2 Site requirements

Deciding what should be planted on a given site and determining an optimal site for a chosen species – such as radiata pine – are two significant but distinct issues for foresters. In the latter case, if there is freedom to choose among several locations, there will be additional factors to evaluate that could influence economics or other criteria set by the owner.

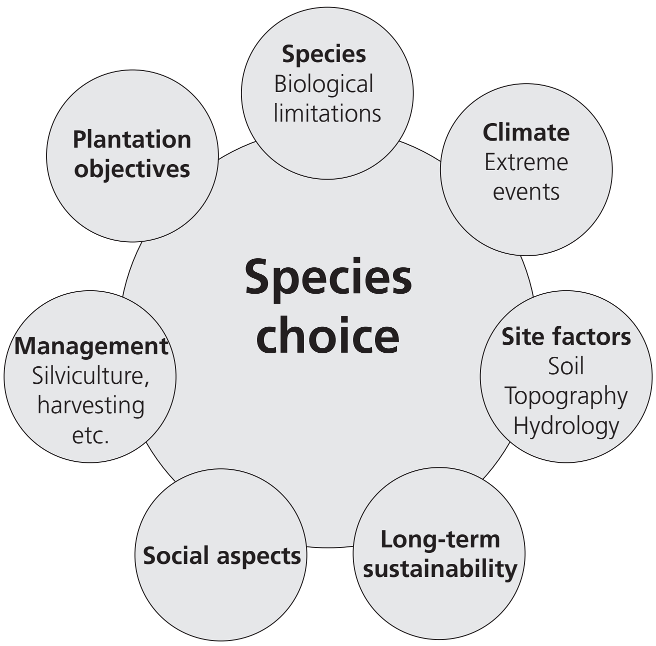
Radiata pine has proved to be a very adaptable species in its main adopted countries. It is often planted on a wide range of sites with seemingly little regard to its ecological niche. However, its history of successes and failures shows that there are places where it should not be planted and other sites where it is ideal. This chapter concentrates on physical or abiotic factors, while the next chapter looks at pests and diseases. These issues are often linked, because insects and diseases can become limiting factors if trees are planted on sites that stress them. Competing ground vegetation, a site factor that also limits growth, is covered in Chapter 8.

The abiotic factors that affect tree growth include variables such as climate, topography and soil. Of these, only factors related to soil can be altered appreciably by managers in ways to improve tree growth; a manager's influence on large-scale climatic factors is minimal, although microclimate can be changed to a limited degree. Nevertheless, the negative impacts of climate change and other biotic damage can be managed to some degree.

MATCHING SPECIES TO SITE

Before looking at radiata pine in detail, it is useful to summarize the principles of matching species to site. The main factors to consider are the biology of potential species, site attributes, plantation objectives and management, environmental and social aspects, and sustainability (Figure 2.1). For any given site, the choice is usually

FIGURE 2.1
The interaction of factors affecting the choice of tree species



limited. However, the following points should always be considered:

- the suitability of the species for the site;
- extreme events as well as climatic averages (e.g. a 1-in-20-year frost could wipe out a stand);
- species that grow naturally on similar sites or that others have found successful;
- why the trees are being planted;
- for commercial plantations, issues related to markets, roading and harvesting requirements (for example, there are sites in New Zealand where radiata pine plantations will never be able to be economically harvested);
- the silvicultural and management implications of your choice;
- written material, computer information packages and the knowledge of experts.

CLIMATIC LIMITATIONS

Natural habitat

The natural populations in California and on the Mexican islands have been described as Mediterranean and maritime in nature. The climate is strongly influenced by the Pacific Ocean and the cold south-flowing currents. This results in an even climate, with summer fogs on at least 120 days per year, and cool summer temperatures (McDonald and Laacke, 1990; Lavery and Mead, 1998). Mean monthly temperatures are in the range 9–11 °C in winter and 16–18 °C in summer. Extreme temperatures range from -5 °C to 41°C, and there are about 300 frost-free days per year.

Rainfall averages 380–890 mm per year but varies greatly from year to year. Winter, from December to March, accounts for 60–80 percent of annual precipitation. July and August are typically dry, although summer fog drip can reach 15 mm per week at higher altitudes. Indeed, all natural radiata pine stands in California are within the fog zone; beyond this, the summer drought is too severe and radiata pine gives way to oak woodlands. No snow falls in the natural range of radiata pine. Año Nuevo is the wettest of the three mainland locations, Cambria is the driest and Monterey is the foggiest.

The two island populations, Cedros and Guadalupe, experience typically Mediterranean climates, with greater drought and temperature extremes compared with the mainland populations. Since radiata pine occurs on these islands at an altitude above 290 m, it is thought that summer fogs are of great importance to the species' ecology.

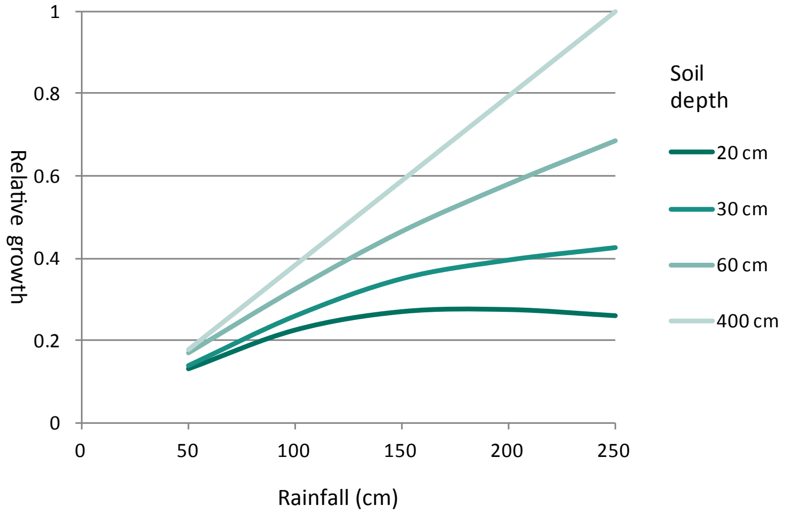
Exotic plantation experience

Radiata pine plantations have been established in a wide variety of climatic types but have only been successful in temperate areas where the summers are relatively dry. Most Australian, Chilean and some Spanish plantations occur in a Mediterranean climate. The northern New South Wales plantations tend more toward summer rainfall, while the southeastern plantations have a uniform rainfall pattern. Galicia in Spain and the Valdivia area of Chile are temperate-oceanic in nature, but with rainfall concentrated in the winter months. The New Zealand climate is more varied, ranging from subtropical in the north to more temperate further south. Rainfall in New Zealand is highly variable and often evenly distributed throughout the year, although summer drought is not uncommon.

