8 Establishment and early tending

The establishment of plantations is part of an ongoing, integrated sequence of operations (Figure 1.1). For radiata pine, this sequence usually includes the selection of the seed source, propagation of the planting stock in a nursery (see Chapter 7) and planting on a prepared site. After the first crop is harvested, radiata pine usually follows in the next rotation, and its establishment will be influenced by the previous rotation and harvesting operations. This chapter explores both initial forest plantation establishment and the establishment of subsequent stands. Mistakes made during the establishment phase can affect the whole rotation and substantially reduce the value of the crop. Decisions made at establishment are among the most important decisions that forest plantation managers will make.

ESTABLISHMENT PLANNING

It is apparent from Figure 1.1 that no part of the forest plantation cycle is independent, and what happens at one stage will influence how the stand develops and subsequent operations. An integrated schedule of operations should be designed to meet management objectives optimally; by extension, a systems approach is recommended. While the specifics may vary, the overall objective of most establishment planning is to create stands at the desired stocking and spacing with:

- uniform, fast growth
- low risk (of biotic and abiotic problems, including wind and fire)
- optimum tree quality
- minimum expenditure of resources and risk of failure
- optimal financial returns
- no site degradation or adverse impacts on the environment
- a satisfying landscape
- fulfilment of statutory and certification requirements.

Establishment decisions are usually based on an interrelated set of factors that will determine the final characteristics of the stand (Figure 8.1). For radiata pine establishment, this planning begins at least one year before planting and ends at 4–5 years of age, by which time the trees have achieved dominance over competing vegetation. On most sites, radiata pine should be about 3 m tall by age 3 years (Menzies, Holden and Klomp, 2001). Figure 8.1 emphasizes the importance of management objectives, nursery and field operations and site-specific characteristics. The link to seed source and nursery is especially important because good, well-conditioned nursery plants are best able to tolerate tougher establishment conditions (Trewin and Cullen, 1985; Trewin, 2005).

Table 8.1 outlines the planning of establishment operations. The process begins by clearly defining the establishment goals and specifying the ideal stand for a particular area at the end of the juvenile growth phase, before tending is undertaken. Once an ideal stand is specified, it is possible to work back through the sequence of operations necessary for success, noting those that are critical, and defining criteria for each operation married to the characteristics of the site. Overlay maps or geographic information systems can assist with this process, particularly on heterogeneous sites. A site inspection is essential; this requires recording the following key features:

- topography, including aspect and the location of special features such as ridges, streams and rocky outcrops;
- the location of current and proposed roads and tracks;

- soil types and boundaries, erosion features and susceptibility to erosion;
- vegetation, including species (and frequency of occurrence), stage of growth and areas of contrasting types;
- watershed features, such as streams, riparian strips and remnant vegetation;
- other features, such as fences, power lines, irrigation works, fire ponds, buildings and ownership boundaries.

Mapping – including the use of satellite imagery, LiDAR and geographic information systems – is a particularly powerful management tool that can assist with planning, operational control and cost assessment. It will also assist in determining how the site will be harvested, which is especially important in steeper, broken country. Harvesting difficulties may suggest that it is better not to plant in some areas or to use non-commercial species.

In step 5 (Table 8.1) the major factors that might limit regeneration need to be identified for the stand as a whole and for subareas. The next step is to integrate everything to develop an establishment plan. Decision-support systems, if available, can help. Detailed costs will usually be undertaken at this point, and these could possibly lead to changes in the plans. Action plans should consist of an appropriate timetable, perhaps a series of maps delineating where certain operations should occur, and quality-control requirements, including checklists, to ensure everyone knows how to proceed and how to react if there are problems.

The final step in a management plan is to follow up on establishment success. This usually occurs in the first growing season and involves checking on aspects such as survival and weed control, but it should also be undertaken at the end of the establishment phase. Such assessments provide information for stand records and enable managers to learn how well the process worked, and to provide the basis for adaptive management. Assessments should look at growth, tree form (e.g. toppling and

