years	Jones, 2004

[1] The number of study sites used in the determination of soil carbon stock change.

Site Preparation

The impacts of two different forest soil cultivation techniques (spot-mounding and line-ripping) at two different sites with contrasting soil conditions (Rotoehu in the Bay of Plenty and Lochinver in the central North Island) were studies by Jones (2007). At both sites, soil carbon stocks in disturbance features to 30 cm depth were compared with those in adjacent undisturbed soil. It was found that spot-mounding resulted in a significant net, area-adjusted, reduction in carbon stocks of about 4 Mg/ha in the top 30 cm of mineral soil 15 months after cultivation at the relatively fertile Rotoehu site whereas line-ripping of a relatively infertile site (Lochinver) was found to have had no significant effect on the carbon stocks in 0-30 cm depth range 38 months after cultivation.

Site Improvement

Few studies have examined the effects of fertiliser application on soil carbon stocks in New Zealand. Smith *et al*. (1994, 2000) reported that there was no effect of fertiliser on soil carbon in three of the six long term site productivity trials five years after harvesting. However Baker *et al*. (1986) reported a significant (more than two-fold) increase in the concentration of soil organic carbon in the 0-5 cm depth range after the application of mixed fertiliser (including 960 kg N/ha over 10 years) to the sandy soils in Woodhill Forest. More recently Smaill *et al* (2008b) reported that repeated fertilisation in the long term site productivity trials increased soil carbon in the FH layer by 5.8 Mg/ha after 8-16 years. Also Watt *et al*. (2008) have found that mixed fertiliser (N, P, K, Mg, S, and Ca) application led to a significant increase in topsoil (0-10 cm) carbon concentration measured after harvesting of 4 year-old densely-stocked plots across 31 experimental sites in plantation forests throughout New Zealand. The influence of fertiliser on carbon stocks (as opposed to concentrations) was not reported in the paper. Overseas studies indicate that although fertiliser generally increases soil carbon storage in forest soils, this is not always the case and effects tend to be site specific (Johnson and Curtis, 2001; Jandl *et al*., 2007).

Understory management (weed control) is another aspect of site improvement that may alter soil carbon stocks in exotic plantation forests. These effects have not been widely studied in New Zealand. Chang *et al*. (2002) studied the effect of the presence and absence of a pasture understory on soil carbon at a *Pinus radiata* agroforestry site on the Canterbury plains. They found that there was a significantly lower carbon concentration in the top 10 cm of soil where ryegrass pasture was absent (bare ground) than where it was present under the trees. No effect was observed in the 10-20 cm depth range. In a study of the effects of hauler-based forest harvesting on soil properties at Mahurangi Forest north of Auckland, Jones (2004) found a significant increase in the carbon concentration of the top 10 cm of mineral soil about two years after harvesting. The increase was thought to be due mainly to the growth of grasses and weeds after harvest, but decomposition of the slash residue may also have contributed. Over a two-year period the increase in the soil carbon sock in the 0-10 cm depth range amounted to about 10 Mg/ha. Thus, in addition to inhibition of nutrient leaching, rapid revegetation of cutovers can have the added benefit of increasing soil carbon levels.

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9. FOREST FERTILISATION

Summary
- *Fertiliser type and application rates for the key nutrient elements are given.*
- *Fertiliser application rates trials have been conducted for nitrogen, phosphorus, magnesium and boron. These trials suggest that the recommended application rates produce close to the maximum potential growth response. Lower application rates can often give substantial responses, suggesting there may be scope to reduce application rates.*
- *There are opportunities to increase productivity by applying fertiliser, where needed, at establishment, thinning and pruning, and to more mature stands. Fertiliser application at establishment should be accompanied by weed control.*
- *The size of fertiliser response varies greatly and depends on the amount of available nutrient in the soil, unidentified nutrient deficiencies, stand age and silvicultural history, the presence of weeds and the tree species.*
- *Further work is required to test and refine models for predicting fertiliser response.*
- *Nitrogen fixing species such as Lotus can be used in place of mineral fertilisers to supply nitrogen, though it may be necessary to apply phosphorus if it is limiting.*
- *Guidelines for nitrogen fertiliser application to minimise loss of nitrogen by leaching are provided. Care is needed to ensure fertiliser does not enter waterways during aerial application.*

Where foliar symptoms or foliar analysis indicate the presence of a nutrient deficiency, there is the potential to correct the deficiency by applying mineral fertiliser or, in the case of nitrogen deficiency, by using legumes to fix soil nitrogen. In some situations it may be possible to make use of wastes (effluent or biosolids) to correct a deficiency.

In contrast to livestock farming, fertilisers are not applied to forests in a routine manner in New Zealand, although there are many areas where growth responses to fertiliser application might be obtained. The use of fertilisers in plantation forests in New Zealand began in the mid-1950s and probably peaked in the early 1980s (Will 1985). There are no published accounts showing statistics of fertiliser use on forests since then.

The use of fertiliser may increase in future if economic conditions justify application. A reduction in forest area, for example as a result of the conversion of forests to other land uses, may see an increase in the use of fertiliser, especially nitrogen, to sustain wood flows. The use of fertilisers may also increase if there is a need to replace nutrients removed in logs at harvest to sustain long-term productivity.

Mineral Fertiliser Types and Application Rates

The main mineral fertiliser types and common application rates used in forestry are listed in Table 9.1. Fertiliser characteristics and application rates are discussed for individual nutrients in the following sections.

Nitrogen Fertilisers

Fertiliser Types
Urea is the most commonly applied nitrogen fertiliser to forests as it has a high nitrogen concentration and is usually the lowest-cost form of nitrogen. It is applied at rates up to 450 kg/ha (207 kg nitrogen/ha). Urea is rapidly immobilised in forest soil organic matter and is less subject to leaching losses than ammonium nitrate, but leaching losses may occur at high rates of urea and it

may be better to apply split applications to minimize the risk of such losses. Studies have shown up to 30% of urea-nitrogen may be lost through volatilization so during summer urea should be applied before rain to reduce possible volatilization losses. Diammonium phosphate (DAP) has an N:P ratio of 0.9 and may be used where phosphorus is also required. It is most often used at planting. Ammonium sulphate (N:S ratio = 0.85) is rarely used in forestry; it has some advantages in that it is the safest form of nitrogen (in granulated but not crystalline form) to mix with other fertilisers. It also has low volatility compared to urea and is therefore more flexible with regard to timing of application. Ammonium sulphate has a greater acidifying affect on the soil than other ammonium fertilisers, and urea.

Application Rate
Results from nitrogen rates trials with radiata pine from around New Zealand indicate that the response generally appears to plateau at about 200 kg/ha (Fig. 9.1, Hunter 1982, Hunter *et al.* 1985) and the normal recommendation is for aerial application of 200 kg N/ha (Will 1985, Olykan 2002). However responses on the pumice plateau have been variable, with one trial showing a linear response to 460 kg N/ha (Mead and Gadgil, 1978), which lead Hunter *et al*. (1985) to suggest that the shape of the nitrogen response curve on the pumice plateau needed further study. Responses plateauing at lower rates (80-150 kg/ha) have also been recorded (Hunter 1990).

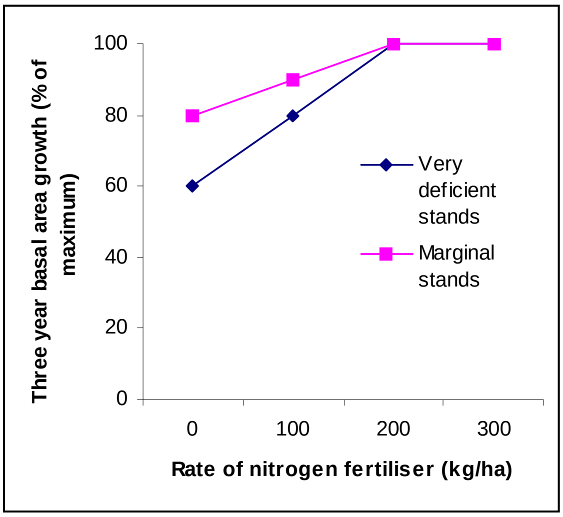

Fig 9.1. Response by radiata pine to different rates of nitrogen fertiliser (from Hunter 1982).

Phosphorus Fertilisers

Fertiliser Types
Phosphorus fertilisers include the water soluble phosphates (superphosphates and ammonium phosphates), the insoluble rock phosphates, and mixtures of super and rock phosphates. Superphosphates are made by reacting phosphate rock with sulphuric acid to convert the phosphorus into the more readily available phosphate form. Single superphosphate is the most commonly used phosphate fertiliser in agriculture, as it supplies sulphur in addition to phosphorus (P:S ratio = 0.86). Sulphur deficiency has not been observed in plantations in New Zealand so the sulphur component is not required. Triple superphosphate (P:S ratio = 20), made by reacting rock phosphate with phosphoric acid, is more commonly used in forestry because of its higher phosphorus concentration giving lower carting and spreading costs. Rock phosphates can be used on acid soils (soil pH less than 6.0 – includes most forest soils) to provide a slow release form of phosphate, giving a longer term response than superphosphates. Rock phosphates are finely ground to increase contact with soil particles, and because of the fine sandy form dust and drift can

be a problem when spreading. Partially acidulated rock phosphates contain a mix of both readily available phosphates and unreacted rock phosphates and, like rock phosphates, are suitable for use on acid soils. 'Longlife' superphosphate is a mixture of single superphosphate (70%) and rock phosphate (30%) aimed at increasing the response period of single superphosphate. Diammonium phosphate is commonly used at planting (see nitrogen fertilisers).

Table 9.1. Fertilisers and application rates recommended for radiata pine at planting and in established stands (after Mead 2005).

	Nutrient content (%)							Rate of application	
Fertiliser	**N**	**P**	**K**	**S**	**Ca**	**Mg**	**Other nutrients**	**At planting (g/tree)**	**Established stands (kg/ha)**
Urea	46	0	0	0	0	0		25-60	250-450
Ammonium sulphate	20.5	0	0	24	0	0		60-100-180	500-950
Diammonium phosphate (DAP)	18	20	0	1	0	0		40-85	250-500
Magnesium ammonium phosphate (Magamp)	18	8	0	0	0	14		50	-
Superphosphate	0	9	0	11	20	0		60-100-180	300-1200
Triple super	0	20	0	1	14-16	0		40-90	150-600
Reactive rock phosphates	0	11-16	0	0-1	32-38	0		[1]	250-900
PARR phosphate[2]	0	17	0	0	20	0		50-100	200-500
Potassium chloride	0	0	50	0	0	0		25-50	100-200
Potassium sulphate	0	0	42	17-18	0	0		50	125-250
Magnesium sulphate (Epsom salts)	0	0	0	13	0	10		-	500-1500
Kieserite	0	0	0	22	0	16		-	250-800
Dolomite	0	0	0	0	23	11		-	500-1500
Calcined magnesite	0	0	0	0	1.7	50		-	100-300
Copper sulphate	0	0	0	13	0	0	25Cu	-	20-40
Cuprous oxide	0	0	0	0	0	0	89Cu	-	6-11
Zinc sulphate	0	0	0	18	0	0	36Zn	-	10-30
Borax[3]	0	0	0	0	0	0	11B	4	20-80[4]
Ulexite	0	0	0	0	0	0	10B	4	20-70[4]
Colmanite	0	0	0	0	19	0	16B	4	25-70[4]

[1] Rock phosphate, perhaps in mixture with super, can be band or broadcast applied at establishment at 500 - 1000 kg/ha.
[2] PARR is partially acidulated reactive rock phosphate. Rock acidulated with sulphuric acid contains sulphur; the amount depends on the level of acidulation.
[3] Sometimes added as boronated superphosphate.
[4] See text regarding possible toxicity

Application Rate

Phosphate rate (75 and 150 kgP/ha) by type (three types of rock phosphate and superphosphate) fertiliser trials were established in the Auckland-Coromandel region in the early 1970s at three sites on clay soils with phosphorus retention levels ranging from 0 to 90% (King 1988, Hunter 1989, Table 9.2). The trials were established at age 4-5 years and measured at age 7 years, and again at age 11 years (after thinning). At all three sites the low rate used was as good as the higher rate. There was no difference between phosphate types except at Riverhead Forest, with medium phosphorus retention, where the least soluble rock phosphate (C-grade) gave a poorer response, while the slightly more soluble A-grade type gave results similar to superphosphate.

Table 9.2. Response to different rates and types of phosphorus by radiata pine on clay soils of different phosphorus retention, Auckland-Coromandel region.

Forest	Phosphorus retention (%)	Response at age 7 years	Response at age 11 years, after thinning
Waipoua	0	20%, no difference between types & rates	Trial lost to Cyclone Bola
Riverhead	48	50%, SP and more soluble rock P gave best response, little difference between rates	31% response since thinning, C grade P poorer. No difference between rates.
Tairua	90	12% (not significant), no difference between types & rates	34% since thinning, no difference between types & rates

A further study examining rates of superphosphate (0, 63, 125 and 250 kg P/ha) on clay soils of varying phosphorus retention was undertaken in two northern North Island forests (Hunter and Graham 1982, Skinner *et al*. 1995). The soils were of medium phosphorus retention; the trials were established between ages 6-8 years and measured at rotation end (age 26-31 years). At Whangapoua, there was a good (63%) response to 63 kgP/ha and a further smaller response to 125 kg P/ha, but no significant additional response to 250 kg P/ha. At Riverhead there was a large response (360%) to 63 kg and again a further smaller response to 125 kg P/ha, and no additional response to 250 kg P/ha (Table 9.3). Although at both sites the maximum response was achieved at 125 kg P/ha, at the lower rate of 63 kg P/ha yields were about 87% of those of the heavier rate. Additional split-application treatments included in the trials showed there was no advantage in applying 125 kg P/ha as two applications 10 years apart.

Table 9.3. Response by radiata pine to four rates of superphosphate supplying 0, 63, 125 and 250 kg P/ha, on medium phosphorus retention clay soils in the Auckland – Coromandel regions.

Forest and region	Phosphorus retention (%)	Bray P (mg/kg)	Foliar P (%)	Stem volume at rotation end (m^3/ha)
Whangapoa Coromandel	50-60	2.3-4.8	0.07-0.08	0kg: 494 63 kg: 714 125 kg: 822 250 kg: 849
Riverhead Auckland	30-50	1.9	0.06	0 kg: 104 63 kg: 480 125 kg: 550 250 kg: 550

A trial at Mamaku Forest (Kaimai Range central North Island) with 7-year-old radiata pine on a sandy podzol on ash deposits showed a response to 50 kg P/ha after four years, but no further response to 100 kg P/ha (Skinner *et al*. 1995). Further monitoring would be required to show whether 50 kg/ha would be adequate in the longer term.