Radiata pine does not tolerate damp summer heat, which renders it susceptible to fungal pathogens (Lewis and Ferguson, 1993; Lavery and Mead, 1998; Burdon, 2001). Attempts at planting radiata pine in Uruguay, Brazil, Venezuela and the eastern United States were abandoned because of the moist, warm summers.

General experience suggests that productivity falls off in areas receiving less than 1 000 mm annual rainfall, although radiata pine has been grown successfully in areas

FIGURE 2.2
Radiata pine relative growth rate in relation to rainfall and soil depth



10 CM DEPTH LINE HAS BEEN OMITTED.
SOURCE: BASED ON JACKSON AND GIFFORD, 1974.

receiving as little as 500 mm. Commercial plantations require a minimum annual rainfall in the range 600–750 mm. In temperate locations that are unlikely to have seasonal water deficits, the optimal average annual rainfall is 1 500–2 000 mm (Kirschbaum and Watt, 2011). Rainfall and rooting depth interact strongly (Figure 2.2) because they influence root-zone water storage (Jackson and Gifford, 1974; Watt *et al.*, 2008a, 2010). *Dothistroma* needle blight becomes prevalent above an average annual rainfall of about 1 400 mm and is often serious where rainfall exceeds 2 000 mm per year (see Chapter 4).

Although radiata pine prefers a drier summer environment, severe summer drought or soil moisture deficits may cause establishment problems. Stands may also be prone to repeated dieback. A good example of this is in the Blackwood Valley region of Western Australia, which has a mean annual rainfall of 850–1 080 mm, but where only 10 percent of this falls during the five summer months. There, tip dieback and mortality have sometimes been very high in drier years, particularly where soils are shallow, such as on upper and northeasterly slopes (Figure 2.3).

FIGURE 2.3
Drought deaths in a radiata pine stand in the Blackwood region of Western Australia

FIGURE 2.4
Severe defoliation due to abnormal climatic events in New Zealand causing physiological drought

Occasional episodic defoliation (physiological needle blight) of radiata pine stands on both the North Island and the South Island of New Zealand has been attributed to water stress (Gould, Bulman and Dick, 2008; Bulman, Ganley and Dick, 2008). Rapid changes in relative humidity in winter/early spring have resulted in needle death in mid-rotation radiata pine stands (Figure 2.4). Such outbreaks have usually affected less than 5 000 ha (L. Bulman, personal communication, 2012).

Extremes often control where a species can grow. Frost studies suggest that radiata pine seedlings may tolerate temperatures ranging from -3 °C to -6 °C in summer and -12 °C to -14 °C in winter (Burdon, 2001). This tolerance can be increased by conditioning in nurseries (see Chapter 7). There are also genetic differences between provenances (Año Nuevo is the most tolerant geographical seed source) and families. The extremes where it is commonly grown have absolute minimum temperatures of -10 °C. In 1956, severe cold (-10 °C to -15 °C) killed 25 000 ha of radiata pine in coastal Gipuzkoa, Spain (Allen, 1973). This was due to a continental cold air mass in February that struck after the trees had flushed. Similarly, temperatures ranging from -6 °C to -22 °C killed 30-year-old radiata pine trees in Oregon, United States.

The tolerance of radiata pine to cold differs from that of many other conifers because it is a polycyclic species (also called a multinodal habit) that is adapted to grow throughout the year if the climate is suitable (see Chapter 5). Juvenile radiata pine does not form a dormant bud like cold-climate pines such as *P. contorta* and *P. sylvestris*. These latter species can survive much colder winter conditions but are more susceptible to unseasonal frosts.

Temperature is a major factor controlling growth rates, as shown by site-growth modelling studies and other experiments (Madgwick, 1994; Gerding and

TABLE 2.1
General climate profiles for radiata pine and *Pinus taeda* developed for models used to select regions to grow these species

Profile descriptors	*P. radiata*	*P. taeda*
Mean annual rainfall (mm)	650–1 800	900–2 200
Rainfall regime	Winter; uniform	Summer; uniform
Months dry season (<40 mm rain)	0–5	0–2
Mean annual temperature (°C)	11–14	14–20
Mean maximum temperature hottest month (°C)	18–30	20–25
Mean minimum temperature coldest month (°C)	-2–12	4–18
Absolute minimum temperature (°C)*	≥ -11	≥ -5

* Not used in some models because data not always available.

Source: Based on Jovanovic and Booth, 2002: Booth, Jovanovic and New, 2002; Yan *et al.*, 2006

Schlatter, 1995; Watt *et al.*, 2008a, 2010; Kirschbaum and Watt, 2011). Radiata pine prefers cool night temperatures of about 5 °C and a maximum photoperiod temperature of approximately 20 °C (Rook and Whitehead, 1979). Shepherd (1995) found that ambient field temperatures of about 10–24 °C gave the best diameter growth. In a New Zealand-wide study, the optimum mean annual air temperature was in the range 12–15 °C (Kirschbaum and Watt, 2011). A high incidence of frost in autumn also leads to decreased growth, most probably because it reduces the length of the growing season (Watt *et al.*, 2010).

Models have been developed to assist in the selection of species (Booth, Javonvic and New, 2002). These are based on climatic profiles for areas where the species have been grown successfully. The climatic profiles of radiata pine and loblolly pine (*Pinus taeda*) in Table 2.1 illustrate how these two pine species are suited to different types of climate. Radiata pine prefers winter rainfall and drier summers and tolerates lower temperatures than loblolly pine.