FIGURE 8.1
Factors affecting the stand at the end of the establishment period

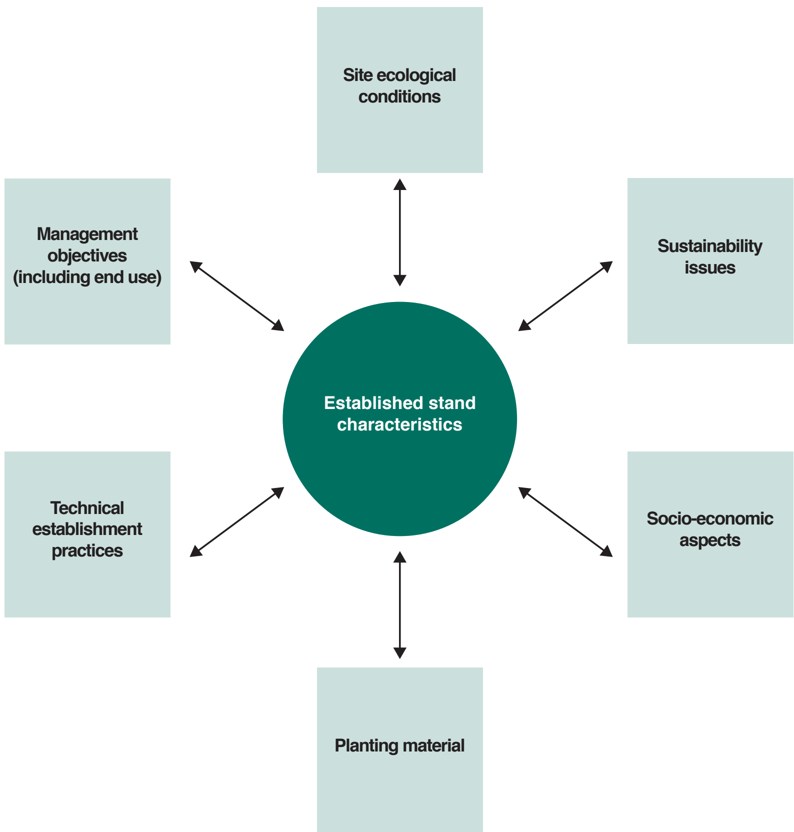


TABLE 8.1
Steps in the establishment planning process

Step	Items to consider
1	Identify goals and owner's objectives
2	Define the ideal state of the stand at age 4–5 years
3	Characterize the site (inspection, mapping, topography, soils, watercourses, vegetation and constraints)
4	Identify special considerations (legal, environmental, social, equipment, skills, finance, etc.)
5	Define limiting factors (brings together 3 and 4)
6	Produce an integrated establishment plan (methods, timetable, control maps, economic evaluations and quality control)
7	Evaluate (inspections, evaluation of success, actual costs and stand records)

sinuosity), stand uniformity and the incidence of other damaging agencies (e.g. disease, insects, animals and climatic events). Was the ideal stand achieved? If not, why not?

Trewin (2005) strongly recommended establishing quality-assurance indicator plots that allow the forest manager to judge if best practices were employed. These plots would be established by supervisors at the same time as the trees are planted. The recommended procedure is to have five alternate rows of ten trees carefully assessed for firmness and then uprooted to show seedling quality, planting depth and root placement. The uprooted trees would be replaced with trees that have been carefully selected, handled and planted. Workers can be assisted immediately to correct planting defects and any stock deficiencies reported to the nursery. These plots, with alternate rows of standard and optimum treatments, can be reassessed over time until thinning or pruning is undertaken.

THE BIOLOGICAL LIMITS TO EARLY GROWTH

The biology and development of radiata pine stands is outlined in Chapter 5 and some important aspects on the raising of plants in nurseries are discussed in Chapter 7. The following additional factors are relevant to the establishment phase while the trees are in a juvenile phase of growth.

Small plants are under considerable stress after planting. This is why conditioning in the nursery is important, particularly for bare-rooted stock, as it helps the trees withstand and eventually overcome this stress. Immediately after planting, the main source of stress is poor root contact with the soil. At planting, loose and cultivated soil may need compacting to enable good opening with a spade to be made for the planting stock. After planting it is necessary to firm the soil (Trewin, 2005). If air gaps form at the root–soil interface, the trees often undergo a period of water stress until new roots regenerate and are able to make more intimate contact with the soil. Root growth tends to be opportunistic in nature, exploring and exploiting the most favourable areas first. These will be areas of good tilth, adequate moisture and with a reasonable supply of nutrients. Dry soils, for example, not only result in root desiccation but increase mechanical resistance. A frequently observed example of this opportunistic nature is the way tree roots explore along ripped lines following subsoiling operations.

Thus, new root growth is important in ensuring good root–soil contact; the rate of this regeneration is a major factor in ensuring fast initial growth. Furthermore, the nature of the root system seen in the field is largely a reflection of soil conditions, within the genetic limits of the plant. On top of this will be modifications resulting from the choice of planting material (e.g. bare-root or container seedlings, or cuttings) and how they have been treated in the nursery (see Chapter 7), and planting practices that result in further deformations, such as twisted roots. Poor planting practices can lead to juvenile toppling, or to root strangulation that causes trees to fall over in mid-rotation. These are major problems in many radiata pine stands and can severely reduce their value (Mason, 1985), although the link between root deformations and toppling has not been definitively proved with radiata pine (Moore *et al.*, 2008). In southern pines, survival and ultimate growth are affected marginally by some bad practices, but planting depth is important for subsequent growth (VanderSchaaf and South, 2003; South, 2005).