In 1983 a series of five trials was established at sites in both the North and South Islands to test a range of nitrogen and phosphorus rates (Hunter *et al*. 1989, Hunter 1990). Five rates of each fertiliser were tested, but not in all combinations. Phosphorus was applied as mono calcium phosphate. Trial locations and details are summarized in Table 9.4.

Table 9.4. Location, soil and foliar characteristics for phosphorus and nitrogen rates trials at five sites in North and South Islands.

Forest	Soil	P retention (%)	Bray P (mg/kg)	Foliar P in controls (%)
Parengarenga Northland	Podzolised sand	3	2.2	0.115
Maromaku Northland	Podzolised clay ex pasture	16	6.3	0.106
Waimihia Southern Kaingaroa	Pumice	52	33.5	0.185
Motueka Nelson	Brown Soil	33	2.6	0.103
Nemona Westland	Podzolised Pakihi	5	8.9	0.077

The trials were established at age 4-5 and the response was measured after seven years. Results (Hunter 1990) are summarized in Fig 9.2 for phosphorus response with and without nitrogen fertiliser. The with-nitrogen data are derived from a range of nitrogen rates (80-400 kg N/ha). Responses to phosphorus were evident at three of the five trials. At Maromaku there was a response to the 40 kg P/ha rate (only in the presence on added nitrogen) and continuing response to additional increments up to the highest rate of 200 kg P/ha. The Maromaku trial was damaged by Cyclone Bola so the results should be treated with caution. At Motueka there was a strong response to the lowest rate of phosphorus in both the presence and absence of nitrogen fertiliser, but no additional response to higher rates, while at Nemona there was also a strong response to the low rate, and a further response to 120 kg P/ha was also apparent. The lack of response at Parengarenga was unexpected given the low soil Bray-P level and foliar P level. The low productivity at Parengarenga in comparison with the other sites indicates some other factor may have inhibited a response to phosphorus there.

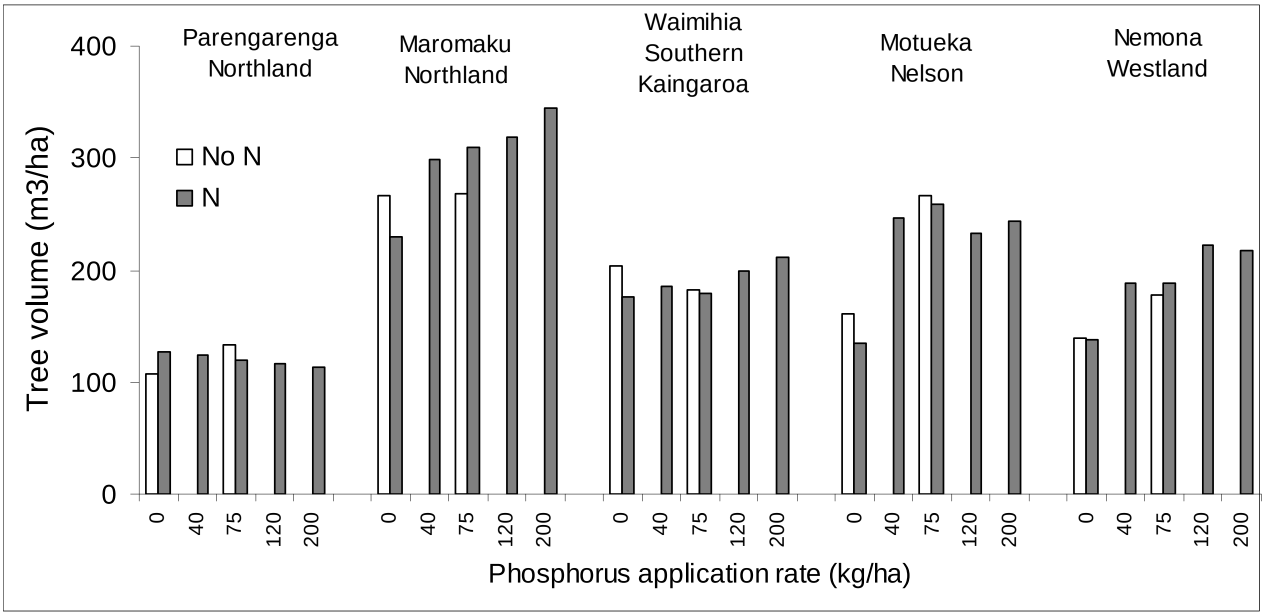

Figure 9.2. Response by radiata pine to five rates of phosphorus fertiliser at five trial sites, in the presence and absence of nitrogen fertiliser.

In summary, the results from the trials on Northland and Coromandel clay soils, where much of the phosphorus rates work has been done, as well as on the pakihi podzol in Westland, indicate that while responses may be obtained to very high rates of phosphorus, most of the response is achieved at rates of 60-70 kg P/ha. The soil phosphorus retention level appears to have little bearing on the rate or type of fertiliser required, though one study showed highly insoluble rock phosphorus may not be useful on soils with medium phosphate retention. The only phosphorus rates trial on a soil outside of the northern clay and podzol group, on a Brown soil, indicated rates of 40-50 kg P/ha may give optimum growth.

Magnesium Fertilisers

Fertiliser Types

Calcined magnesite (magnesium oxide, calmag) has a higher magnesium concentration than other magnesium fertilisers and so is generally the most cost effective form of magnesium. It is commonly applied in forestry at 200 kg/ha, to supply magnesium at 100 kg/ha. It is a fine powder and does not spread as well as other fertilisers, nor is it suitable for mixing with other fertilisers. Kieserite, a magnesium sulphate mineral (18%Mg), is used to produce Epsom salts (10% Mg); both have substantially lower magnesium concentrations but higher solubility than calcined magnesite. Despite lower solubility, calcined magnesite has been found to be more effective at increasing soil exchangeable magnesium on pumice soils, and may therefore be a more suitable fertiliser. Dolomite is a fine powder with a low magnesium concentration (10%) and is infrequently used in forestry.

Application Rate

Responses to magnesium at rates up to 400 kg/ha, applied as dolomite, were evaluated in radiata pine on a volcanic soil at Tauhara forest in central North Island (Olykan *et al*., 2001). The fertiliser had been applied at age five when magnesium deficiency symptoms were evident, and the effect was assessed at mid-rotation. Magnesium added at 20 kg/ha caused a substantial reduction in upper mid-crown yellowing, and higher rates (150 and 400 kg/ha) caused further, though not significantly greater, reductions. In Kaingaroa forest, magnesium applied at 25 kg/ha to a five-year-old stand showing severe magnesium deficiency symptoms greatly reduced upper mid-crown yellowing symptoms Olykan *et al*. (2001). Thus, relatively low rates of magnesium may substantially reduce upper mid-crown yellowing. At Tauhara the 150 kg/ha rate also significantly increased foliar magnesium concentrations; lower rates of 20 and 55 kg/ha also raised the foliar magnesium level, but not significantly. Different fertiliser types – dolomite, calcined magnesite, kieserite, Epsom salts and serpentine – added at 50 kg Mg/ha, reduced upper mid-crown yellowing symptoms and increased foliar magnesium concentrations by similar amounts. No growth response to magnesium was recorded – the lack of response was thought to be due to defoliation caused by the needle cast fungus *Cyclaneusma minus*. At southern Kaingaroa, six-year-old trees showing extreme deficiency responded to magnesium applied at 100 kg/ha (Hunter *et al*., 1986). In summary, although the usual recommendation has been to apply magnesium at 100 kg/ha (calcined magnesite at 200 kg/ha), lower rates may substantially alleviate symptoms on some sites.

Potassium Fertilisers

Potassium chloride (muriate of potash) has a greater potassium content than other forms of potash fertilisers, is more readily available, dissolves readily, mixes well with other fertilisers and is the only form of potassium fertiliser used in forestry. No rates of potassium trials have been conducted in New Zealand – the recommended application rate is 100 kg/ha (potassium chloride at 200 kg/ha).

Sulphur Fertilisers

Although sulphur deficiency has not been observed in New Zealand it is possible that deficiency may develop in future. Sulphur could be readily applied as straight superphosphate (P:S = 0.8) or as one of the various sulphur fortified superphosphates, if phosphorus was also limiting, or as ammonium sulphate if nitrogen was also limiting, or as Kieserite if magnesium was also limiting. If none of the other major nutrients was limiting, sulphur could be applied as calcium sulphate (gypsum) or as elemental sulphur, though the latter is explosive when finely ground (as is required to be effective) and cannot be used on its own for aerial topdressing. Application rates for sulphur have not been evaluated. As sulphur occurs in organic matter in a similar proportion to that for phosphorus it is suggested that application rates follow those for phosphorus.

Boron Fertilisers

Fertiliser Types

The mineral ulexite contains water-soluble sodium borate and water-insoluble calcium borate, and thus provides both fast and slow release forms of boron – it is the main form of boron applied to forests in New Zealand. Ulexite varies in composition and it may be worthwhile independently testing boron levels in ulexite from new suppliers. Borax (sodium borate) and colemanite (calcium borate) have been used previously but have been generally replaced by ulexite. A study comparing different forms of boron fertiliser on a Pumice soil at Rerewhakaaitu Forest showed that, although borax (particularly) and ulexite were more soluble, giving higher initial foliar boron levels than colemanite, in the longer term the three fertilisers gave similar results (Fig. 11.3, Xue *et al*. 2006).

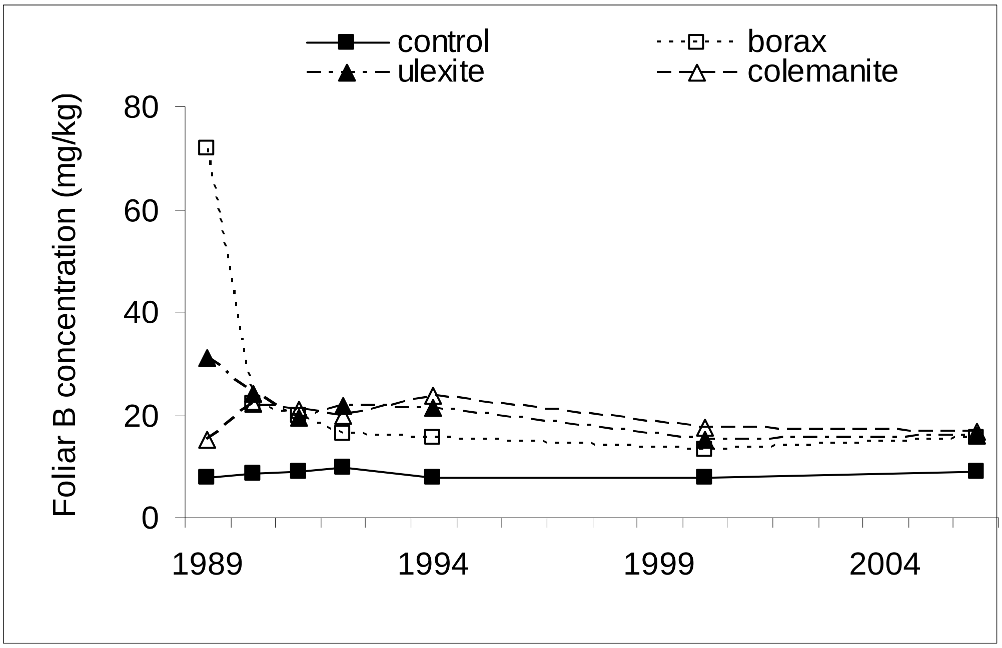

Fig. 9.3. In a long-term trial on a gravelly-sand soil on scoria at Rerewhakaaitu Forest, three boron fertilisers (borax, colemanite, ulexite) applied in 1989 initially increased foliar boron by widely different amounts. However after 17 years there was no difference between the fertilisers, with all fertilisers increasing foliar boron levels significantly above the control.

Application Rate

Care has to be taken when applying boron fertilisers, as high rates cause toxicity, especially on free draining gravel soils. Will (1985) recommended application rates of 4 to 8 kg B/ha for radiata pine, the lower rate to be used on lighter sandy soils. However, recent trials have examined responses by radiata pine to boron applied as ulexite, at rates up to 32 kg/B/ha (Olykan *et al*., 2007, Xue unpublished). These have shown boron may be applied as ulexite at rates up to 16 kg B/ha, even on free draining gravel soils, but rates of 32 kg B/ha are likely to cause a growth depression. At two sites where a growth response was recorded, near maximum growth was observed at 4 kg B/ha on a Pumice soil near Taupo and at 8 kg B/ha on a Brown soil near Lake Tekapo. The commonly recommended rate for ulexite is 60 kg/ha (6 kg B/ha). There is evidence that Douglas-fir is less tolerant than radiata pine to high boron rates; growth reductions have been observed in Douglas-fir when boron was broadcast at 8 kg B/ha (as ulexite) at two high country sites on Brown Tekapo and Cass silt loam soils (Davis unpublished data).

Other Micronutrient Fertilisers

Copper is the most commonly applied micronutrient to forests, but it is mainly applied as a fungicide for treatment of *Dothistroma* disease, in the form of cuprous oxide foliar spray, rather than as a nutrient. Both cuprous oxide and copper sulphate may be used to correct copper deficiency. Copper and zinc sulphates can be applied as foliar sprays or mixed with superphosphate (in factory mixes) if phosphorus is also being applied. Manganese and iron deficiencies are only likely to be treated in nurseries. If applied to the soil, these elements are rapidly converted to unavailable forms, so deficiency is best treated with foliar applications, either as mineral salts or as organic chelates, which are more easily dissolved and more readily absorbed.

Application Methods

When applied to seedlings at establishment, fertiliser is usually placed in a concentrated spot near the seedling to ensure that seedling roots are able to absorb it, to reduce access by competing weeds, and to limit immobilization of phosphorus in soils with a high phosphorus retention capacity. The fertiliser is commonly placed in a spade slot about 15 cm from the base of the plant. On slopes the fertiliser should be placed to the side rather than above the plant. Where urea is applied the slot should be stamped closed after application to reduce volatilization loss. Where heavier rates are required, a follow-up broadcast application by hand around seedlings, or spot or band application near individual seedlings, may be given after one or two years. Band application using a tractor spreader to supply high rates may be feasible in some situations, but is not recommended for soluble fertilisers because of potential leaching loss.

In established stands where root systems are more extensive and weeds have been suppressed, fertilisers are normally broadcast using aircraft (Fig 9.4), but may also be applied using ground spreaders where conditions permit. Ground spreaders give greater control over application and a greater ability to avoid waterways. Helicopters have a smaller working circle than fixed-wing aircraft, but provide better spreading control for smaller or irregular shaped areas and non-uniform areas with hills and valleys or gullies. In such situations it would be expected that helicopters would achieve a more uniform application due to their ability to fly more slowly and to follow contours. Uniformity of spread is important to achieve even crop growth. To ensure even spread, aircraft should be fitted with a global positioning system to show boundaries of the block to be fertilized, and record flightlines. It is common practice to fly “half-overlap” and apply the fertiliser at half the specified application rate at each pass. Use of granulated fertilisers will also aid even distribution. Best practice application would require that the aircraft used has undergone an auditable calibration process so that the forest manager can have some level of confidence that the aircraft will achieve an even spread. The calibration should provide an acceptable coefficient of variation of the application rate. The ‘Spreadmark’ code of practice for aerial topdressing suggests that the coefficient of variation should be no more than 15% for high analysis fertilisers and 25% for superphosphate.