Other abiotic factors

Hail and snow can limit site suitability for radiata pine. In South Africa and Australia, hail is a major limiting factor; it often results in dieback from subsequent infection by *Sphaeropsis sapinea* (see Chapter 4). In New Zealand and parts of Australia, snow has caused considerable damage, toppling young trees and breaking crowns in older trees. Planting on snow-prone sites, particularly on the leeward side of ridges, should be avoided.

Wind is one of the greatest risks to plantations (Figure 2.5). In New Zealand, for example, wind damages about 1 000 ha of plantations each year, which is equivalent to 2.7 percent of the annual harvest (McFarlane, Pearce and Moore, 2002). Even so, it is considered to be a lesser risk to pine plantations than fire. The following points can be made:

- While it is easy to see that wind is a limiting factor, the nature of the damage that occurs and the factors that predispose radiata pine stands to damage are complex.
- Wind can result in leaf damage, broken branches, stem malformation from leader loss, compression wood formation, resin pockets, toppling and butt sweep in young stands, and bending, windthrow and breakage of older trees.
- Windthrow is more severe if soils are saturated or shallow. Breakage (usually at mid-stem and sometimes associated with forks or very heavy whorls) is more common where deep rooting occurs.
- Severe wind damage has been reported in radiata pine plantations at wind speeds of 50–170 km per hour, but well-managed radiata pine shelterbelts are often stable at higher wind speeds.

- Topography, soils, stand layout and silvicultural and harvesting practices all influence the level and type of damage.
- Growth rates, as measured by site index, are linearly reduced by increasing mean annual wind speed (Watt *et al.*, 2010).

The risk from windthrow can be reduced by selecting planting sites that have low wind conditions. Thus, planting should be avoided in places where wind funnels between mountains, on very exposed ridges, or in areas of wet or shallow soils that cannot be ameliorated. Stand edges that are newly exposed by logging are often prone to windthrow (Figure 2.6), but this can be reduced by the careful planning of logging operations. Planting aged cuttings and reducing crown size by judicious pruning can be used to reduce toppling risk in young stands (see Chapter 8), while thinning practices can also be altered to reduce windthrow following this operation (see Chapter 9). Management can reduce the risks from a single major event by ensuring a normal age-class distribution.

Sporadic, scattered damage from lightning strikes sometimes occurs but cannot be considered a limiting factor, although relatively large groups of trees can be affected. Lighting strike can be identified by ruptured bark strips on the stem. Trees struck directly by forked lightning usually die.

Radiata pine is reasonably tolerant to salt spray, as its natural habitat is close to the coast. Edge trees can sometimes show salt burn, but trees four or five rows back are less affected. Commercial radiata pine plantations have been used extensively to stabilize coastal sand dunes in New Zealand.

Stem sunscald occurs on some sites in Chile and Australia. Frequently it is found on pruned edge trees and typically the damage occurs at maximum insolation in mid afternoon (Figure 2.7; Huber and Peredo, 1988). Stem sunscald causes cambial death and may subsequently lead to blue stain infection by *Sphaeropsis sapinea*.

FIGURE 2.5
Windthrow in a radiata pine stand the Nelson region of New Zealand

FIGURE 2.6
Stand edge windthrow following logging, which could have been avoided by careful planning

FIGURE 2.7
Sun-scald on radiata pine, Western Australia

PHOTO: RAY FREMLIN

FIGURE 2.8
Fire damage to young stand of radiata pine

Fire

In its native Californian habitat, radiata pine grows in a fire-adapted ecosystem because of repeated fires associated with the activities of Native Americans. In particular, fire has resulted in thicker bark on mainland populations compared with island provenances (Stephens and Libby, 2006). In Australasia, radiata pine is considered to be more fire-sensitive than *Pinus elliottii*, *P. pinaster* and *P. caribaea* (Forest Fire Management Group, 2007). Crown scorch reduces growth rates and can kill trees. However, it is possible to carry out fuel-reduction burns under older trees if the fires are low intensity (200–300 kW per m) and the duff (the heavier forest floor material) does not ignite.

The annual loss to fire recorded in New Zealand over 60–70 years has been about 0.12 percent of the estate, although this has fallen to about 0.03 percent in the last two decades, partly as a result of improved management practices (Pearce *et al.*, 2008; Figure 2.8). The annual cost of fire protection is about NZ$12 (US$8) per ha. The principal causes of plantation fire are arson, escaped burns, forestry operations, spontaneous combustion, vehicles and campsites, with fires started outside the plantations themselves posing the biggest risk. Fires in plantations only account for about 6 percent of the total area burnt in rural areas. In terms of risk, the New Zealand forest industry rates fire lower than wind but greater than pests and diseases (McFarlane, Pearce and Moore, 2002). Fire risk is lower in wetter regions, but some areas of New Zealand are predicted to be at considerably greater risk of fire due to climate change (Pearce and Clifford, 2008).

Large wildfires, which are relatively frequent in Australia, are not typically associated with softwood plantations, although they can be affected by them. Incomplete data on forest fire in Australia suggest that fire losses in softwood plantations range from 0.1 percent per year in South Australia and Tasmania to 0.4 percent in Western Australia (Forest Fire Management Group, 2007). Nevertheless, fire is an important threat to Australian pine plantations and is expected to become a greater risk as a result of climate change (Singh, Davey and Cole, 2010). A model of fire behaviour in radiata pine plantations and a guide to the susceptibility of fire in various ages and conditions of radiata pine plantations have been published (Cruz, Alexander and Fernandes, 2008; Cruz, de Mar and Adshead, 2011).

In Chile, fire destroys an average of about 7 000 ha of radiata pine plantations per year (Raga, 2009), which is about 0.5 percent of the country's radiata pine estate. Fire is also a major threat to Spanish plantations and it has been recommended that silviculture be modified to reduce the impact, including as it relates to the use of grazing animals (Fernández and Sarmiento, 2004; Pasalodos-Tato *et al.*, 2009). Recent fires have had a minimal impact on radiata pine plantations in South Africa, although they have affected other plantation species in the country (Forestry Technical and Information Services, 2009).

Latitude and altitude

Latitude and altitude are poor guides to where a species should be planted; climate arguably plays a more critical role. However, climate is inherently related to these two factors because temperatures are lower and the climate is often more extreme at higher latitudes and altitudes. Thus, in Chile, latitude was an important variable in explaining site quality (Gerding and Schlatter, 1995).