For radiata pine, Trewin (2005) recommended that a deep hole be made with a spade using a "lock and lever" technique. After lowering the tree to the bottom of the hole, the soil is replaced with the side of the boot while the seedling is held upright. This is followed by a positive pull-up to straighten the roots. The final step is to firm the soil on either side of the planting stock with the boot sole to eliminate air pockets.

Radiata pine root tips exude a mucigel that adheres to adjacent soil particles and increases soil–root contact, presumably reducing the likelihood of dehydration during drought. Care should be taken not to remove the soil from the roots during lifting in the nursery (see Chapter 7).

The early growth of radiata pine, after the initial planting shock, is usually exponential until the site becomes fully occupied (see Chapter 5). On friable soils, such as sand dunes, roots may extend rapidly and may begin to compete with adjacent trees before the canopy closes. On less friable, heavier clay soils, root exploration is greatly reduced. By mid-rotation, for example, lateral roots on sand dunes may extend 20 m, while on the clay soils they seldom extend beyond 8 m (Mead *et al.*, 1991). Root initiation after planting may be delayed until the soil temperature rises above 11 °C, even where soil moisture is satisfactory (Nambiar, Bowen and Sands, 1979). The optimal temperature for the extension of lateral roots is about 15 °C. For radiata pine root growth to occur, soil moisture needs to be above wilting point and is optimal at field capacity (Gautam *et al.*, 2003).

The development over time of the root system's architecture influences tree anchorage as well as nutrient and water uptake. On a deep soil such as sand dunes, radiata pine will put down sinker roots to 4–5 m, which not only increases tree stability but also allows the trees to draw water and nutrients from depth (Nambiar, 1990). On low-rainfall sites, such as in South Australia, radiata pine may draw down water stored in the soil profile in the early years after planting. Studies comparing planted radiata pine seedlings with vegetatively produced plants show that, while the latter may have poorer root morphology at planting, they often go on to develop more sinkers. This, coupled with differences in their crowns, may be a reason for vegetatively produced planting stock having greater juvenile stability (Gautam *et al.*, 1999; Trewin, 2005; Moore *et al.*, 2008).

In common with other plants, most of the fine-feeding roots of radiata pine are in the topsoil, and typically they account for 70–95 percent of root length (Nambiar, 1990; Madgwick, 1994). The fine root density of radiata pine is very low compared with many of the weeds and other competitive plants encountered in plantations (Table 8.2), which partly explains the nature of competition between young radiata pine and other plants. While competition for moisture and nutrients often reduces tree growth, it can sometimes have positive attributes (Mead, 2010b). Competitors may temporarily store nutrients, prevent leaching and erosion, biologically fix nitrogen, control the rate of initial growth of the trees, and provide food for animals. Long-lived perennials with dense fine roots such as grasses, some woody weeds (e.g. acacias and eucalypts in Australia; Bi and Turvey, 1994) and plants with rhizomatous storage organs, such as bracken fern, often compete strongly and reduce radiata pine growth. In contrast, short-lived annuals and bryophytes have less adverse impacts.

Gautam *et al.* (2002) showed that fine root density was higher in pasture-free

TABLE 8.2
Fine root density of radiata pine and weeds in young stands growing in a sandy soil, South Australia

Soil depth	Root length density (cm per cm^3)	
	P. radiata	Weeds
0–10	0.06–0.18	32–44
10–20	0.10–0.32	7–8
23–30	0.05–0.15	4–6
30–40	0.02–0.05	2–4
40–50	0.02	1–2