Timing of Fertilisation

Key times for fertiliser application are at planting, when thinning and pruning operations are undertaken, and in older stands where crowns have thinned because of disease or other cause. Fertilisation may be required at other times if deficiency becomes apparent from symptoms, or where foliar analysis indicates declining foliar nutrient concentrations.

Fig 9.4 Aerial fertiliser application with a fixed wing aircraft.

At Establishment

Where fertiliser is required at establishment on nutrient-deficient soils, fertiliser is normally applied at, or within a few months of the time of planting to avoid potential loss of productivity. Early application is particularly important in cases of severe deficiency. Early, pre-emptive, application is also important in the case of boron deficiency to avoid stem malformation occurring as a result of terminal bud or shoot dieback.

At Thinning and Pruning

Once full canopy closure is achieved, fertiliser response may be limited because of the lack of space available for canopy expansion. This is especially so for nitrogen for which it is well recognized that, where this nutrient is limiting, greater responses may be obtained where fertiliser application is timed to follow thinning and pruning. Further, application to thinned stands will ensure the response goes on to fewer, larger stems than in unthinned stands. It is recommended that fertiliser is applied at the time of, or soon after, thinning to achieve maximum response; too long a delay may allow sufficient crown canopy development to restrict the size of the response. Pruning reduces the amount of green crown and an internal source of nutrients for translocation to new growing points. Fertiliser application can offset this loss (Fig 9.5)

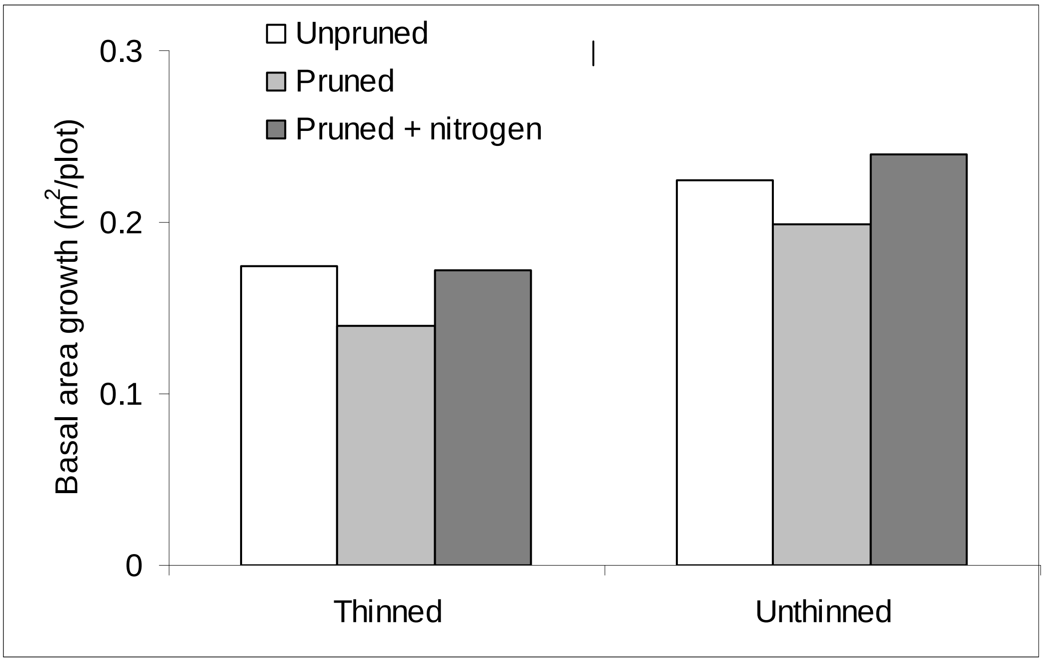

Fig 9.5. The effect of pruning (to 2 m) and nitrogen fertilisation on 2-year basal-area growth of 6-year-old radiata pine growing on a pumice soil. The bar (upper centre) shows the least significant difference. From Ballard (1984)

Mature Stands

Although there are a number of reports of growth responses to fertiliser nitrogen in old northern hemisphere boreal forests, there are relatively few reported responses in pole-stage or middle-aged natural stands anywhere on soils of moderate fertility, presumably because nutrient cycling, both within the tree and through the litter layer, is relatively efficient at this age (Miller *et al*. 1992). However there are examples indicating that responses can be obtained from mid-rotation to mature stands in New Zealand.

- The first forest fertiliser trials in New Zealand were on severely phosphorus-deficient Northland clay soils in 20- to 24-year-old stands. These trials showed spectacular responses to phosphorus that tripled stand basal area over a 24-year period (Weston 1958).
- Two trials were established on infertile Moutere gravel soils in Nelson to examine nitrogen and phosphorous response in 14- and 40-year-old radiata pine stands (Mead and Gadgil 1978). Trees in the older stand responded to nitrogen (62% increase in volume after five years), but not phosphorus, while trees in the younger stand responded to both nitrogen (23% volume response) and phosphorus (14% volume response), and there was a strong interaction between the two nutrients (67% response).
- In conjunction with these trials a series of simpler N + P trials was conducted elsewhere in Nelson (14-44 year-old stands), as well as at Balmoral Forest in Canterbury (a 17-year-old stand). All of these showed positive volume responses (Mead and Gadgil 1978).
- Responses to nitrogen in mid-rotation stands (13-14 year-old) were also reported for central North Island pumice soils by Wollons and Will (1975). In contrast to the previous studies, these responses were obtained in high-producing stands.
- A new study was initiated in 2004 to determine if responses could be obtained to nitrogen and phosphorus on sites of varying nitrogen and phosphorus status in stands aged 15 to 22 years. Nitrogen was applied at 0 and 200 kg/ha and phosphorus at 0 and 75 kg/ha. After four years, average basal area over the four sites was significantly increased by 13-15% by

nitrogen or phosphorus application. Basal area or height responses were recorded at all except one site which had high initial foliar nitrogen and phosphorus concentrations (Xue unpublished).

Timing of Fertiliser Application in Relation to Leaching and Volatilisation Losses

Nitrogen from fertilisers, including urea, may be converted to nitrate in the soil if conditions are suitable and nitrate can be readily leached. Nitrogen fertilisers should therefore not be applied during winter months, especially late winter, when the soil is likely to be saturated. Potassium and magnesium are less readily leached than nitrate, as they are held on soil cation exchange sites. However they may be leached under some conditions, and application of these fertilisers should likewise be restricted when soils are saturated.

Nitrogen can be lost through volatilization in warm temperatures, so it is important to try to apply fertiliser before rain if it is to be applied in summer. Because of leaching and volatilization concerns, it is best to apply nitrogen in spring or autumn when soils are moist but not saturated, and when temperatures are moderate and root activity and potential nitrogen uptake are high.

Phosphorus and boron are not subject to leaching or volatilization and phosphorus can be applied at any time. However, boron deficiency is exacerbated by drought, so if boron fertilisation is required it should be done before summer.

Fertiliser Application and Weed Control

Where weeds are present they will compete with the crop for the nutrients applied in the fertiliser and restrict potential growth response. Additionally, weeds are likely to respond to the added fertiliser and compete more strongly for existing resources of light, water and nutrients. Hence in young stands, prior to canopy closure when weeds are suppressed, it may be necessary to undertake weed control operations in conjunction with fertiliser application, or alternatively delay fertiliser application until the tree canopy is well above the weeds.

Fertiliser Storage and Spreading Characteristics

Most solid fertilisers can be stored over a season as long as they are kept in a cool dry place. Urea and other nitrogen products absorb moisture from the atmosphere and should be stored in closed sealed bags. Long term storage of these products should be avoided.

Many fertilisers are manufactured as granules or prills to facilitate handling and spreading. It is important that the product is uniform (i.e., similar in granule size with no lumps) to allow uniform spread. Finely ground fertilisers or materials that cake or separate into their constituent materials may cause clogging of equipment or uneven distribution. The spreading equipment must be able to cope when these materials are used. Spreading equipment must be calibrated before use.

Health and Safety

Some fertilisers are hazardous to use and safety precautions may be required. Label instructions regarding safety should be followed and fertilisers should be stored and transported safely. Breathing apparatus (e.g., a respirator) may be necessary when handling fine or dusty fertilisers.

Fertiliser Compatibility

The supply of multiple nutrients can be achieved through the use of compound fertilisers (see Table 9.1) or through the use of mixtures. Where more than one nutrient is required, and this cannot be achieved through the use of a single compound it may be necessary to mix fertilisers. Generally, fertilisers are chemically compatible in that no explosive or toxic mixtures are produced, but chemical reactions can occur that can lead to absorption of moisture, setting in storage and handling problems. If two fertilisers with different particle sizes are mixed, segregation of the materials will occur; the greater the difference in sizes, the greater the segregation. If segregation occurs, uneven application will result. A fertiliser compatibility chart is provided by Ravensdown Fertiliser (www.ravensdown.co.nz)

Response to Fertiliser

Size of Response

Response to nitrogen and phosphorus

Where nutrient deficiencies severely limit tree productivity, large responses to fertiliser are possible. Responses in excess of 200 m^3/ha over a rotation have been obtained following phosphorous fertilisation of phosphorous-deficient Northland clay soils. Much smaller responses are likely where stands are mildly deficient and appear visibly healthy. In a series of five trials established at sites where a fertiliser response to nitrogen and/or phosphorus was considered likely, four-year responses to nitrogen and phosphorus ranged from -14 to +67% (Hunter *et al*., 1989, Table 9.5). On a podzolised sand in Northland, small additions of nitrogen and phosphorus produced a 20-30% increase in periodic current annual increment, but larger additions reduced the response. On a Northland podzolised clay, nitrogen and phosphorus applied alone did not influence growth rate, but together increased productivity by 10-20%, despite the site being a relatively high productivity ex-farm site. Greater responses (50-70%) from phosphorus alone or in combination with nitrogen were obtained on two infertile South Island soils

Table 9.5. Four year volume (m^3/ha) and proportional (%) response to nitrogen and phosphorus by radiata pine. The trees were approximately five years of age when the fertiliser was applied, and were kept mostly unthinned and unpruned. Standing volumes and periodic current annual increments are given for control plots. From Hunter *et al*., (1989).

	Standing volume (m^3/ha)	PCAI (m^3/ha)	Volume response to N alone (m^3/ha)	Volume response to P alone (m^3/ha)	Volume response to N + P (m^3/ha)
Podzolised sand Northland	45	10.6	11.8 28%	13.7 32%	12.1 28%
Podzolised clay Northland[1]	159	33.7	-10 -7.4%	-7.5 -5.6%	28 21%
Pumice southern Kaingaroa	83	18.8	-6.3 -8.9%	-7.1 -9.4%	3 4.0%
Soil from	80	17	-9.7	36.9	41.7

granite			-14.3%	54.1%	61%
Nelson					
Pakahi	69	15.3	1.1	10.5	41.1
Westland			1.8%	14.7%	67.2%

[1] ex farm site

For nitrogen, the size of the response depends on the openness of the canopy. From a total of 44 trial comparisons where 200 kg/ha of nitrogen had been applied to radiata pine, Hunter *et al*. (1986) observed that large basal area responses tended to occur in stands less than 10 years old, particularly if growing on nitrogen-poor soils, and if they had been recently pruned or thinned. Smaller positive responses occurred in older stands, and in stands on soils with total nitrogen greater than 0.2%. Negative responses could occur if nitrogen was applied to stands with Bray-2 phosphorus levels of less than 10 mg/kg. The expectation of a basal area response to nitrogen, based on foliar nitrogen in relation to canopy closure, is shown in Table 9.6 (Hunter *et al*. 1982).

Table 9.6. Expectation of a basal area response to nitrogen fertiliser in pole-aged (6-9 year-old) radiata pine stands. The percentages by which basal area in plots receiving 200 kg N/ha exceeds those of unfertilized plots three years after fertilisation are given for recently thinned stands. Note that (1) A3 stands do not form closed canopies because of needle loss, (2) C1 – a treatment effect greater than 10% is required for statistical significance, (3) B3 and C2 – no information available on responses. From Hunter *et al.* (1982).

Nutritional state			**Canopy state**	
A Very deficient (<1.2%N)	B Low –marginal (1.2-1.4% N)	C Marginal-adequate (> 1.4% N)		
[1]√√ 25%	√√ 15%	U 5%	Recently thinned	(1)
√√	√	U	Open canopy	(2)
Does not occur	U	X	Closed canopy	(3)

[1]√√: Response confidently expected, √: Response expected
U: Response uncertain
X: Response confidently not expected

Response to magnesium
Good gains in growth can be obtained from fertilisation of young stands severely deficient in magnesium. In southern Kaingaroa, a six-year-old radiata pine stand showing severe deficiency symptoms, was treated with 100 kg/ha of magnesium (as a mixture of ground dolomite and Epsom salts). Over a five-year period the trees treated with fertiliser grew 66% more in height and 45% more in root collar basal area than untreated trees (Hunter *et al*. 1986). Responses have not been obtained on sites where the deficiency is less severe, or from older stands that have developed upper mid-crown yellowing (magnesium deficiency) symptoms.

Response to boron
The major impact of boron deficiency is to cause stem malformation, and there is little information on the loss in productivity that the deficiency may cause. Where boron deficiency becomes apparent early in a rotation, corrective action can result in normal growth. If fertiliser is not applied there may be no commercial yield at the end of the rotation. Where deficiency becomes apparent at later stages, it may be possible to recover some merchantable timber, but loss in value may still be large.

Response to mixed fertilisers
The response to a mixture of fertilisers by young, densely planted, radiata pine and *Cupresssus lusitanica* has recently been examined at 35 sites covering all of the main plantation forest environments in New Zealand (Watt *et al*. 2005, 2008). Sufficient amounts of fertilisers were applied to ensure that no nutrient element would be limiting. Most of the sites were established after harvest of pine forest. The average volume response at age two years was 23% and 42% for radiata pine and *Cupressus lusitanica* respectively, while at age four the response was 23% and 54% respectively. The trial results demonstrate that species can differ in the size of fertiliser response. Although a mixture of fertilisers was applied, it is likely that the responses measured were mostly to nitrogen and phosphorus.