Natural stands of radiata pine occur at 35.5–37°N latitude on mainland California and 28–29°N latitude on the islands. In the main grower countries, the bulk of plantations and optimal growth rates are found at similar latitudes to the California stands, but there are contexts in which the species is planted successfully outside this range. For example, in Ecuador the species has been planted close to the equator at an altitude of about 3 000 m and, in Argentina, it has been planted as far south as 50°S. The majority of plantations in the Southern Hemisphere are at latitudes between 34°S and 42°S, while the Spanish plantations are between 42°N and 43.5°N.

Limits to the altitude at which radiata pine can be planted safely are sometimes prescribed because of the risk of snow damage and cold. For example, in New Zealand these limits are approximately 1 000 m in the central North Island (latitude 38°S to 39°S), decreasing to less than half this in some parts of the South Island (latitude 46°S). In Spain, radiata pine is planted below 800 m, and optimum growth is obtained at 200 m where the climate is Mediterranean (Romanyà and Vallejo, 2004).

Both latitude and altitude influence wood properties. The outer wood density of radiata pine decreases by about 7 kg per m^3 for each 100 m rise in altitude or each 120 km change in latitude (Cown, 1999). Other wood properties also change (see Chapter 5).

Aspect

Aspect can influence growth patterns, primarily because it alters the amount and pattern of radiation. In the Southern Hemisphere, north-facing slopes are warmer than south-facing slopes. East-facing slopes receive more morning sun, while the west receives afternoon sun. At the southern latitudes at which the species is planted, northwesterly aspects are often more exposed to high winds than are other aspects.

The resulting changes to tree growth can be more complex, however, since aspect can interact with moisture stress and other climatic factors such as drying winds or the direction of wind-driven rain or snow. The complexity of such relationships is illustrated by a study in Chile that surveyed growth on a strip of land in a narrow latitudinal range that ran from the coast to an altitude of 1 000 m and descended into the Central Valley (Ruiz and Schlatter, 1985). On the coastal side of the hills, growth diminished with altitude; northerly aspects were more favourable at low and high altitudes and southerly aspects were best at intermediate altitudes. On the western Central Valley side of the coastal hills, growth was better at higher altitudes, partly because of a rainfall gradient and soil factors. Again, the effects of aspect varied with altitude.

Potential impacts of climate change

The polycyclic nature of radiata pine enables it to respond readily to changes in climate. Predictions for California suggest that the natural coastal sites will witness a rise in temperature of 2–4 °C in winter and 2–7 °C in summer (Hayhoe *et al.*, 2004). Rainfall will change relatively little. Based on plantation experience, these changes in themselves will not generate great concern. However, the impact of climate change on fog and the balance between oak and radiata pine forests is less clear, although there is evidence of less fog in recent years (Johnstone and Dawson, 2010). Urban development, fire and invasive organisms may be greater threats to the natural stands than climate change.

Both New Zealand and coastal Australia are predicted to experience small but increasing temperature rises with generally fewer frosts, longer growing seasons, a greater number of hot days and changing rainfall patterns (Watt *et al.*, 2008b; Battaglia *et al.*, 2009). Depending on the extent to which increased concentrations of atmospheric carbon dioxide (CO_2) improve growth rates, it is likely that radiata pine growth rates will increase in most areas of New Zealand (Mason, 2009). In Australia, however, growth rates are expected to decrease because of reduced rainfall (ABARES, 2011a). In some areas, droughts will cause greater stress and could lead to more dieback or damage by *Sirex noctilio* (see Chapter 4). In New Zealand, wind damage is expected to become a bigger problem, as is the severity of *Dothistroma septosporum* in areas with increased rainfall. Snow damage might be reduced in New Zealand, although confidence in the prediction of decreased snowfalls is low.

In Chile, the climate is expected to become drier in the northern part of the radiata pine range, but changes to the climate may better suit the species in the south. In the longer term, this will influence where radiata pine is planted and overall may lead to reduced productivity. In Spain, increased temperatures are likely to have a positive impact, although more unstable weather patterns could create problems with wind damage, fire, disease and insects.

The increasing cost of energy, the need to shift to renewables, and climate change itself, are likely to alter radiata pine management. A long-term strategy is required to preserve the gene resource in natural stands in California and Mexico (Rogers, 2004) and *ex situ* (Gapare *et al.*, 2012). Management changes in response to climate change could include the following:

- The development of emissions trading schemes and carbon (C) markets could increase the returns from radiata pine plantations and lead to longer rotations with higher stockings (Manley and Maclaren, 2012);
- The development of bioenergy markets could result in the greater use of wood wastes and alter silviculture, again to favour higher numbers of trees per ha, which would accentuate volume production.
- Forest management could be adapted to ensure energy use is optimized (Mead and Pimentel, 2006).
- Tree breeding programmes could be adapted to produce genotypes that will cope better with drought and disease and can make efficient use of higher concentrations of atmospheric CO_2.

Radiata pine afforestation can lead to increases in soil carbon on low-carbon soils such as recent soils or arable land, but on grasslands it can result in decreases in soil carbon and in some cases this decrease can be substantial (Mead, Scott and Chang, 2010; Chapela *et al.*, 2001). Afforestation also leads to change in the albedo, which partly offsets the additional carbon storage (see Chapter 3).

EDAPHIC LIMITATIONS

In its natural mainland California habitat, radiata pine grows on a range of soils and parent materials but, in general, the best growth occurs on deep sandy loams derived from marine sediments and with a thick duff layer (McDonald and Laacke, 1990).

Most sites are on sloping ground and are reasonably well drained. There may be a clay layer at 50–85 cm, which assists in moisture storage. Mycorrhizal roots exploit this layer. The soils are generally acid to strongly acid. Inferior growth is found on thin, podzolized soils with poorer drainage.