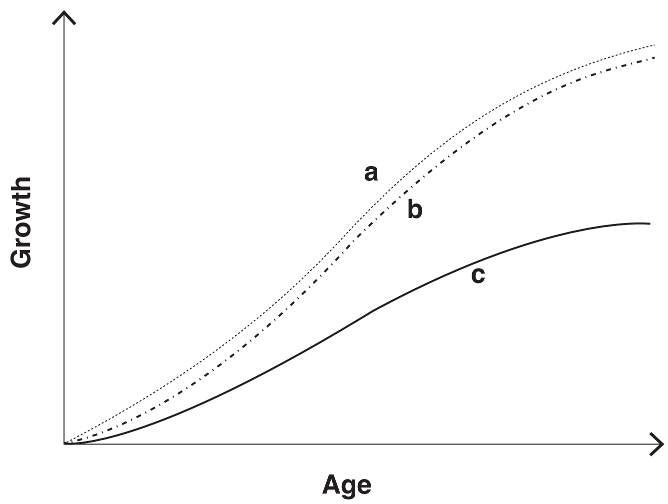
Source: Nambiar, 1990

riplines than in uncultivated soil under pastures and also where soil moisture was higher. Gautam *et al.* (2002) also showed that physiologically mature tissue-culture clones of radiata pine had greater ability than seedlings to exploit favourable soil conditions, in line with the observation that older radiata pine trees have higher root densities than younger ones (Nambiar, 1990).

Root growth patterns may be constrained or altered by soil factors such as texture, structure, bulk density, profile form, mineralogy, organic matter, pore size, soil pathogens and nutrient status. Root growth in radiata pine is inhibited at soil penetrability levels greater than 3 Mpa (Sands, Greacen and Gerard, 1979; Mason, Cullen and Rijkse, 1988). Nutrient cycling through needle fall is minimal during the juvenile phase of growth, so nutrient demand on the soil is high.

Site factors such as microclimate, soil structure, drainage, fertility and the vigour and composition of other vegetation on the site can be altered, in a positive or negative manner, by establishment practices. Significant changes in the soil structure or nutrient capital of sites often results in large, diverging patterns in growth for long periods (Figure 8.2). Where the site is not greatly altered, such growth differences may be short-lived and the end result will be parallel growth curves (Snowdon and Khanna, 1989; Mead, 2005a). The difference associated with such parallel growth may still be

FIGURE 8.2
Growth responses to silvicultural treatments



Note: following a short-term growth response (between lines a and b), subsequent growth trends are parallel. Diverging growth patterns, as between lines b and c, are characteristic of a major change to the site or the trees. Sometimes the initial growth response is lost over time (not shown).
Source: Snowdon and Khanna, 1989

economically important, however. Short-term growth responses can be obtained from herbaceous weed control, for example, or by adding small amounts of starter fertilizer. A third type of response is characterized by a temporary increase in growth rate.

SITE PREPARATION PRINCIPLES

Site preparation methods are species-, site- and region-specific. The operations chosen will depend on the nature of the site – such as its topography, soils, drainage, vegetation and climate – and on the availability of equipment and manpower as well as socio-economic factors. The forest manager needs to define what is to be achieved, and only then can the choice of technique be made within other constraints.

To achieve plantation objectives it is usually necessary to manipulate the ecosystem for the benefit of the young trees. Establishment operations are able to alter the microclimate, the forest floor and vegetation, the physical and chemical attributes of the soil and the impact of other biotic agents. For radiata pine, the following principles should be adhered to:

- For optimal, even growth rates, all trees must have favourable conditions, including a suitable microclimate and adequate nutrients and moisture. For example, the removal of vegetation alters the microclimate, as does altering the colour of the soil surface (Menzies and Chavasse, 1982). Trees should not be subjected to excessive exposure, desiccation or frost immediately after planting. Cultivation may be used to improve soil aeration and reduce compaction, regulate water movement and drainage, mobilize nutrients by increased mineralization, and alter the distribution of topsoil. Applying fertilizers and other practices will change soil fertility.
- Controlling competition is very important for the first few years after planting and may be used to control growth rates. The trees' competitors need to be put at a disadvantage, removed, or replaced by an advantageous secondary species. Competitors may physically smother the young trees or they may reduce the amount of light, nutrients and moisture available to them. However, some types of ground vegetation may have positive benefits, so an alternative strategy could be to replace or promote such species at the expense of more competitive weeds. Understorey competition can be used to control the adverse effects of very fertile sites (Mead, 2010b) or to improve radiata pine's corewood properties (Watt *et al.*, 2009a).
- Wind firmness should be promoted through the choice of planting stock and planting practices and by ensuring there is adequate soil rooting depth and artificially reducing the wind drag on the crowns. On windy sites the use of aged cuttings is advantageous because they have lighter crowns and because they allocate more carbohydrates to structural roots (Watson and Tombleson, 2004; Moore *et al.*, 2008).
- Site preparation methods, vegetation control and the manipulation of other on-site material may be used to improve access, reduce the fire hazard, alter biodiversity and manage wildlife and other pests or diseases.
- With a careful choice of techniques, suited to local conditions, it should be possible to avoid erosion, nutrient depletion and other environmental problems. The maintenance of site productivity is vital.