Factors Influencing the Size of Response

A number of factors may influence the size of the response to fertiliser, including:

- The amount of available nutrient in the soil; the greater the amount the smaller the response.
- The amounts of other potentially limiting nutrients in the soil. For example if nitrogen is added but if phosphorus is limiting there could be a nil or even negative response to nitrogen addition.
- The age and silvicultural history of the stand. Unthinned stands will respond provided they have not closed canopy, therefore young stands may respond, and thinned and (or) pruned stands often respond well, especially to nitrogen. Older stands at or near canopy closure are unlikely to respond.
- The presence of weeds. Fertilisation will enhance the growth of competing weeds and can limit the response to fertiliser through competition for light, moisture and other nutrients. Therefore in young stands where fertiliser is applied prior to canopy closure, it may be necessary to control weeds to obtain benefit from fertilisation.
- Disease. Stands affected by fungi that reduce needle mass, effectively thinning the canopy, may respond to fertiliser, especially nitrogen, which will be used to rebuild the canopy.
- The tree species.

Longevity of Response

- Spot applications of nitrogen, phosphorus and boron fertilisers at planting usually provide a short term response seldom exceeding 3-5 years.
- Broadcast phosphorus fertilisers usually give a sustained response of 15-20 years, though responses can be of short term duration on highly impoverished soils, and a number of applications may be required.
- Broadcast boron fertilisers give a sustained response. Insoluble forms (e.g., ulexite) were thought to give a better long-term (10 years) response than soluble forms (borax) (Hunter *et al*. 1990), but recent evidence indicates that over the long term (10+ years) soluble and insoluble forms appear to be similarly effective in maintaining foliar boron levels (Fig 9.3). The ability of soluble fertilisers to match the insoluble sources may be explained by plant uptake and subsequent release of boron from litterfall and slash (Olykan 2004).
- Broadcast magnesium fertilisers also give a sustained response (10 or more years).
- Responses to broadcast nitrogen are short term. Typically responses peak at 2-4 years, and then growth rates decline to those of unfertilised stands 5-10 years after application. Rapid immobilization of nitrogen into organic forms may be the main reason for the short-term response to nitrogen.

Modelling Response to Fertiliser using Foliar Nutrient Concentrations

Estimation of fertiliser response involves many calculations that are best performed using the assistance of a growth model such as STANDPAK using an appropriately specified silvicultural regime. This model can predict the growth of stands, calculate diameter distributions at harvest and produce stand volumes by log size and quality. Costs and prices can then be entered to predict economic outcomes. As STANDPAK does not predict fertiliser response, additional models must be used to provide this information.

Example of modelling response to nitrogen and phosphorus fertiliser
Potential growth responses and economic outcomes from the use of nitrogen and phosphorus fertilisers have been estimated for central North Island, Bay of Plenty and South Auckland forests, using foliar nitrogen and phosphorus concentrations. To predict the response to nitrogen fertiliser at foliar nitrogen levels of more than 1.2%, a growth model developed from Kaingaroa forest data was used (Elliot and Goulding 1976). This model contains a nitrogen fertiliser response function based on nitrogen fertiliser response from the central North Island and Bay of Plenty areas. Other (unpublished) models were used for sites where foliar nitrogen was less than 1.2% (developed from data collected in coastal sand forests) and to predict the response to phosphorus from foliar phosphorus concentration (developed from fertiliser trials on clay soils in the northern half of the North Island). Calculated volume responses to fertiliser, applied at age 8, at harvest at age 28, are shown in Table 9.7 for nitrogen and phosphorus applied alone and in combination. Testing the applicability of such models over a range of environments, and further model refinement where necessary, is required.

Table 9.7. Predicted growth responses (m^3/ha) to phosphorus fertiliser applied singly and in combination with nitrogen. Growth responses modelled from foliar nitrogen and phosphorus concentrations.

Fertiliser Applied (kg/ha)	Foliar N (%)	Foliar P (%)		
		<0.11	0.11-0.13	>0.13
P 75	>1.19	48	30	0
		Foliar N (%)		
		<1.2	1.2-1.5	>1.5
N 200	-	44	26	0
		Foliar P (%)		
		<0.11	0.11-0.13	>0.13
P 75 + N 200	<1.2	64	58	44
	1.2-1.5	58	35	26
	>1.5	48	30	0

Nitrogen Fixers

As the name implies, nitrogen fixers are plant-microbial associations that are capable of “fixing” nitrogen from the atmosphere, usually in root nodules, into mineral forms that can be used by the plants themselves, and ultimately by other plants in the ecosystem after death and decay of root nodules and other parts of the nitrogen-fixers.

Historically, the yellow flowering tree lupin (*Lupinus arboreus*) nitrogen-fixer was sown extensively in New Zealand where coastal sand dune forests were established, as raw sands have very low levels of nitrogen. Tree lupin was introduced after initial stabilization of the sand with marram grass, and was capable of fixing nitrogen in sufficient quantities to sustain forest productivity. In some areas molybdenum was deficient and fertilisation with this element was required for the nitrogen fixation process (Gadgil 1983). Tree lupin was devastated by the fungal disease *Colletotrichum gloeosporioides* in the 1980s and is now not sown for nitrogen fixation in sand dunes. The potential of other legumes that might take the place of tree lupin in sand forests has been researched and some species have been recommended (Douglas *et al*., 2004), but there has been no operational seeding of these species in sand dune forestry.

The pasture legume lotus (*Lotus pedunculatus*, Fig 9.6) is widespread in pine forests, particularly in moister areas, and in some areas the induced tetraploid cultivar “Maku” lotus has been introduced to improve soil nitrogen status by aerial seeding at a rate of about 5 kg/ha. On sites with low phosphorus status, fertiliser topdressing with 200 kg/ha or more of superphosphate may be required to stimulate growth and nitrogen fixation. Seed should be inoculated with *Rhizobium* bacteria just prior to seeding. *Rhizobium* cultures can be purchased from seed firms and can be applied following the manufacturer’s instructions. Shrubweeds occurring in forests capable of fixing nitrogen include tree tutu (*Coriaria arborea*), broom (*Cytisus scoparius*) and gorse (*Ulex europeus*). These species may fix 100-200 kg/ha/yr of nitrogen in the few years prior to their suppression by forest canopy closure. A vigorous sward of lotus may fix in the order of 500 kg/ha/yr of nitrogen.

Fig 9.6. A vigorous sward of the nitrogen-fixer lotus may add up to 500 kg/ha/yr of nitrogen in young stands.

Impacts of Fertilisation on Water Quality

Binkley *et al.* (1999) reviewed the results of several dozen studies from around the world on the impacts of nitrogen and phosphorus fertilisation on stream water quality. They concluded that forest fertilisation commonly leads to moderate increases in streamwater nutrient concentrations. The greatest increases came from the following:

- direct application to streams;
- use of ammonium nitrate fertilisers;
- the application of high rates or repeated doses.

Some of the highest nitrate concentrations in streamwater came from forests saturated with nitrogen from air pollution, which is (so far) not important in New Zealand. The review also showed that the quality of water draining forests was much better than that from agricultural lands, whether or not the forests were fertilised. They found no evidence of detectable effects of forest fertilisation on the productivity or composition of stream communities, though few studies had been undertaken.

There have been few studies of nutrient leaching following fertiliser application to forest land in New Zealand. A lysimeter study by Worsnop and Will (1980), on a Taupo silty sand soil in Kaingaroa Forest showed no effect of fertilisation (200 kg/ha of urea) on leaching loss of nitrogen or other nutrients for the three years of monitoring after fertiliser application. Similarly Clinton and Mead (1994) were able to recover in soil and plant material all of the ^{15}N labelled nitrate they added to a young (4-year-old) stand of radiata pine on a silt loam soil in Canterbury, indicating leaching losses would not have occurred in that environment.

Nitrogen leaching occurs more readily on sands. Thomas and Mead (1992) applied ^{15}N-labelled urea (150 kg N/ha, broadcast) to 2-year-old seedlings on bare coastal sand in Canterbury in either single or split applications. For the single application, 30% was lost below the main rooting zone through leaching, but when split into three applications of 50 kg/ha, more nitrogen was retained in the soil and none was detected below the root zone at 80 cm depth. At Woodhill Forest Smith *et al*. (1994) compared nitrate leaching (in suction cups at 60 cm depth) following harvest of a 42-year-old stand, in the presence and absence of urea application. Where urea was added (200 kg/ha/yr in quarterly additions of 50 kg/ha for 2 years) nitrate concentrations had increased in the leachate 20 weeks after harvest, and remained at elevated levels in most treatments throughout the monitoring period to nearly 2.5 years after harvest. Both of these experiments show the potential of sands to leach nitrogen after fertiliser application.

Because of the paucity of information on nitrogen leaching following fertiliser application to forests, in order to follow a conservative approach to prevent leaching of nitrogen, Davis (2005) proposed the following guidelines for nitrogen fertiliser applications in forestry:

- Broadcast applications of N at any time should not exceed 200 kg/ha.
- Spot applications after planting should not exceed 30 g N/tree.
- Application during winter or other wet periods when soil water drainage is likely should be avoided.
- Except where plantations are severely deficient, broadcast applications should be made in conjunction with thinning and pruning operations when N demand is high.
- Application decisions should be based on results of nutrient analysis of foliage.

As noted in the Binkley *et al*. (1999) review, unless precautions are taken, fertiliser may directly enter stream channels during aerial topdressing operations. In a New Zealand study, Leonard (1977) monitored streamwater nitrogen concentrations from a 389 ha catchment on the volcanic plateau planted in radiata pine, of which one third had been topdressed with 230 kg N/ha as urea. There was no attempt to avoid the stream channel. He measured a net stream loss due to fertilisation of 95 kg N (0.74 kg/ha, 0.33% of the total applied) during the first four months after application. Nearly half (48%) was lost during the first six days of fine weather, which the author attributed largely to fertiliser landing directly in the stream channel. He suggested using a buffer strip of 20-m-wide on either side of the stream to prevent direct entry of N into the channel. Additional studies with both urea and superphosphate are reported in Neary and Leonard (1978). To prevent fertiliser entering stream channels they recommended:

- Using 20-m-wide buffers.
- Topdressing during no-wind conditions.
- Using larger granule fertilisers dropped from lower altitudes.

Avoiding stream channels is important for copper application, as copper is toxic to fish.

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10. MANAGING FOREST NUTRITION

Summary

- *Nutritional management of a forest stand involves an assessment of its nutritional status, fertiliser treatment if required, followed by monitoring of the stand nutrient status and growth to assess the response to fertiliser.*
- *Effective management of forest nutrition requires an understanding of the nutritional status of the stand and how it changes over time and with management practice.*
- *Development of a foliar nutrient database will assist in providing such an understanding.*

Assessment of Nutrition Status

Assessment of nutrition status may be made from:

- observation of nutrient deficiency symptoms;
- foliar analysis of samples collected at a single point in time;
- foliar data from analyses at different stages in the rotation;
- soil analyses;
- results of fertiliser trials.

Symptoms of a nutrient deficiency may clearly indicate that tree growth is limited by the deficiency, but reliance on observation of nutrient deficiency symptoms for assessment of stand nutrition status is inefficient. Opportunities for increasing productivity from correcting growth-limiting deficiencies where foliar symptoms aren't present or clear are likely to be lost. Effective management of forest nutrition requires an understanding of the nutritional status of the stand and how it changes over time. In turn, this requires a sound database of the foliar nutrient status of the forest and, ideally, information on the soils present and their distribution. Because of cost and lack of consistent threshold criteria, soil chemical analysis is rarely used for nutrition monitoring.

Forest nutrition is monitored with varying degrees of intensity. Some companies, more likely those with a high proportion of sites where nutrient deficiencies are expected, monitor foliage regularly and intensively across their forests. Others – those with little known history of nutrient limitation – might limit sampling to occasional low intensity check sampling. The need for monitoring is likely to increase in future as the number of forest rotations increases and nutrients are removed from the site in harvest products.

Building a Foliar Nutrient Database

Building a foliar nutrient database should be a priority and an ongoing part of forest management. Key times for monitoring foliar nutrients are:

- When nutritional problems are suspected from slow growth rates or foliar symptoms.
- At age 3-4 to check the nutrient status of stands entering the high-demand canopy-forming phase.
- After pruning and thinning events, again a period of high demand during canopy rebuilding.
- The season following fertiliser application to check for effectiveness of fertiliser additions – an increase in the concentrations of the nutrient applied in the fertiliser and/or a possible decrease in the concentration of other nutrients because of dilution, which may require correction.

Nutritional data may be used to define the nutritional status of the stand it was drawn from and whether fertiliser is required. It may also be stored in a database where it can be linked to other data collected from the same area, stand or forest at the same or different stages in the rotation. Over time such data may be used to provide an understanding of the nutritional state of the forest, and how stands are likely to change with stand development and respond to management practices.

Use of Soil Maps

Soil nutrient supply varies greatly between soil types – some soils have large nutrient reserves, others small. Such variation influences the onset of nutrient decline and the need for fertiliser. Soil types as displayed on soil maps can therefore be used as a basis for integrating information, such as foliar nutrient and fertiliser response data, providing such data can be unequivocally linked to soil type, and prescribing fertiliser. There are few forest-specific maps so reliance has to be placed on district soil maps which have been drawn for much of the country – map availability can be ascertained by contacting Landcare Research.

Payn *et al*. (2000) examined usefulness of different scale maps for optimizing the phosphorus nutrition of radiata pine. The national soil map (1:1 000 000 scale) was found to be not useful for operational scale planning. It was concluded that 1:100 000 maps were adequate for general nutritional management planning and definition of areas likely to be responsive to fertiliser. More detailed maps (1:10 000) allowed further refinement in some situations, depending on the soil pattern.

Fertiliser Trials

Results of previous fertiliser trials may be used to provide an assessment of nutritional status if they were carried out on the same, or a similar, soil type. They are particularly useful if rates of application were compared, as such trials can give a guide not only as to whether or not a deficiency is present, but also the likely response size and the appropriate rate of fertiliser to correct the deficiency.

Fertilisation

Decision aids such as the Phosphate Decision Support System (Skinner *et al.* 1998) and the more recent “N x P x Weeds Radiata Young Stand Rotation Length Ready-Reckoner” (unpublished) can be used to assess expected response to fertiliser.

Recommended rates and types of fertilisers and methods of application for the key deficiencies in New Zealand are given in section 9. The rates have been developed for radiata pine, but, in the absence of other information, should be applicable to other species.

Monitoring the Response

It is important to verify tree growth responses to fertiliser addition by regularly measuring tree diameters and calculating basal area response. To estimate the response it is necessary to have an unfertilised control. These data will improve future management decisions regarding the value and effectiveness of fertiliser additions. They may also assist in the interpretation of foliar nutrient data which can fluctuate from year to year – if trees are healthy and growing then there will be no cause for concern even though certain foliar nutrient concentrations appear to be lower than normal. It is also useful to sample and monitor foliar nutrition after fertiliser application, as noted above.