In the Southern Hemisphere plantations, radiata pine has proved adaptable to a wide range of soils, from recently formed sand-dunes and volcanic soils to older leached red earths and podzols (Turner and Lambert, 1986). Deep soils with gradational profiles (in texture, pH, etc.), high biological activity, good drainage and stable microstructures are often associated with high productivity. In Spain, the species has been planted on a wide range of soils, with pH ranging from <4.0 to neutral (Romanyà and Vallejo, 2004; Afif-Khouri *et al.*, 2010). Radiata pine does not tolerate very wet soils (wet feet), salinity or highly calcareous soils. Numerous studies have shown that soil groups and parent materials are useful indicators of radiata pine productivity (Turner and Lambert, 1986; Gerding and Schlatter, 1995; Toro, 2004; Romanyà and Vallejo, 2004; Ross *et al.*, 2009; Watt *et al.*, 2010).

Physical properties of soil

Soil depth, texture, drainage characteristics and soil moisture storage have all been found to be important determinants of radiata pine growth because they influence soil moisture and nutrient storage (Madgwick, 1994; Gerding and Schlatter, 1995; Romanyà and Vallejo, 2004; Watt *et al.*, 2008a). The species prefers deep, well-drained soils. The interaction of rooting depth with rainfall, illustrated in Figure 2.2, shows that on soils greater than 60 cm in depth, volume increment increases with rainfall. On shallow soils, in contrast, water logging results in decreased growth when rainfall exceeds 1 500 mm (Jackson and Gifford, 1974).

Radiata pine growth is also influenced by soil bulk density, or soil porosity and the degree of soil compaction. For radiata pine, growth has been reported to decrease with bulk densities above 1.25 tonnes per m^3; 64 percent porosity is considered optimal (Madgwick, 1994; Watt *et al.*, 2008a). Penetrometers have frequently been used to measure soil strength. Radiata pine rooting density decreases rapidly when soil strength is above 3 000 kilopascals (Greacen and Sands, 1980; Madgwick, 1994). This critical value is often used in studies on the effects of soil compaction by logging and when deciding whether to improve the site to ensure good tree growth (see Chapter 8).

Nutrient stresses

Nutrient stresses in radiata pine first became apparent in Australia, New Zealand and South Africa in 1910. Early reports described problems including yellow needles, dieback, rosetting, needle fusion and thin crowns. Zinc and phosphorus deficiencies were identified as the first causal factors of these problems; remedial applications followed soon thereafter as part of stand management (Table 1.1). The first recommended fertilizer application was in 1925 in South Africa, and zinc sulphate solutions became routine from 1940 in parts of Australia. The first aerial application in forests was in 1955, when superphosphate was applied at Riverhead Forest in New Zealand (Conway, 1962). Nutrient deficiencies are also common in Chile and Spain. The main nutrient deficiencies of primary concern today include nitrogen (N), phosphorus (P), boron (B) and zinc (Zn) and less frequently magnesium (Mg), potassium (K), calcium (Ca), sulphur (S), manganese (Mn) and copper (Cu) (see Chapter 9).

The concentration of hydrogen ions in the soil solution (i.e. pH) influences the ion-exchange equilibrium between nutrient reserves, soil colloids and the soil solution. Spanish research suggests that the optimum pH range for radiata pine is 4.1–5.7, but because the species will tolerate a pH as low as 3.6 and as high as 7.1 it is seldom considered an important factor in controlling growth (Romanyà and Vallejo, 2004).

Site studies have shown that the most important nutrients controlling radiata pine growth are the concentrations of phosphorus and nitrogen (or, alternatively, the C:N ratio); exchangeable cations are generally less important (Madgwick, 1994; Romanyà and Vallejo, 2004; Watt *et al.*, 2008a).

When a tree is under nutrient stress it exhibits symptoms such as changes to foliage colour, stunting of foliage, premature loss of foliage, and various types of dieback or other malformations. The shedding of older leaves and changes in leaf colour are caused in part by the translocation of scarce nutrients to new growth. Wood formation is affected by boron, copper and calcium deficiencies.

Nutrient deficiencies characteristically show up in groups of trees rather than isolated individuals. Even within a tree, symptoms are usually expressed in a regular pattern, not on isolated branches. Characteristic nutrient deficiency symptoms are summarized in Table 2.1 and described in greater depth by Will (1985) and Turner and Lambert (1986). At a regional level, soil types and parent materials may help in diagnosing nutrient problems. In New Zealand, country-wide maps have been produced indicating where nutritional problems occur.

Severe nitrogen deficiency, which is infrequent, usually occurs in soils low in organic matter, such as recent sands, or where nitrogen mineralization is slow. It can be corrected by fertilizer and by using nitrogen-fixing legumes. Even healthy stands will often respond to nitrogen fertilizer. High-fertility soils with too much available nitrogen can cause problems, however. For example, trees planted on fertile pasture sites may have poor form due to increased sinuosity and changes to wood properties, although this may be offset by improved calcium nutrition (Hopmans, Matt and George, 1995; Espinoza *et al.*, 2012). Sulphur deficiency, which has been studied in Australia, produces similar symptoms to nitrogen deficiency (Table 2.1) and can be aggravated by the application of nitrogen (Turner and Lambert, 1986). Sulphur deficiency has been associated with *Dothistroma* needle cast.

Phosphorus deficiency is one of the most common nutrient deficiencies and is often associated with soils that are old, heavily podzolized, eroded or worn out by agriculture. Responses have been related to rainfall as well as soil properties (Turner and Lambert, 1986). Calcium deficiency sometimes occurs in tandem with phosphorus deficiency; the application of calcium phosphate fertilizers such as superphosphate can rectify this. Potassium deficiency is not widespread in the Southern Hemisphere but has been recorded on peats, deep sands, podzols and ultrabasic soils. In Spain, potassium deficiency is most common in the Asturias (Afif-Khouri *et al.*, 2010); it can be corrected readily with potash fertilizers.

In New Zealand, magnesium deficiency was first identified in radiata pines growing on coarse rhyolitic volcanic ash showers; it is aggravated by drought and pruning (Will, 1985). In older trees there is a condition called "upper mid-crown yellowing", which is likely to be caused by magnesium deficiency. The condition – which has become widespread in New Zealand – is believed to be aggravated by a nutritional imbalance involving potassium, low magnesium in the soil, and genetic changes due to tree-breeding (Beets *et al.*, 2004). It is also common, along with phosphorus deficiency, in parts of Spain (Zas and Serrada, 2003; Romanyà and Vallejo, 2004). The application of magnesium fertilizers is uncommon, however.

Boron deficiency in radiata pine is the most widespread of the micronutrient deficiencies. (see Figure 2.9) It is found in eastern parts of Australia, New Zealand, Chile, Argentina and parts of Africa (Will, 1985; Schlatter and Gerding, 1985; Turner and Lambert, 1986). Boron deficiency commonly occurs in patches of trees, with the most severe cases manifesting on eroded soils. Because boron is poorly retranslocated within the tree, a deficiency in it can be accentuated by drought. Calcium borate fertilizers are commonly used to correct boron deficiency. For more detailed information on boron deficiency in forestry see Lehtoa, Ruuhola and Dell (2010).

Zinc deficiencies are common in deep sandy soils in Victoria, South Australia and

FIGURE 2.9
Boron deficiency can cause repeated dieback

Western Australia, but are of anecdotal importance in other countries that grow radiata pine (Turner and Lambert, 1986). Copper deficiency has been found in localized situations in a number of countries. The application of nitrogen and phosphorus fertilizers may accentuate both deficiencies due to the dilution effects caused by faster growth rates, but both are easily corrected by fertilizers.

With radiata pine, both manganese and iron (Fe) deficiencies are typically associated with calcareous soils, but manganese deficiency occurs in South Africa on strongly podzolized soils with good drainage (Grey and de Ronde, 1988). The correction of manganese deficiencies is feasible on podzolized soils but not easy on calcareous soils.

Diagnosing nutrient deficiencies

A prerequisite for corrective treatment is diagnosis (Mead, 1984). The symptoms described in Table 2.2 are not always clear-cut, particularly where there are multiple deficiencies. Such symptoms can sometimes be confused with damage caused by diseases, animals and herbicide sprays. Furthermore, their appearance occurs when trees are under severe stress and it is preferable to begin treating the problem before growth is checked. Consequently, other diagnostic tools have been developed for radiata pine.

Soil and foliage analyses both depend on calibrating nutrient concentration with growth. The relationship is often portrayed as curvilinear, with growth increasing from deficiency through adequacy to luxury consumption and then with growth decreasing again as toxicity occurs. For forest management, the most important division is between deficiency and adequacy, and these critical values or bands define likely fertilizer responses. Table 2.2 gives critical values for foliage concentrations.

It is important to follow standardized sampling procedures for testing foliage against these values. The procedure may differ slightly between countries. In Australasia the procedure involves collecting current foliage from upper crown branches (second order in New Zealand and second main whorl beneath the leading shoot in Australia) in autumn (New Zealand) or late autumn/winter (Australia).

Other diagnosis approaches based on foliar analyses are to use nutrient ratios, or the Diagnosis and Recommendation Integrated System (DRIS) indices (Mead, 2005b). Nutrient ratios emphasize the requirement for nutrient balance. The DRIS is a holistic system that can include other measures of productivity as well as plant analysis. For radiata pine, however, only foliage analysis has been used, with the nutrient ratio norms for DRIS based on healthy trees.

Soil values have proved more difficult to establish and the only one in widespread use for radiata pine is for phosphorus using the Bray 2 or repeated Bray 2 extraction method (Ballard, 1974; Mason *et al.*, 2011). In practice, this has mainly been used as a guide for applying phosphate at planting; the repeated test has proved better than the single extraction in determining when to do so. The use of Bray 2 extract has also been suggested for determining phosphorus retention, cation status and nitrogen mineralization potential (Ballard, 1978a,b; Carlyle *et al.*, 1990).

Biological tests include the use of pot experiments and various types of field fertilizer trials (Mead, 1984). One innovation has been the use of foliar vector analysis, which relies on short-term field experiments coupled with foliage analysis (Mead, 2005b). Unlike ordinary foliage analysis, where nutrient concentration is the main variable, this approach also involves obtaining fascicle dry weights. The response to added nutrients is interpreted from the way nutrient concentration, foliage dry weight and nutrient content differ between the fertilizer treatment and unfertilized controls. The pattern of change or vector shift differs depending on

TABLE 2.2

Nutrient deficiency symptoms in radiata pine, marginal foliage nutrient concentrations and the confidence in these levels

Nutrient	Symptoms	Marginal foliage levels	Confidence rating
N	Uniform yellow-green to yellow short needles; loss of older foliage; fine branching; usually severe from 6–15 years; root:shoot ratio higher	1.2–1.4%	**
P	Dull green, short needles; loss of older foliage; thin spire-like crowns	0.11–0.14%[a]	***
K	Yellow-green tips (sometimes necrosis) in lower crown; intense in winter/spring; loss of older foliage	0.4–0.5%	**
Mg	Golden-yellow needle tips (sometimes necrosis); usually 1-year-old foliage in upper-mid crown; observed in spring	0.07–0.10%	**
Ca	Bud resin exudation, bud death and die back; usually severe after mid-rotation; indications are deficiency results in hooked or fused needles	0.10%[a]	*
S	Overall yellowing, pronounced at needle base	80 ppm SO^4	*
B	Tip death and/or shoot dieback; leads to stunted, multi-leadered trees when severe; shoot may bend over; pith necrosis; reduced wood lignification/fine roots	8–12 ppm[b]	**
Cu	Twisting of branches and leader; seedlings have drooping needles and necrosis	2–4 ppm	**
Zn	Rosetting from short needles; chlorosis/necrosis if severe; multiple leaders	11–12 ppm	**
Mn	Pale yellow-green or bronze foliage; dieback	10–30 ppm[c]	**
Fe	Pale yellow or yellow-white immature needles towards tree top	25–40	*

Note: ppm = parts per million; a = critical level has been related to rainfall in Australia (Turner and Lambert, 1986); b = B deficiency is often associated with drought and critical levels may vary with rainfall. Toxicity may show as tip reddening/necrosis when soluble B fertilizers are applied on light soils or high rates are applied. A foliage concentration of ≥250 ppm indicates toxicity (Khan *et al.*, 2012); c = Mn can accumulate to >1 500 ppm in foliage without adverse effects. Deficiency details from Grey and de Ronde, 1988; confidence ratings: * = insufficient information to confidently predict a response; ** = good prediction of a response below the marginal range; *** = reasonable prediction of a response in the marginal range.