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11. NUTRITION MANAGEMENT IN TREE NURSERIES

Summary

- *The need for fertiliser application in nurseries can be assessed by soil analysis prior to sowing, or foliar analysis, or the presence of visual symptoms in the growing crop.*
- *Fertiliser can be applied in solid form to the soil before or after the crop is established, or in liquid form to the growing crop.*
- *Soil organic matter content and soil acidity need to be managed, as both influence soil nutrient supply.*
- *Mycorrhizae are of key importance in nutrient uptake, and inoculation of nursery soils with mycorrhizal fungi may be necessary in some circumstances.*

In New Zealand most planting stock are raised in bare root nurseries. Forest nurseries are an intensive form of land management and annual nutrient removal in crops is high requiring fertiliser application to maintain soil fertility and productivity.

Identifying the Need for Fertiliser

Soil Analysis

Soil nutrient analyses can be used as a guide to managing nursery soils, especially if they are performed periodically so that changes in nutrient levels can be monitored over time. Soil samples should consist of about 20 cores taken randomly to a depth of 10 cm from a nursery block or area with similar soil and management history. Guidelines for interpreting soil analytical “quick test” values as used in agriculture were provided by Knight (1978) for tree nursery use (Table 11.1).

Table 11.1. Interpretation of quick test values[1] for use in forest nursery soils for producing radiata pine stock (modified from Knight 1978).

Nutrient status	Calcium	Potassium	Magnesium	Phosphorus[2]	Fertiliser need
Satisfactory/high	4	8	7	31	Undesirable
Satisfactory	3	7	6	21-30	Not-needed
Marginal	2	4-6	4-5	11-20	Low rates needed
Low	1	3	3	10	High rates needed

[1] For approximate conversions of cation quick test values to me/100g of soil, multiply calcium values by 0.6, potassium values by 0.05 and magnesium values by 0.04.
[2] Phosphorus values are for the 0.5 hr Olsen test, and are given as ppm.

Although somewhat arbitrary, the values in Table 11.1 were used with reasonable success for evaluating N.Z. Forest Service nursery fertiliser requirements before sowing. In addition to the values for particular nutrients, attention should be paid to the balance of potassium and magnesium. The ratio of K:Mg (i.e., K value x 0.05: Mg value x 0.04) should not exceed 2:1 to avoid potassium interference with magnesium uptake.

For nitrogen, Knight (1978) noted that fertiliser will be needed where soil total nitrogen is very low (≤ 0.1%). No appropriate tests for nurseries are available for sulphur or the micronutrients.

Foliar Analysis

Foliar analysis can be used as an aid for diagnosing nutritional status of the growing crop. Samples should be obtained from 15 or more individual plants from within the area of interest (nursery block, area of slow growth, plants exhibiting deficiency symptoms; if the latter two, then a healthy plant sample should be collected for comparison). It is convenient to collect whole shoots of one-year-old nursery plants. Interpretation of foliar analyses is based on comparison of sample data with crop data of known nutritional status and preferably of similar growth stage, but published data is scarce. Comparative data for radiata pine are given in Table 11.2. For two-year-old plants, foliar analyses should be compared with 'deficient' and 'adequate' values given in Section 5, for foliage collected as described in Section 5. Comparative data for glasshouse and nursery-grown *Eucalyptus* seedlings are given in Table 11.3.

Table 11.2. Marginal (growth limiting) nutrient concentration ranges in radiata pine seedlings (from Boardman *et al.* 1997).

	Seedlings whole shoots	Seedlings young mature foliage
N (%)	-	1.0-1.2
P (%)	0.09-0.14	-
K (%)	<0.35	-
Ca (%)	-	-
Mg (%)	0.07-0.10	-
Mn (mg/kg)	5.0-20.0	-
Fe (mg/kg)	40-80	-
Zn (mg/kg)	-	11-12

Table 11.3. Deficient and adequate nutrient concentration ranges observed in youngest fully expanded leaves of three-month-old Eucalyptus seedlings in glasshouse trials (Dell *et al.* 1995). The values are for the ranges found in four species; *E globulus*, *E. grandis*, *E. pellita*, and *E. urophylla*. Also shown are critical values for nitrogen[1] and adequate values for phosphorus, potassium and magnesium for four nursery-grown *Eucalyptus* species (Will 1964, unpublished).

	Deficient	Adequate	*E. camaldulensis*	*E. delagatensis*	*E. pilularis*	*E. saligna*
N	0.6-2.5	2.5-4.0	2.4-2.8	2.0-2.3	1.7-1.9	2.4-2.7
P	0.03-0.08	0.13-0.40	0.15	0.11	0.11	0.15
S	0.09-0.13	0.19-0.32				
K	0.3-0.5	0.9-1.8	0.80	0.75	0.59	0.94
Ca	0.02-0.17	0.31-1.1				
Mg	0.05-0.19	0.16-0.44	0.055	0.10	0.14	0.11
Fe	15-32	52-104				
Zn	5-12	13-31				
Mn	5-16	43-546				
Cu	0.4-1.6	3.0-5.5				
B	8-12	12-32				

[1] Critical values for nitrogen established from a nursery fertiliser trial. Values are for foliage samples collected at the end of the first growing season (May). Seedlings did not respond to phosphorus, potassium and magnesium, so critical values lie below those given.

Foliar Symptoms

Symptoms of nutrient deficiencies in radiata pine seedlings, a number of which have been seen in New Zealand nurseries, are summarised in Table 11.4. Symptoms for Douglas-fir seedlings are shown in Table 11.5.

Table 11.4. Deficiency symptoms of radiata pine seedlings that have been observed in nurseries (from Will 1985). Symptoms of sulphur, calcium and boron deficiencies are from Knight (1978).

Deficiency	Symptoms
Nitrogen	Foliage a fairly uniform light green (moderate deficiency) to yellow green (severe deficiency) (Fig. 11.1). Discoloration is even along the length of individual needles and occurs over the whole plant. Common.
Phosphorus	Possible bluish green needles with slight to moderate deficiency. In acutely deficient seedlings, growth is severely stunted and the apical tuft of foliage consists of short, slightly yellow-tipped needles that curve upwards and inwards to give seedling tops a flat appearance. Uncommon. In new nurseries, may be associated with poor mycorrhizal development.
Sulphur	Yellowing of young foliage. Not described for New Zealand nurseries.
Potassium	Needles yellowish, discoloration more pronounced on the tips (in contrast to nitrogen deficiency), but extending over the full length of the needle (in contrast to magnesium deficiency). Uncommon.
Calcium	Apical growing point damaged. Not described for New Zealand nurseries.
Magnesium	Needle tips golden yellow, remainder of needle normal green (Fig. 11.2). As severity increases, more of the needle is discoloured. Common, especially in pumice nurseries. Magnesium uptake can be restricted in strongly acid soils, cold and wet soils, and soils high in available nitrogen and potassium.
Iron	Young seedlings (3-5 cm) develop a pale greenish-yellow colour in the terminal needles (Fig. 11.3). Occasional, and often self-correcting. Iron (and possibly manganese) deficiency may be induced by over-liming.
Copper	Drooping of needles in the apical tuft, needle tips die back (Fig. 11.4). Uncommon, may be induced by over-liming.
Zinc	Development of a rosette of buds in place of the terminal bud (Fig. 11.5). Foliage may become bronze. Uncommon, may be induced by over-liming.
Boron	Apical growing point damaged. Not described for New Zealand nurseries.

Fig 11.1. Nitrogen stress in radiata pine seedlings in foreground. Yellowing is relatively uniform over the whole seedling.

Fig 11.2. Magnesium deficiency. Needle tips to most of needle golden yellow. Fertilised seedlings are in right foreground.

Fig. 11.3. Iron deficiency in radiata pine seedlings.

Fig. 11.4. Copper deficiency in radiata pine seedlings.

Fig. 11.5 Zinc deficiency in radiata pine seedlings. View from above showing various degrees of resetting of the terminal buds in zinc deficient plants.

Table 11.5 Visual symptoms of nutrient deficiencies in Douglas-fir. The symptoms are described from seedlings grown for periods of six months or longer (from Walker and Gessel 1991).

Nitrogen	Light green foliage; in severe deficiency, needles are small and yellow, terminal growth is restricted and older foliage turns brown and sheds prematurely.
Phosphorus	Unspecific symptoms characteristic of a mobile element – browning and death of older needles
Sulphur	Upper needles yellowish, older needles green
Potassium	Needle tips become brown, starting in the older foliage, this necrosis progresses back from the tips with severe deficiency
Calcium	Death of terminal buds and some lateral buds
Magnesium	Beginning with older needles, the tips turn brown and there is a yellow region between the brown tip and green basal portion; this progresses until the entire needle is brown.
Boron	Death of terminal buds, foliage exceptionally dark green
Iron	Upper (younger) foliage bright yellow, older foliage remains green

A key for identification of deficiency symptoms in eucalyptus seedlings is given in Table 11.6. The key uses occurrence of symptoms in old or young leaves to separate deficiency symptoms of mobile and less-mobile elements. Photographs of deficiency symptoms in eucalypt species can be found in Dell *et al.* (1995).

Table 11.6. Key for identification of deficiency symptoms in Eucalyptus seedlings (from Brundrett *et al.* 1996).

Symptoms	Deficiency
Symptoms appearing first in older leaves	
Leaves uniformly pale green, then turning yellow.	Nitrogen
Leaves with reddish blotches, or uniform reddish discoloration	Phosphorus
Leaf margins turn yellow then brown as tissues become dry.	Potassium
Leaves yellow with broad dark green veins, especially midrib	Magnesium
Symptoms appearing first on younger leaves	
Leaves uniformly yellow-green	Sulphur
Leaves yellow with narrow green veins	Iron
Leaves yellow-green with broad green veins	Manganese
Leaves small and crowded together on shoots	Zinc
Distorted leaves with corky veins, leaf tips pale green	Boron
Leaves twisted, dark green	Copper
Early death of shoot apex, leaves develop brown margin	Calcium

Fertility Management

Mineral Fertiliser Addition

Once a nutrient deficiency has been diagnosed by one or more of the above methods, it may be corrected by fertiliser application. Amounts of fertiliser that can be incorporated into the soil before sowing to raise soil nutrient status to a satisfactory level are listed in Table 11.7. Liming (see soil acidity below) is also best done before sowing so that the lime can be worked into the soil.

Table 11.7. Rates of fertilisers (kg/ha) that can be incorporated into the soil during seedbed preparation to raise soil status from low or marginal to a satisfactory status (from Knight 1978).

Nutrient required	Fertiliser	Soil status	
		Low	Marginal
P	Superphosphate	500-1000	250-500
K	Potassium chloride	250-375	125-250
Mg	Dolomite	500-750	375-500
Mg	Kieserite	250-400	125-250

Two or more applications of fertilisers may be required during the active growth period to sustain rapid growth, especially on soils with poor nutrient reserves. At the Scion nursery in Rotorua these are applied in early (late December) and late summer (late February) as side dressings between seedling rows to reduce seedling damage by burning (Menzies *et al*. 2005). The granulated compound fertiliser used contains 12%N, 5%P, 14%K, 4%S, 1.2% Mg plus micronutients, and is applied at 130 kg/ha at each dressing. For Douglas-fir, nitrogen should not be applied in late summer-autumn of the second year to ensure a late flush is avoided (Menzies and Brown 2005).

Foliar applications of fertilisers can be used to give a quick response to cure particular deficiencies, but to avoid scorching foliage only weak solutions can be used, and hence limited amounts of nutrient can be applied. Repeat applications at 2-3 week intervals may be necessary to achieve the desired effect. At Scion nitrogen and magnesium are applied at 2.5% (w/v) as urea and magnesium sulphate respectively, while iron is applied at 0.05% (w/v) in chelated form (Menzies *et al.* 2005).

Organic Matter Addition

Organic matter in soils has several important functions. It provides sites for cation exchange, aids soil moisture retention, provides a substrate for soil microbial activity which influences soil structure, and supplies some nutrients. Cultivation increases microbial respiration which depletes organic matter, thus organic matter must be continually added to maintain levels in the soil. Although organic matter is beneficial in soils, trials in nurseries in the UK have shown that high organic matter content is not essential if adequate and sufficiently frequent additions of inorganic fertilisers are made (Van den Driessche 1984) Soil organic matter, however, provides a safety buffer as it moderates changes in soil moisture and nutrient supply; hence it would be unwise to let organic matter levels decline substantially.

Materials that can be added to improve organic matter levels include animal housing waste (pig, horse, fowl manure), crop residues (pea straw) and forest residues (forest duff, sawdust and bark). Alternatively, 'green manuring' may be practiced, whereby tree seedling crops are alternated with crops such as legumes and grasses that are ploughed into the soil. Biomass from such crops tends to decompose rapidly, however, resulting in little long-term effect on soil organic matter levels. Even low-nitrogen materials such as sawdust break down rapidly. As an example it has been calculated (Davey, 1984) that 65 % of sawdust added at 50 tonnes/ha would decompose in the first year and 90% would be gone after two years, giving a residual increase in soil organic matter of 0.25% (soil weight basis). Materials that are low in nutrients (such as sawdust and bark) immobilize nutrients from the soil during decomposition and it is common to add about 10 kg of nitrogen for every 1 tonne of such material applied.

Soil Acidity Management

Soil acidity affects nutrient availability. The optimum pH range for nursery soils seems to be around 5.0-6.0 (van den Driessche 1984). Most macronutrients are most readily available at soil pH values above 6 (phosphorus availability declines above pH 7), but micronutrients are most available in soils with pH values below 5.5. Additionally the activity of damping off fungi increases at high soil pH. Soil acidity generally increases (i.e., pH falls) over time as nutrients are removed in the crop, or by leaching. Fertilisers can affect soil acidity; fertilisers containing ammonium decrease pH (especially ammonium sulphate), calcium and potassium nitrate increase pH, phosphate fertilisers have no effect or increase pH (unless they contain ammonium).

Soil pH may be raised in nursery soils by applying ground limestone. If magnesium is deficient, dolomite (11-13% Mg) can be used instead of limestone. Apart from soils with very coarse or fine textures, lime applications tend to produce similar pH change over a wide range of mineral soils. An application of 10 tonnes/ha of good quality lime will generally raise soil pH by about 1.0 unit. The need for repeat applications can be assessed by periodic (3-4 years) monitoring of soil pH levels.

Conifers tend to become chlorotic in soils of neutral or alkaline pH because of iron (Fig. 12.3) and manganese deficiency; this condition may be induced by over-liming (lime-induced chlorosis) (Will 1985). Soil pH can be reduced by applying elemental sulphur which is converted to sulphuric acid in the soil by bacteria. The amounts needed will vary depending on the soil – van den Driessche (1984) gives examples for Canadian nurseries of 560 kg/ha of elemental sulphur reducing soil pH by about 0.5 units (in the pH 5.5-7.0 range), and 1680 kg/ha reducing the pH by 0.7-0.9 pH units (from pH 5.6). Elemental sulphur is toxic to conifer seedlings at high concentrations and should therefore be applied as long as possible before sowing seed.