Source: Based largely on Will, 1985; Turner and Lambert, 1986; Mead, 2005b whether deficiency, luxury consumption, dilution or toxicity is involved. While this combination of short-term fertilizer tests has proved effective for detecting deficiencies and fertilizer needs, it has not been widely used for radiata pine. Vector analysis was broadened to include the study of competition effects in radiata pine in order to distinguish between nutrient and moisture effects (Mead, Scott and Chang, 2010).

Soil microbiological factors

The most important soil-related microbial factor controlling the growth and health of radiata pine is the tree's association with ectomychorrhizal fungi. The absence of such mycorrhizae in nurseries can sometimes pose a problem (see Chapter 7), but generally radiata pine stock is well infected during the nursery phase. Mycorrhizal fungi also occur in forest soils, which can lead to a change in species as trees age (Chu-Chou and Grace, 1988). Mycorrhizae genera associated with radiata pine include *Rhizopogon*, *Hebeloma*, *Cenococcum*, *Amanita*, *Laccaria* and *Thelophora*, but there are many others (Madgwick, 1994, Dunstan, Dell and Malajczuk, 1998, Walbert *et al.*, 2010).

The major role of the fungus–tree symbiosis is that it enables the tree to tap nutrient sources that would not otherwise be available. Ectomycorrhizae enhance nitrogen and phosphorus uptake from soil organic matter and facilitate the uptake of phosphorus from soil minerals such as apatite. They have also been shown to increase the uptake of other nutrients, such as zinc. In closed stands of radiata pine, ectomycorrhizae may affect tree nutrition by reducing the rate of litter decomposition (Gadgil and Gadgil, 1975). There is evidence that ectomycorrhizal fungi may be involved in the reduction of soil organic matter when grasslands are converted to radiata pine plantations (Chapela *et al.*, 2001). Additionally, ectomycorrhizae may also enable trees to resist soil-borne diseases. These diseases are covered in Chapter 4.

OTHER SITE CONSIDERATIONS

A number of site characteristics can affect the viability of commercial plantations by making silviculture, harvesting and other management practices more difficult. For this reason, the following factors should be kept in mind before establishing plantation forests:

- Location in relation to industries, markets and infrastructure is economically important.
- Topography has a major impact on the types of operation used in establishment and harvesting and hence also affects costs (see also chapters 8 and 9).
- Four-wheel-drive vehicles are suited to flatter or rolling terrain free of frequent obstructions such as boulders, and with tracking can access slopes of 12–15º. In Chile, animals are still used for thinning radiata pine stands where the terrain is suitable.
- Tracked bulldozers can be used on slopes of 20–25º, depending on attachments, and excavators on slopes of less than 30º. On steep slopes or in erosion-prone country, hauler or cable systems are the usual logging method. Hand operations, aerial spraying and helicopter logging are less limited by topography.
- Ground vegetation can have a significant impact on cost and potentially on growth (see Chapter 8). Many woody weeds cause problems as they are often very competitive and difficult to control. Re-establishment after clearfelling will have to contend with slash and sometimes with a different suite of weeds.
- Microsite differences such as ridges and frost hollows may perform differently or pose special silvicultural problems.
- Soils susceptible to erosion are likely to need special consideration.
- Radiata pine afforestation can cause a reduction in stream flow (see below).
- For new plantations, land-use regulations, which may differ between site and location, need to be assessed, as they can constrain management.

Catchment hydrology

Radiata pine plantations can have a positive effect on soil stability (O'Loughlin, 2005). Radiata pine root systems give mechanical reinforcement to the soil, while their evapotranspiration can dry the soil, enabling it to absorb more rain before it becomes saturated. The size of the root system increases as stands age. For newly planted sites, the root system is able to produce erosion rates similar to those observed in indigenous forests after about eight years (Box 2.1). Compared to established forests, mass wasting on erodible pasture country can be over ten-fold higher. Knowles (2006) estimated that full protection occurs when there is a root biomass of 30 tonnes per ha. At clearfelling, the roots decay but will still be effective in preventing mass erosion for about two years; there will be a critical 5–6 year window where large storms could cause damage to replanted radiata pine plantations. The impact of raindrops from the canopy is of

BOX 2.1

Radiata pine plantations reduce landslides

Surveys of landslide frequency were carried out for various vegetation types in highly erodible hilly country in the east coast region of New Zealand following cyclone Bola in 1988, which dumped more than 900 mm of rain over three days. Evergreen indigenous forest greater than 80 years of age and radiata pine plantations older than eight years had 16 times fewer landslides than pasture and radiata pine younger than six years. Radiata pine in the 6–8-year age group and regenerating closed canopy scrub (*Leptospermum* and *Kunzea* species) were four times less susceptible to mass wasting. Following cyclone Bola, the indigenous forest and older radiata pine plantations had five landslides per 100 ha, while the younger plantations (i.e. under six years of age), as well as pastures, averaged 53 landslides per 100 ha. The roots of radiata pine are effective at strengthening erodible soils at eight years of age.

Source: Marden and Rowan, 1993

Erosion on a hill-country farm compared with a radiata pine plantation, Hawkes Bay, New Zealand, following a storm in 2011.

PHOTO: PETER SCOTT

little consequence provided there is a litter layer or understorey. However, roading, tracking and logging can expose the soil and funnel water; roads often affect slope stability in steep country. These latter impacts can be minimized by careful planning and execution (O'Loughlin, 2005). However, there are some very erodible sites where using radiata pine may not be the best option because of the species' relatively short rotation and the difficulty of using it in continuous-forest-cover silvicultural systems.

Water quality in streams under radiata pine plantations is similar to that in natural forests, with low or lower concentrations of nutrients and suspended solids (Quinn, 2005; O'Loughlin, 2005). With age, radiata pine forests leak slightly more nitrate. Forest harvesting may degrade water quality, but this will be temporary provided the harvested area is revegetated. In New Zealand the most serious problems have been associated with constructing roads, tracks and landings and occasionally with landslides. Burning after clearfelling can increase nutrient runoff so is usually avoided. Fertilizer use in radiata pine plantations has only minor effects and can largely be eliminated by preventing the contamination of streams (May *et al.*, 2009a). The afforestation of pastures may lead to stream changes but, again, this is temporary. The use of permanent riparian strips, which are not managed for wood production and which often use native plants, is increasingly being recognized as best practice. Riparian buffers are also important for the conservation of stream fauna (see Chapter 3), but they do reduce the productive area and sometimes complicate harvesting. While buffers of at least 10 m are often recommended, it is just as important to match width to streamside topography (O'Loughlin, 2005). In Australia, stream buffers more than 20 m wide and more than 100 m long are recommended because of their benefits for biodiversity (Cawsey and Freudenberger, 2008).

Evapotranspiration in forests is greater than for low plants such as pastures and some crops. Thus, afforestation of a total catchment can, after canopy closure and depending on rainfall, reduce annual stream flow by as much as 35–50 percent (Quinn, 2005; O'Loughlin, 2005; Garmendia *et al.*, 2012). Summer flows and storm peak flows (from small and intermediate sized storms) are also reduced, although this reduction may be less in mature plantations (Box 2.2). Scrub often uses almost as much water as plantations, so converting scrubland to radiata pine plantations has a smaller effect. A Chilean study found lower summer flows in forest plantations compared with native forests (Lara *et al.*, 2009). Changes in leaf area index with stand age and silviculture is a major factor determining water use by radiata pine plantations (Beets and Oliver, 2007; Vertessy, Zhang and Dawes, 2003). Thus, after clearfelling, there may be up to seven years of increased stream flow (Quinn, 2005). Similarly, thinning can increase stream flow for a couple of years.

The location of plantations in a catchment can also influence stream water flow, with plantations lower down in the catchment causing a greater reduction in water flow (Vertessy, Zhang and Dawes, 2003). In larger plantation forests, where there is a mosaic of different aged stands within a large catchment, the overall effects are muted. Nevertheless, the average stream flow will be lower than for pasture, although water quality will be better.

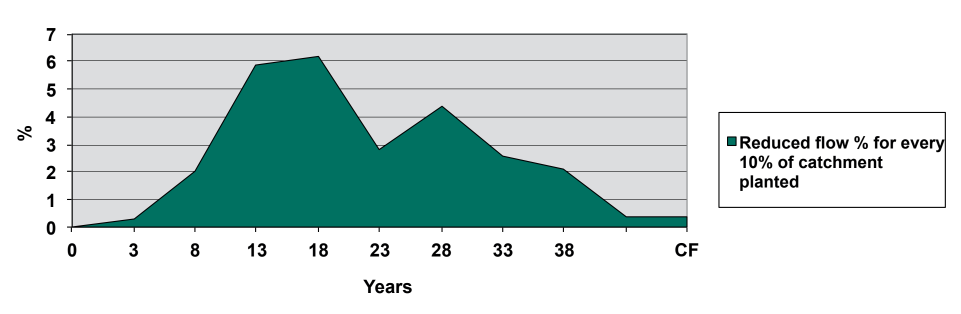
The biggest conflicts about water use associated with plantations have largely been in areas of low rainfall and where there is an existing demand for water by other users (O'Loughlin, 2005; Scott, 2005). O'Loughlin (2005) lists approaches to managing the impacts of plantations on water availability. In parts of Australia, plantation forests could be important in reducing salinization (Vertessy, Zhang and Dawes, 2003).

BOX 2.2

Longer-term effects of radiata pine plantations on stream flow

In South Africa, a long-term longitudinal paired catchment study collected data over a period of 68 years. The annual rainfall of the site was about 1 400 mm. One of the catchments was partially planted with radiata pine and the other was kept as native evergreen scrub, which was taller near streams. After 17 years of precalibration, 36 percent of the radiata pine catchment was planted at 1 370 stems per ha in 1956. The mean annual increment of the plantation was 15 m^3 per ha per year. The trees were grown on a pruned and thinned sawlog schedule, with a final stocking of 200 stems per ha. Clearfelling occurred over five years, when the trees were 43–48 years old.

Percentage reduction over time in stream flow for each 10 percent of catchment planted.



AT AGE 3 AND AFTER AGE 40 THE REDUCED FLOW WAS NOT SIGNIFICANTLY GREATER THAN FOR THE SCRUB VEGETATION; BASED ON 5-YEAR AVERAGES.

An effect of the radiata pine plantation on stream flow was first detected six years after planting. Annual flow reduction peaked at age 17 with a reduction equivalent to 53 mm for each 10 percent of catchment planted. After age 30, streamflow reduced gradually to half the peak value and for many later years did not differ from the untreated catchment. This pattern of water use follows the time-trend for foliage mass in radiata pine (Bi *et al.*, 2010).

The key conclusions to be drawn from the study are that:

- Planted trees initially draw on stored water.
- After age 6, the radiata pine plantations reduced stream flows as their leaf area and transpiration increased.
- Using longer rotations may reduce the plantation impact on water resources because of reduced differences in leaf area between the plantation trees and scrub vegetation.

Source: Scott and Prinsloo, 2008

RADIATA PINE'S ECOLOGICAL NICHE

Based on this review of site requirements, the ecological niche of radiata pine involves the following aspects:

- a climate with winter rain and relatively dry summers. This need not be the classic Mediterranean climate, since the species also grows well where rainfall is relatively uniform;
- rainfall greater than 600 mm per year, although the species will survive in lower rainfall areas. It will also tolerate rainfall in excess of 3 000 mm but may be more disease-prone, particularly if humidity is high;
- a lack of tolerance of hot, humid conditions (summer damp);

- long-term minimum temperatures above -10 °C. Growth rates improve with increasing mean annual temperature, but the optimum is currently poorly defined;
- deep (>60 cm), well-drained soils. Soil depth interacts with rainfall, indicating the importance of soil moisture. The species dislikes "wet feet";
- fertile, acid soils. Compared with many other pine species, radiata pine has high nutrient demand, although many localized nutrient deficiencies have easily been corrected. There have been problems with excessively high available nitrogen;
- the availability of ectomycorrhizae, which are critically important for facilitating nutrient uptake;
- moderate tolerance of salt spray;
- a latitude zone of 34–44°, although the species has been planted successfully outside this range.