Mycorrhizae

Trees require mycorrhizae for survival and growth in all but the most fertile situations so it is essential that seedlings become mycorrhizal with appropriate species in the nursery, before or soon after planting out. Severe chlorosis and poor growth of Douglas-fir has been frequently reported in New Zealand, particularly in the South Island (Gilmore 1958), as a result of nursery stock lacking appropriate mycorrhizae. Gilmore (1958) found the problem could be corrected by puddling seedling roots in a clay:forest duff mixture before planting, or placing a handful of duff (the litter layer plus the upper 0.5 inch of mineral soil from a healthy 23-year-old Douglas-fir forest) in the planting hole. Severe chlorosis in Douglas-fir seedlings in Edendale nursery in 1981-1982 was found to be due to lack of appropriate mycorrhizae – seedlings were mycorrhizal but the fungal species present were ineffective (Chu-Chou and Grace 1987). The problem was corrected by inoculating seedlings in the bed with spores of an effective species (*Rhizopogon parksii*). These experiences indicate that new nurseries, nursery beds that have not had a recent crop of Douglas-fir, and container grown plants, may need to be inoculated with mycorrhizae, particularly if the above symptoms are observed in the nursery (or have been previously observed in seedlings after out-planting). Lack of mycorrhizae has not been reported to be a problem for pines or other exotic forest species in New Zealand.

Mycorrhizal Inoculation

The techniques described below were used for inoculation of radiate pine ─ similar techniques to those described could be used to inoculate Douglas-fir with spores of *R. parksii*. Sporocarps of *R. parksii* are produced under Douglas-fir stands in autumn – nurserymen would need to approach Douglas-fir growers to obtain supplies of sporocarps.

Theodorou (1984) described a technique that was used successfully to inoculate newly established nursery beds of radiata pine at Mt. Gambier, South Australia. Soil was inoculated with a suspension of inoculum of *Rhizopogon luteolus* spores which had been prepared by macerating air-dry sporocarps (fruiting bodies) in water (4 g/l). The suspension contained 4.5 x 10^7 spores/ml and was applied at 350 l/ha and mixed into the soil by raking followed by watering. Beds can be inoculated before or after seedling emergence.

An alternative method of introducing mycorrhizae is to inoculate seed with spores before sowing. This method can be used only where seed is not treated with a fungicide. Theodorou and Benson (1983) described a technique for inoculating radiata pine seed with spores of *R. luteolus*. For this, sporocarps were collected, air dried and stored in a fridge. A suspension of spores was prepared by macerating 100 g air-dry sporocarps in 200 ml of water in a food blender and diluting the suspension to 6 l. This contained 2.9 x 10^8 spores/ml and was used to inoculate 10 kg of stratified radiata pine seed. The seeds were covered with the suspension in a drum and shaken for five minutes, excess suspension was drained, and the seeds were spread on a plastic sheet to air dry before sowing. A spore count showed 1.8 x 10^5 spores/seed. Chu-Chou *et al.* (1978, unpublished) achieved greater numbers of spores of *R. rubescens* on seed (9.0 x 10^6) by initially soaking seed in a 1:500 latex solution for 1-2 minutes. The wet seeds (250 g) were placed in plastic bags containing 100 g of ground sporocarps and shaken until the seeds were evenly coated with spores. The coated seeds were placed on trays and dried in a forced draft oven at 22^{o}C for 22 hours before sowing

Nutrition Effects on Stock Performance after Planting Out

Seedlings produced with good nutrition in the nursery should theoretically survive better and grow faster than seedlings of poor nutrition after planting out in the forest. Nursery fertiliser effects on survival and growth of radiata pine seedlings after planting out at Whakawerawarea Forest were studied by Hunter and Hunter (1987, unpublished). A high fertiliser treatment in the nursery produced seedlings with 50% more top weight and 33% more root weight than a low fertiliser treatment; this translated to a 50 cm height gain at age 2. The well nourished seedlings had better survival in the field, though there was no difference in growth increment between the two treatments. Experience has shown that sturdy plants survive and grow better after planting. For radiata pine, plants should have a height of 20-30cm and root collar diameter of 5 mm for seedlings or 7-8 mm for cuttings (Menzies *et al.* 2005). For Douglas-fir 2-year-old seedlings of 30-45 cm height and 8-10 mm root collar diameter are suggested (Baker and Ledgard 1991).

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12. MATCHING GENOTYPES TO SITES

Summary

- *The use of genotypes that are tolerant of nutrient limitation is one alternative for dealing with forest soils that are deficient in nutrients.*
- *Provenance, family or clonal differences in tolerance of nutrient levels and response to fertiliser have been demonstrated.*
- *New research is being undertaken to further identify potential genetic variation for key nutrient deficiencies in genotypes of radiata pine, Douglas-fir and cypress.*

The use of tolerant genotypes offers one alternative for dealing with forest soils that are deficient in essential nutrients for healthy and productive tree growth. Suitably adapted genotypes might be used exclusively or in combination with fertiliser to enhance nutrient uptake and allow a reduction in fertiliser use. Fertilisation, intensive site preparation and sustained weed control have become common practice in New Zealand, but the use of genotypes that are better adapted to problem soils has received much less attention. It is envisaged that in future forest managers could choose particular genotypes, in conjunction with existing best management practices, for a given site.

Genotypic Variation in Nutritional Traits

Genetic variation in nutritional traits, including: foliar nutrient concentration, nutrient content, tolerance to nutrient deficiency and fertiliser response have been reported between species, and among provenances, families and clones within a species. Examples of within-species variation for radiata pine and Douglas-fir are given in Table 12.1. Such variation indicates the potential for selecting genotypes for nutrient-deficient sites.

Fig. 12.1. Susceptible (left) and non-susceptible (right) clones of radiata pine to magnesium deficiency. Dalethorpe Forest, Canterbury. (Euan Mason)

Table 12.1. Examples of genotypic variation in nutritional traits in radiata pine and Douglas-fir.

Species	Genetic level	Trait or Characteristic	Expression of genetic variation	Reference
Pinus radiata	Provenance	Tolerance of B deficiency	About 25% of 'island' provenance trees showed deficiency. No deficiency seen in Californian or NZ provenances. Deficiency associated with low foliar B.	Burdon & Bannister 1973
	Provenance	Salinity tolerance	Variation in tolerance. 'Cambria' provenance had greatest tolerance, 'Guadalupe' least. Solution culture study.	Cromer *et al*. 1982
	Clone	Tolerance of P deficiency	Clone '72' had good growth on a low P site. Clone '67' was severely depressed on the low P site but showed normal vigour on more fertile sites.	Burdon 1971
	Clone	Foliar N, P, K, Mg and Ca concentrations	Frequent within-site clonal differences. Differences not maintained across sites.	Burdon 1976
	Clone	Foliar nutrient concentrations	A proportion of the variance in foliar concentration was due to clone. The proportion varied from 2% (Cu) to 48% (B)	Knight 1978
	Family	Response to N	Different basal area growth responses to N. Response ranged from 9-99%	Fife & Nambiar 1995
	Clone	Foliar N, P, K, Ca, Mg concentrations and upper mid-crown yellowing	P, K, Ca & Mg concentrations differed between clones. Heritabilities ranged from 0.5-0.62. Clonal differences in foliar Mg, K & N explained a significant amount of clonal variation in upper mid-crown yellowing	Beets & Jokela 1994
Pseudotsuga menziesii	Provenance	Foliar N, P, K, Ca and Mg concentrations	In pot culture, differences in foliar N, P, K, Ca and Mg concentrations among 4 Douglas-fir provenances at 3 years old ranged from 8 to 18%. The differences seemed little affected by N treatment.	van den Driessche, 1973
	Provenance	Growth and foliar N, P, K, Ca and Mg concentrations	In nursery culture, differences in growth and foliar N, P, K, Ca and Mg concentrations were found among 3 Douglas-fir provenances within sites. There was a significant provenance by site interaction.	van den Driessche, 1973
	Provenance	Growth and nutrient uptake response to N	Ashley provenance grew better than Tramway, with a larger difference at low N supply due to an N by provenance interaction. Sand culture. 'Ashley' had a greater ratio of needle to whole plant dry weight, and uptake of N and other nutrients, and allocated a greater proportion of nutrients to	Xue *et al.* 2004

			shoots.	
	Family	Foliar nutrient concentration response to N	Tree growth and foliar nutrient concentrations varied among families No interaction between family and fertiliser response	DeBell 1986
	Family	Growth and nutrient uptake response to N & P application	Nursery culture. Significant interaction between family and N & P for seedling dry weight, but not relative growth rate. Net nutrient uptake rate per unit root dry weight showed small differences among families for N, but large differences for P, with K being intermediate.	van den Driessche & El-Kassaby, 1990

Matching Tree Genotypes to Site Resources – Current Research

A national genotype by environment (GxE) trial series has been established in New Zealand to further identify nutritional variation for key nutrient deficiencies (nitrogen, phosphorus magnesium and boron) in genotypes of radiata pine, Douglas-fir and cypress. The trials have been installed at 14 sites that vary in (1) nutrient and/or moisture supply status, (2) previous land use (ex-forest, ex-pasture) and (3) rainfall. Radiata pine (45 genotypes), cypress (30 genotypes) and Douglas-fir (25 families) are planted as separate trials (in plots) at appropriate sites. The trials are also being used to examine if there are genetic differences between genotypes in their tolerance to water stress.

Fig. 12.2. Radiata pine in a GxE trial located on a nitrogen-deficient sand at Woodhill Forest, Auckland.

Initial results have been obtained from two G×E trials installed in 2002 at Aniseed Valley and Balmoral Forests, in Nelson and Canterbury respectively. The findings for radiata pine genotypes are summarised as follows:

- There were significant site and genotype differences and site by genotype interactions in tree growth. The tested genotypes could be grouped into four categories:
    - potentially tolerant to both nutrient and water stress
    - potentially sensitive to both nutrient and water stress
    - potentially sensitive to nutrient stress but tolerant to moisture stress
    - potentially sensitive to moisture stress but tolerant to nutrient stress.
- Large genotypic variation was found in physiological traits, including needle chlorophyll fluorescence (Fv/Fm, an indicator of photosynthesis efficiency), nutrient concentrations (nitrogen, phosphorus, potassium, calcium and magnesium) and $\delta^{13}C$ (an indicator of water use efficiency) of radiata pine genotypes.
- The were strong positive correlations between genotype means of foliar Fv/Fm and growth parameters (height, diameter or volume) at Balmoral, a summer dry site, indicating that Fv/Fm could be a suitable indicator for screening genotypes with better tolerance to drought stress and growth potential under dry conditions. At Aniseed Valley, a high magnesium site, there were significant correlations between genotype means of growth parameters and foliar concentrations of phosphorus (positive), magnesium (negative) and iron (positive), and between genotype means of height increment and foliar $\delta^{13}C$ (negative).
- At Balmoral Forest, significant positive correlations were found between genotype means of growth parameters and foliar concentrations of phosphorus, potassium, calcium, magnesium and boron, and significant negative correlations were found between genotype means of growth parameters and foliar nitrogen concentration. These results indicate that foliar nutrient concentrations might be suitable indicators for selecting nutrient efficient genotypes to match site resources.

The significant site-by-genotype interactions for tree growth show that genotypes could be selected for local conditions, especially for sites with strong expression of water limitation or nutrient deficiency.

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13. MYCORRHIZAS AND NUTRITION

Summary

- *Mycorrhizas enhance nutrient uptake, water uptake, and may provide some resistance to disease.*
- *There are two main types of mycorrhizas important for plantation forest species – arbuscular mycorrhizas (AM) and ectomycorrhizas (EM).*
- *All pines, Douglas-fir and larch form EM, while the cypresses (macrocarpa, Mexican, Lawson and Leyland cypress) and redwood are important AM species.*
- *Species which form EM have a greater ability to exploit nutrients, especially nitrogen, from soil organic matter than species which form AM, giving EM species an advantage in cooler upland and other environments where organic matter mineralization rates are slow.*
- *The type of mycorrhiza a species develops has management implications for siting, fertiliser requirements, weed control and potential spread as wildings.*

Mycorrhizas are associations between soil fungi and plant roots. Most vascular plants form mycorrhizal associations in which the fungus benefits from photosynthetically derived carbon compounds. In return, the plant gains the use of the fungal mycelium's very large surface area and small diameter that allows penetration of much finer soil pores than root hairs, to absorb water and mineral nutrients from the soil. Additionally, mycorrhizal plants may be more resistant to diseases, such as those caused by microbial soil-borne pathogens.

Mycorrhizal Types

Mycorrhizal associations are characterised by their morphology (Allen 1991, Brundrett *et al*. 1996, Marschener 1995). Several different types of mycorrhizas have been recognised but only two are important in New Zealand tree species, namely ectomycorrhizas (EM) and arbuscular mycorrhizas (AM). EM are characterized by the presence of a mantle of fungal hyphae[2] around the root surface, and hyphae that penetrate the spaces around root cortical cells, the Hartig net, which is the main site for nutrient exchange. In AM, the fungal hyphae penetrate host plant cells and develop structures called arbuscles and vesicles within the root cortical cells. Arbuscles are the main sites of nutrient exchange while vesicles (not present in all AM) are storage organs. Many EM fungi produce conspicuous fruiting bodies, some of which are well known (*e.g., Amanita, Boletus*), or are truffle-like and fruit beneath the soil surface (e.g., *Rhizopogon*). In contrast AM fungi produce inconspicuous fruiting bodies.

Mycorrhizas of Important New Zealand Exotic Tree Species

Many tree species from the northern hemisphere that have become important forest species in New Zealand, including all pines, Douglas-fir and larch, form EM. The cypresses (macrocarpa, Mexican, Lawson and Leyland cypress) and redwood are important AM species. In species of some genera both EM and AM can occur together on the same tree root system – the proportions present may depend on factors such as the soil water content and soil aeration, or the age of the trees (Marschener 1995).

A list of exotic tree species important in New Zealand and their mycorrhizal type is given in Table 13.1. The list includes forest species (including species of minor importance), some common

[2] A **hypha** (plural **hyphae**) is a long, branching filamentous fungal cell. A mass of hyphae is collectively called a mycelium.

amenity (often forest species in other countries) and erosion control species as well as important forest weed species. It is notable that all of the forest weed species listed in Table 1 form AM; the mycorrhizal status of an additional species, Himalayan honeysuckle (*Leycestaria formosa*), has not been reported. Eucalypts, poplars, willows and acacias are examples of species that are reported to form dual mycorrhizas (EM and AM). In the Eucalypts there are reports that seedlings may initially form AM, but these are replaced by EM as they mature (Gardner and Malajczuk 1998), while the significance of EM species in acacias is controversial (Brundrett *et al*. 1996).

Mycorrhizal Type, Tree Nutrition and Distribution

Mycorrhizas and Nutrition

It has long been known that mycorrhizas enhance uptake of mineral nutrients, particularly of phosphorus. Research in the last 20-30 years has shown that mycorrhizas also play an important role in the uptake of nutrients from organic materials. Ericoid mycorrhizas (mycorrhizas associated with ericaceous species) and some EM species have the potential to degrade structural

Table 13.1. Mycorrhizal types of exotic forest, amenity and forest weed species. The list is compiled mainly from Harley and Harley (1987) and Brundrett *et al*. (1996).

Species forming ectomycorrhizas (EM)	Species forming arbuscular mycorrhizas (AM)	Species forming both AM and EM
Forest species		
Pines (*Pinus* sp.)	Cypresses (*Cupressus and Chamaecyparis* sp.)	Eucalypts (*Eucalyptus* sp.)
Douglas-fir (*Pseudotsuga menziesii*)	Coastal redwood (*Sequoia sempervirens*)	Poplars (*Populus* sp.)
Larches (*Larix* sp.)	Blackwood (*Acacia melanoxylon*)	
Amenity species		
Firs (*Abies* sp.)	Ash (*Fraxinus* sp.)	Willows (*Salix* sp.)
Spruces (*Picea* sp.)	Elms (*Ulmus sp*.)	Acacias (*Acacia* sp.)
Cedar (*Cedrus* sp.)	Walnut (*Juglans* sp.)	Alders (*Alnus* sp.)
European Beech (*Fagus sylvatica*)	Maples and sycamore (*Acer* sp.)	
Birches (*Betula* sp.)	*Prunus* sp.	
Chestnut (*Castanea* sp.)	Rowan (*Sorbus aucuparia*)	
Oak (*Quercus* sp.)		
Forest shrub weeds		
	Blackberry (*Ribes nigrum*)	
	Broom (*Cytisus scoparius*)	
	Gorse (*Ulex europeus*)	
	Pampas (*Cortaderia selloana*)	
	Buddleia[1] (*Buddleja davidii*)	

[1]from Dickie *et al*. (2007)

compounds in plant litter and mobilize nitrogen and phosphorus directly from organic polymers, so that they are able to short-circuit the microbial mineralization process. This gives these species an advantage in environments where nitrogen and phosphorus mineralization rates are slow and the availability of these elements is limiting (see Read and Perez-Moreno 2003 for a review). Therefore

EM species should perform relatively better than AM species under the cooler temperatures that occur at higher altitudes and latitudes or at other sites where nitrogen and phosphorus are limiting (Figure 13.1). Thus, the important AM species in New Zealand forestry, namely the cypresses, tend to be restricted to warmer, lower elevation sites and more fertile soils, hence they are commonly referred to as being “site demanding”.

Mycorrhizas of Indigenous Forest Species

Most indigenous New Zealand forest species, including all the podocarps and most angiosperms, form AM. The exceptions are the beeches (*Nothofagus*) which form EM, and two species related to the eucalypts - kanuka (*Kunzea*) and manuka (*Leptospermum*), both of which, like the eucalypts, form AM as well as EM.

The role of mycorrhizas in the distribution of forest species is evident in New Zealand indigenous forests as described by P. Wardle (1964): “The beech species increase in abundance along environmental gradients that lead away from a moist, mild, fertile optimum”; and subsequently by J. Wardle (1984) in *The New Zealand Beeches*, where he stated “…the beech forests are most prevalent at high altitudes, in the drier eastern and central regions of both main Islands, in the south, and on relatively infertile and poorly drained soils. They tend to give way to softwood/broadleaved-hardwood forest at low altitudes, in the moister western and coastal regions, to the north, and on better drained and more fertile soils. The environmental gradients most relevant to the distribution of beech forest are therefore those associated with changes in altitude, rainfall, latitude and soil conditions.” From this, the natural distribution of the podocarp-broadleaved-hardwood (non-beech) species might be used to provide a template for the siting of exotic forest AM species in New Zealand.

Figure 13.1. An AM species out of its comfort zone. Lawson cypress (*Chamaecyparis lawsoniana*) growing in a cool, upland environment near Lake Coleridge, Canterbury, showing yellowing characteristic of nitrogen deficiency because of slow organic matter mineralization. An EM species, Douglas-fir, is growing satisfactorily in the background and not showing deficiency symptoms.

Mycorrhizas, Wildings and Weeds

All of the tree species that spread as wildings of any consequence in New Zealand form ectomycorrhizas (Hunter and Douglas 1984, Ledgard 2004). Ledgard (2004) lists eight species of pine, plus Douglas-fir and larch as being the ten introduced species that contribute most of the wildings currently seen in New Zealand. The main locations where spread occurs in both the North and South Islands are upland (high country) environments. It seems likely that the ability of EM to mobilize nitrogen and phosphorus in these cool environments is an important factor allowing these species to establish and thrive there. All of the forest-weed species listed in Table 1 form arbuscular mycorrhizas. Three of these are confined to lowland environments, while two species - gorse and broom – occur in upland high country environments. It might be hypothesized that the ability of gorse and broom to grow in upland environments is due to the fact that both are efficient nitrogen-fixers. The arbuscular mycorrhizal habit and lack of ability to fix nitrogen suggests that buddleia, pampas and blackberry will not become major weeds in upland environments.

The type of mycorrhizal association is clearly not the only factor determining forest species distribution – numerous other factors such as tolerance to low temperature, out of season frost, drought, and ability to regenerate under forest canopies are also important. These factors, however, may be subordinate to mycorrhizal type in determining species distribution along climatic and soil fertility gradients.

Mycorrhizas and Nutrition Management

The nutritional differences between mycorrhizal types have implications for siting of species at local scales as well as the broad regional, latitudinal and altitudinal scales indicated above. Nutrient availability varies across landscapes. For example soils may be deeper and more fertile on lower slopes, in valley bottoms or at flush sites; these may be sites where the more 'site demanding' AM species are likely to be best located. Mycorrhizal differences also have implications for fertiliser management. A recent study that compared the growth of radiata pine (EM) and Mexican cypress (AM) at 35 sites across the New Zealand plantation forest estate showed that Mexican cypress responded more strongly to fertiliser than pine, the average volume responses of the two species at age four being 54% and 24% for cypress and pine respectively, though the species-by-fertiliser interaction was not significant (Watt *et al.* 2008). These results indicate that the range of planting sites for AM species might be extended by fertiliser application. Similarly, although unknown, weed competition for nutrients may be particularly important for successful establishment of AM species at the nutritional limits of their range, hence attention to very good weed control may be important in extending the range of sites available for AM species.

While EM species may be better able to access nitrogen and phosphorus than AM species, the opposite may be true for the cations potassium, calcium and magnesium. In the study mentioned above, while Mexican cypress contained lower concentrations of nitrogen and phosphorus than radiata pine in the absence of fertiliser, it contained substantially higher cation concentrations, especially of calcium and magnesium (Davis *et al.* 2007). Magnesium is frequently deficient for radiata pine in New Zealand soils, but magnesium fertiliser application is often ineffective in correcting the deficiency (Beets *et al.* 2004). There may be situations where EM species are severely magnesium deficient but where AM species are capable of satisfactory growth and not affected by magnesium deficiency.

Mycorrhizas and Nursery Management

Trees require mycorrhizas for survival and growth in all but the most fertile situations so it is essential that seedlings become mycorrhizal with appropriate species in the nursery or soon after planting. See sub-section on Mycorrhizae in Section 11 'Nutrition management in tree nurseries' for information on mycorrhizal inoculation.

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14. FERTILISATION AND WOOD QUALITY

Summary

- *Nitrogen, phosphorus, potassium, calcium or magnesium fertiliser application, alone or in combination, has little affect on tree form. Nitrogen especially can increase ring width, cause a small, temporary reduction in wood density and reduction in the proportion of latewood in radiata pine and Douglas-fir. Studies of fertiliser application on wood density of plantation-grown eucalypts have produced inconsistent results.*
- *Application of nitrogen and boron has not been found to affect intra-ring checking, and application of nitrogen or nitrogen plus phosphorus has not been found to affect spiral grain in radiata pine.*
- *Some studies have shown fertiliser application reduces tracheid length in radiata pine, Douglas-fir and Eucalyptus, but other studies have shown no affect of fertiliser (nitrogen, nitrogen plus phosphorus, or complete fertiliser) on tracheid length of radiata pine.*
- *Application of nitrogen, phosphorus, or the two nutrients in combination caused a small reduction in modulus of elasticity (MOE) of radiata pine at two sites in Australia. In a New Zealand-wide study, application of a multi-element fertiliser did not significantly influence MOE in either juvenile radiata pine or Cupressus lusitanica.*
- *Fertiliser application with nitrogen and phosphorus may increase formation of compression wood in radiata pine, though this may have little effect on wood utilisation. Fertiliser application may reduce tension wood formation in Eucalyptus.*

Fertiliser application is one of the most important silvicultural practices available to increase economic production of usable wood. It is necessary to understand the impact of fertiliser application on tree form and wood properties as well as wood growth. Although many wood characteristics are genetically-influenced, silvicultural practices and environmental conditions also influence wood properties. The wood properties most influenced by fertiliser application in forests are ring width, the proportion of latewood, fibre characteristics and wood density.

Effect of Fertiliser Application on Tree Form (shape)

Although severe deficiencies of nutrients, especially boron, can cause tree malformation, evidence for changes in tree form as a result of fertiliser application with other nutrients is conflicting in both New Zealand and overseas (Table 14.1). Application of nitrogen to radiata pine seedlings in pots has been found to increase basal diameter in proportion to height (Will 1977), and branch number and growth more than stem growth (Knight 1973, Will 1977). Most field studies have shown either no effect of fertiliser on tree stem form or a small improvement. Few studies have indicated that fertiliser leads to deterioration in form.

Effect of Fertiliser Application on Wood Density and Proportion of Latewood

Radiata pine

Many fertiliser trials in New Zealand and overseas have shown that fertiliser application, especially with nitrogen, considerably increases ring width and also results in small temporary reductions in wood density (Table 14.2). Increases in ring width in response to fertiliser ranged from 10 to 125%, while densities declined by 1 to 21%, with most studies showing declines of less than 10%. Australian studies (Nyakuengama *et al*., 1993, 2002) have similarly shown small (1-5%) density reductions with fertiliser application. Application of fertiliser in the form of biosolids has also been shown to cause a small but significant reduction in wood density (Wang *et al*., 2006).

Table 14.1. Fertiliser effects on tree form.

Species	Location	Fertiliser	Trial details	Form response	Reference
Pinus radiata	North Kaingaroa, NZ	N, P, K, Mg	12 yr old trees, measured 7 yr after application, 1112 sph	No effect on form	Ballard 1971
Pinus radiata	Central Kaingaroa, NZ	N	14 yr old trees, measured 3 yr after application 370 & 620 sph	No effect on form	Mead and Gadgil 1978
Pinus radiata	Jonkershoek, Stellenbosch, South Africa	N, P, K and Ca in factorial combination	11 yr old trees, measured 11 yr after application, 1332 sph	No effect on stem taper	Donald 1976
Pinus radiata	Scarsdale, Victoria, Australia	P	Three 9-18 yr old stands, measured 2-14 yr after application, 1470-1730 sph	No effect on form	Flinn *et al* 1979
Pinus radiata	Central North Island, NZ	N, N K Mg, and N P K Mg	16 yr old trees, measured 2 yr after application, 490 sph	N increased form factor[1]	Woollons and Will 1975
Pinus radiata	Tokoroa, NZ	N, Mg	14 yr old trees, measured 3 yr after application 490 sph	Fertiliser offset a decline in form factor caused by thinning	Barker 1978
Pinus radiata	Harakeke, Nelson, NZ	N, P, K	14 yr old trees, measured 5 yr after application, 420-990 sph	Marked increase in form factor	Barker 1978
Pinus radiata	Belanglo State Forest, NSW, Australia	N, P & K in factorial combination	12 yr old trees, measured 12 yr after application, 1736 sph	Relative diameter in central portion of stem increased	Snowdon *et al*., 1981
Pinus radiata	Murupara, NZ	N	16 yr old trees, measured 2 yr after application, 200 sph.	No change in form	Hunter *et al*., 1985
Pinus radiata	Trials throughout NZ	N, P		P gave a slight improvement in stem form, N a slight reduction in stem form	Gordon and Graham 1986
Pseudotsuga menziesii	Shawnigan Lake, Canada	N	24 yr old trees, measured 9	No effect on stem taper	Thomson and Barclay 1984

			yrs after application, 3353 sph (planted plus natural trees)		
Pseudotsuga menziesii	Victoria, British Columbia, Canada	N	20 yr old trees, measured 3 yr after application, 939 sph (natural stand)	Stimulation of diameter growth in middle to upper stem relative to breast height	Brix and Ebell 1969
Pseudotsuga menziesii	Oregon Coast Range, USA	N	5-65 yrs, wide variety of stands, fertiliser applied every 4 yr	No effect on form	Weiskittel *et al*., 2006
Eucalytus grandis	Louw's Creek, Eastern Transvaal, South Africa	N, P & K in factorial combination	9 yr old trees, measured after application. 2204 sph.	No effect on form	Donald and Schutz 1977

[1] Form factor is volume/m^2 of basal area

In the study of Cown (1972a), nitrogen treatment resulted in a decrease in wood density and the formation of proportionately more earlywood than latewood during the first two-three years after treatment. In another study (Cown 1972b) the average wood density was significantly reduced ($p < 0.05$) by nitrogen application, particularly when combined with phosphorus (or phosphorus and boron), during the first 1-3 years following treatment. After 4-5 years, the wood density in fertilised treatments had reverted to the previous density levels. Nyakuengama *et al*. (2002) found that density reduction in nitrogen fertilised trees was less than in trees fertilised with phosphorus or nitrogen and phosphorus together, and lasted only two years, whereas it lasted five years where phosphorus was supplied with nitrogen.

Table 14.2. Effect of fertiliser on ring width and wood density in radiata pine. Data are averaged across the years after treatment.

Fertiliser	Age (yr) at treat-ment	Years since treatment	Control ring width (mm)	Ring width increase (%)	Control density (kg/m^3)	Density change (%)	Reference Source
N	11	9	3.0	125	590	-10	Cown 1972a
	11	7	3.6	10	588	-5	Cown 1972b
	14	11			521	+0.2	Cown & McConchie 1981
	14	7	4.5	14	587	-1	Nyakuengama *et al*., 2002
	10	4			493	-2	Nyakuengama *et al*., 1993
	6	3			300	-4	Fife *et al*., 1993
	10	7			420	-5	Woollons *et al*., 1995
P	1-2	27			442	+5	Nelson *et al*., 1980

Fertiliser	Age (yr) at treat-ment	Years since treatment	Control ring width (mm)	Ring width increase (%)	Control density (kg/m^3)	Density change (%)	Reference Source
	17	12			442	+1	Nelson *et al*., 1980
	18	11			432	+2	Nelson *et al*., 1980
	14	7	4.5	15	587	-4	Nyakuengama *et al*., 2002
NP	11	7	3.6	33	588	-7	Cown 1972b
	14	7	4.5	28	587	-5	Nyakuengama *et al*., 2002
	14	11			558	-7	Cown & McConchie 1981
	0	4			406	-17	Nelson *et al*., 1980
NPB	11	7	3.6	46	588	-5	Cown 1972b
N P S K Mg Ca	0	8			545[2]	-21[1]	Beets *et al*. 2001

[1] Estimated from graph

In a comparison of 27-year-old radiata pine on a nitrogen deficient coastal dune site growing with or without lupin plus fertiliser (nitrogen, phosphorus, potassium, magnesium and calcium) at Woodhill forest, mean wood density, earlywood density, and latewood density in individual annual growth rings were significantly lower ($p < 0.05$) in treated than in control stands (Beets *et al*., 2001). Mean density was initially similar in all plots, but diverged from stand age 4 to 5 years to give a maximum treatment difference of approximately 100 kg/m^3 by age eight. Foliar nitrogen explained a significant proportion of the variation in both mean and earlywood density of individual rings. Latewood density was related to foliar nitrogen when the stands were less than age nine years at the time rings were laid down. In an analysis over all years, latewood density was significantly related only to tree age ($p < 0.01$). Foliar concentrations of phosphorus, potassium, magnesium, calcium and micronutrients were not related to wood density after the effect of nitrogen was taken into account. The proportion of latewood was significantly ($p < 0.05$) lower (35 vs. 50% at age eight) in fertilised compared to unfertilised stands, particularly prior to age 15. The proportion of latewood was significantly ($p < 0.01$) influenced by foliar nitrogen status and tree age, but not by other nutrients.

Tree nitrogen status is strongly influenced by soil nitrogen fertility, so it is reasonable to expect that trees on more fertile soils, for example on ex-pasture sites, will have a lower wood density than trees on less fertile forest sites with similar climatic conditions (Beets *et al*., 2001). Results of a study involving four-year-old trees and plots located on all the major plantation forest soil types in New Zealand support this suggestion for radiata pine. Wood density in radiata pine was negatively related to soil phosphorus (organic and total phosphorus) and soil nitrogen (total nitrogen), though not in *Cupressus lusitanica* (Watt *et al.* 2008). In this study, densities were 3% and 8% lower in fertilised than unfertilised plots in radiata pine and *C. lusitanica* respectively, but these reductions were not statistically significant.

Douglas-fir

Effects of fertiliser application on wood density of Douglas-fir are similar to those reported for radiata pine. In a 21-year-old Washington stand, Erickson and Harrison (1974) found that fertiliser application (with nitrogen, phosphorus, potassium and calcium), and thinning, caused production of lower density wood and a reduced proportion of latewood. The effects were evident mainly in the first 3-4 years after treatment, after which density returned to normal. At Shawnigan Lake in Canada, Brix *et al* (1993) found that nitrogen fertiliser application increased ring width and reduced wood density in the lower half of the stem for an initial 3-4 year period post-application. The reduction in density averaged 16% and resulted from a decrease in the proportion of latewood. The reduced wood density corresponded to the 3-4 year period of initial increase in foliar nitrogen concentration. The authors concluded that the decrease in wood density and associated wood properties were not related to the increase in ring width.

Eucalyptus

The effect of fertiliser application on wood density of plantation-grown eucalypts has produced inconsistent results across studies. Wilkins and Horne (1991) reported the effect of a number of silvicultural treatments on basic density of 9-year-old plantation-grown *Eucalyptus grandis* trees near Coff's Harbour, NSW, Australia. In that study, the six treatments included: control (C); ploughing + thinning (P); fertiliser + P (F); and fertiliser, weeding, insecticide + P (A). They found that wood laid down after approximately one year was denser in treatments which produced faster growth (A, F) than that from the control. Silvicultural treatments increased mean log density by up to 11% (in treatment F) and mean log volume by up to 270% (in treatment A). Treatments F and A improved the quality of the merchantable log by altering the density distribution within the stem.

Araxa phosphate rock (with or without sulphate and lime), applied to 6-yr-old *Eucalyptus grandis* stands at two experimental plots in Minas Gerais, Portugal, resulted in a non-significant but systematic reduction in heartwood and sapwood densities (Andrade *et al*., 1994).

Despite a considerable increase in growth in response to fertiliser, no fertiliser effect on average wood density was reported in a 30-month-old eucalypt plantation in NSW, Australia (Bamber *et al*., 1982). Similarly, there was no effect of fertiliser application on wood density in one to six year-old *Eucalyptus urophylla* given different nitrogen, phosphorus and potassium fertiliser treatments in Nanjing, Jiangsu Province, China (Luo *et al*., 1999), or in 15-year-old *Eucalyptus saligna* trees on the island of Hawaii, USA (DeBell *et al*., 2001). DeBell *et al* (2001) concluded that diameter growth (hence, productivity) could be increased substantially through supplemental nitrogen and increased growing space without decreasing wood density; moreover, wood density might be slightly increased with additional growing space.

The apparent inconsistency of fertiliser effect on wood density in eucalypts may be related to an interaction between silvicultural treatment and the environments used for the trials. Fertiliser might increase wood density if there was enough available water to promote growth during the development of dense latewood, but might decrease average wood density or have no effect if water limits later development and the ratio of late/early-wood decreases, or remains unchanged (Goncalves *et al*., 2004)

Effect of Fertiliser Application on Intra-ring Checking

In New Zealand, internal checking occurs in radiata pine. Internal checking appears to arise following collapse of cells with insufficient cell wall strength to withstand tension forces associated with wood drying. In a Central North Island trial, the application of 200 kg N/ha fertiliser in spring immediately following thinning had no significant effect on internal checking (Kimberley *et al.,* 2002).

In two boron fertiliser trials located at Balmoral Forest (North Canterbury) and Lake Taupo Forest, effects of boron fertiliser rate, genotype and site on internal checking of radiata pine were assessed in plots without weed control (Xue *et al.*, 2004). Under these conditions, boron fertiliser significantly increased foliar boron concentrations, but had no significant effect on wood properties, and was ineffective at reducing the severity of internal checking.

Effect of Fertiliser Application on Resin Pockets and Wood Blemishes

Resin pockets and wood blemishes occur in radiata pine and have the potential to cause significant degrade in otherwise high value clearwood products. Clear links between external resin bleeding (Fig 14.2) of standing trees and clearwood quality and value have been established in recent studies (e.g., McConchie *et al*., 2003).

Fig.14.2. External resin bleeding in radiata pine.

The causes of resin pockets and blemishes in radiata pine are complex and poorly understood. Cown and McConchie (1981) found no significant effect of nitrogen or nitrogen plus phosphorus fertiliser on resin content 11 years after fertilisation of a 14-year-old radiata pine stand in Tasman Forest, Nelson. Some preliminary results of the effect of boron on resin bleeding have been obtained from a trial at Puruki Forest, and from a boron fertiliser trial at Balmoral Forest, Canterbury. At Puruki, foliar boron concentration was significantly correlated ($p < 0.05$) with external resin bleeding when family means were used. However, the correlation was weak ($r = 0.31$) and not evident for clone means (Beets *et al*., 2003). At Balmoral, from survey results in 2006, boron fertiliser application caused a small reduction in external resin bleeding (Fig 14.3) (Xue, unpublished data).

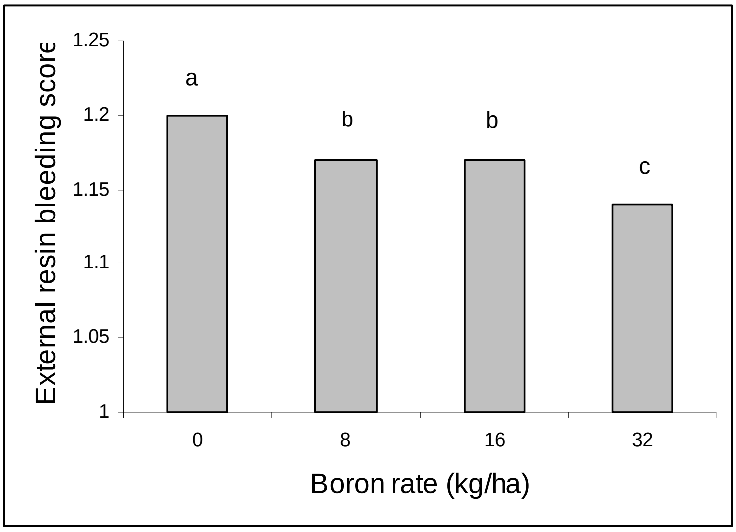

Fig. 14.3 Effect of boron fertiliser rate on external resin bleeding of radiata pine at Balmoral Forest, Canterbury. Treatments without a letter in common are significantly different at $p < 0.05$.
Note: External resin bleeding (ERB) is assessed on a 0-3 scale (McConchie, 2003). 0, no ERB; 1, <10% ERB; 2, 10-40% ERB; 3, >40% ERB.

Effect of Fertilisation on Fibre Properties

Wood fibre properties influence the quality of wood and paper products. For example, a minimum fibre length is required to make paper of acceptable tear strength, and there is a strong correlation between fibre length and tear index (Watt *et al*. 2008). It is expected that tracheid (fibre) length would shorten when growth rate is rapid (such as following thinning and fertiliser application) due to increased anticlinal division of cambial initials (Choong *et al*., 1970). Reductions in tracheid length following fertiliser application have been reported for eucalypt (Higgs, 1973), Douglas-fir (Erickson and Harrison, 1974) and radiata pine (Cown, 1977). Cown and McConchie (1981) found no significant effect of nitrogen or nitrogen plus phosphorus fertiliser on tracheid length, eleven years after fertilisation of a 14-year-old radiata pine stand in Tasman Forest, Nelson. Similarly, from a New Zealand-wide set of 22 plots where *Pinus radiata* was established at high stand density (40 000 stems/ha) and grown over a period of four years, it was found that fertiliser application did not significantly affect fibre length for two age classes of rings (rings 1-2 and rings 3-4) despite its significant effect on tree growth rate (Watt *et al*., 2008a).

Effects of nitrogen and phosphorus fertilisers on average fibre radial diameter, tangential diameter, wall thickness and number of fibres per unit area were studied over seven years of growth after treatment in three mid-rotation radiata pine plantation trials in Australia (Nyakuengama *et al*., 2003). Nitrogen treatment did not significantly affect the number of fibres per unit area or their radial diameter. In contrast, phosphorus addition reduced the number of fibres per unit area and increased their radial diameter, although the effect was small (Table 14.3). The treatments had no effect on the tangential diameter of fibres, but significantly reduced ($p < 0.05$) fibre wall thickness. Nitrogen treatment significantly reduced ($p < 0.05$) fibre coarseness (Table 14.3). The response in ring width (Table 14.2) and fibre properties peaked at two years following fertiliser application and gradually disappeared after 4-5 years. The changes in fibre anatomy were much smaller than those in ring width.

Table 14.3. Effect of fertiliser application on fibre properties of radiata pine. Values with the same letters in the same column are not significantly different (p < 0.05). Percentage changes relative to the control are indicated (Nyakuengama *et al*., 2003).

Treat-ment	Number of fibres per unit area		Fibre radial diameter		Fibre tangential diameter		Fibre wall Thickness		Fibre coarseness	
	n./mm^2	% change	µm	% change	µm	% change	µm	% change	µg/m	% change
Control	1069ab		32.35b		29.30ab		3.28a		526a	
N	1093a	2	32.02b	-1	29.01b	negligible	3.21b	-2	511b	-3
P	1034c	-3	33.22a	3	29.39a	negligible	3.18b	-3	522ab	-1
NP	1060bc	-1	32.93a	2	28.95b	-1	3.09c	-6	503c	-4

In *Eucalyptus grandis* in Portugal, Andrade *et al*., (1994) found that fibres had a smaller diameter and fibre walls were thinner in trees treated with phosphate and gypsum. Trees treated with lime had fibres and vessel elements of larger diameter, and thicker fibre walls.

Effect of Fertiliser Application on Modulus of Elasticity

The modulus of elasticity (MOE) is a measure of the resistance of wood to deformation under an applied load. It is used as a threshold criterion in machine stress grading of structural timber and is also a key property for determining quality of laminated veneer lumber. In radiata pine, MOE is a useful indicator of corewood quality and is often considered more important than strength (modulus of rupture) for predicting wood quality (Walford, 1985).

Addition of fertiliser induced a small but significant reduction in MOE (and lower density and higher microfibril angle as well) of radiata pine at two sites located at Longford (age 14) in south-east Gippsland, Victoria and Carabost (age 17) in north-west of Tumbarumba, NSW, Australia (Downes *et al*., 2002). In a series of plots established at sites encompassing the range of climatic and soil conditions for radiata pine in New Zealand, application of a multi-element fertiliser did not significantly influence MOE in either juvenile radiata pine or *C. lusitanica*, despite its significant effect on growth rate (Watt *et al*., 2006, 2008b). These authors also found that MOE was relatively insensitive to considerable increases in soil concentrations of Bray and Olsen extractable phosphorus, inorganic phosphorus and exchangeable potassium.

Effect of Fertiliser Application on Reaction Wood

According to Timell (1986) fertiliser application does not normally affect production of compression wood. However, Cown and McConchie (1981) found that nitrogen and phosphorus fertiliser application increased basal area growth, and the proportion of compression wood in 14-year-old radiata pine in Nelson, when measured 11 years after application. The growth response to fertiliser and increased formation of compression wood were closely related. As the increased compression wood did not lead to abnormal shrinkage, it was concluded that it would have little practical effect on wood utilisation.

Washusen *et al*., (2005) found that cellulose crystallite width increased with thinning intensity and this was mitigated when fertiliser was applied at the time of thinning. As there is a positive relationship between crystallite width and tension wood occurrence, the results demonstrate that heavy thinning of *E. globulus* at this age can contribute to tension wood formation. However, tension wood production may be greatly reduced where fertiliser is applied. This is possibly because increased diameter growth as a response to fertiliser application stabilises the stems enabling the trees to cope with internal stresses that are generated from wind in destabilised stands following thinning.

Effect of Fertiliser Application on Spiral Grain

Cown and McConchie (1981) found no significant effect of nitrogen or nitrogen plus phosphorus fertiliser on spiral grain 11 years after application to a 14-year-old radiata pine stand in Tasman Forest, Nelson. Similarly, Dumbrell and McGrath (2000) also found no effect of nitrogen fertiliser on spiral grain on radiata pine in south-western Australia. The authors concluded that accelerated growth in the first ten years will not adversely affect wood quality by increasing spiral grain angle.

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