Other general concepts are to:

- have as little impact on the site as possible;
- conserve nutrients to ensure long-term sustainability;
- use decision-support systems, including energy or life cycle analyses and economic analyses (Richardson *et al.*, 2006; Mead and Pimentel, 2006);
- prevention is usually more effective and less expensive than later having to cure a problem. Insufficient inputs in site preparation may lead to poor stands of

trees that require subsequent higher management costs, or they may result in substantially lower final returns;
- achieve well-stocked, uniform stands at the first attempt, making future silvicultural operations easier;
- employ integrated establishment techniques.

RADIATA PINE SITE PREPARATION METHODS

Five basic methods are used during establishment, often in combination over all or part of the site (Table 8.3). They are:
- hand tool methods;
- machine methods, including harvesting;
- fire;
- chemicals;
- animals or other biotic agencies.

There are few situations in which no site preparation or competition control is required.

Hand tool methods

In countries where labour is scarce, wages are high or planting programmes are large, the use of hand methods is less common than half a century ago. Furthermore, it has been recognized that such methods are limited – for example, they cannot alter the site through cultivation, and the quality of the operation is often poorer than with machines – and the end result may therefore be suboptimal (e.g. Zwolinski, Johnson and Kotze, 2002). Issues with worker safety, supervision requirements and time restraints may be other disadvantages of hand tool methods. Nevertheless, there is a limited role for them (García *et al.*, 2000; Fernández and Sarmiento, 2004; Little *et al.*, 2006). The basic advantages are that they:
- require only small capital outlays;
- often require only simple skills;
- seldom, by their nature, do much damage to the site or cause pollution;
- are applicable in difficult terrain or areas with other restrictions that can limit some alternatives.

The tools and techniques used depend on the vegetation and the site. Common methods include pre-planting line-cutting, to felling larger material with chainsaws, to releasing trees after planting with slashers or powered brushcutters. The labour requirements also vary widely. Where labour costs are high, the hand-clearing of vegetation is usually restricted to small areas where chemicals or machines are not warranted or cannot be used readily because of access, topography or other constraints. Cultivation and drainage are usually limited to what can be achieved during the actual planting operation. However, spade planting and the application of fertilizers and other chemicals by hand are widely practised, even on easy terrain (see sections on chemicals, planting and fertilizer at establishment).

Mechanical techniques

Mechanical site preparation methods are widely employed in the establishment or re-establishment of radiata pine plantations (Hall, 1995, 2005; García *et al.*, 2000; Fernández and Sarmiento, 2004). However, they are not always required, for example, after harvesting with haulers. Experience and research have shown that machines used prior to planting:
- often give better results, leading to faster, more uniform growth;
- may be used to control some types of weeds (for example, ploughing has been used in Australia to reduce the regrowth of lignotuberous eucalypts, while ripping may reduce the impact of certain weeds);

TABLE 8.3
Site preparation methods commonly used in radiata pine plantations

Methods[a]		Slope	Soil factors ameliorated						Frost	Vegetation type				Cost[b]
			Shallow hard pan	Compact surface	Poor drainage	Very dry sands	Erodible	Fertility		Herbs and pasture	Bracken fern	Woody weeds	Logged site	
Hand	Clear	Any										* S, B		H
	Release/ line-cut	Any									*S	* S		M
	Fertilizer – individual tree	Any						**						L[b]
Mechanical	Towed roller (R)	<20°										** S, B	*** S	M
	Gravity roller (R)	>15°										** S, B	*** S	M/H
	Root-rake windrow (V)	<30° c										*S	** S	M/H
	V-blade (V)	<20°			* [d]				*S[d]				S	M
	Line or V-rake (V)	<25° c											** S	M
	Rotary slash	<20°										*S		M
	Discing (D)	<20°		**						*S	*S			H
	Ripping (R)	<15°	***[e]	***[e]	**[ef]						*S			M
	Rip/mound (R)	<15°	***[de]	***[de]	***[def]				***S[d]	**S	* S	*S	* S	L to H
	Spot clear/ cultivate	<30°	**[e]	***[e]	**[ef]		**						** S	M
	Line furrow (F)					**S[e]								M
Chemical	Aerial spray (S)	Any							*	*[g]	**D	** R, V	** R, V	L[b]
	Band spray (S)	<15°				***				***	**D	** R, V	** R, V	M[b]
	Spot spray (S)	<70°				***				***[g]	**D	R,V	** R, V	L[b]
Burn	(B)	Any										** R, S	R, S	L to H
Graze		Any								**S[g]		S		L
Over-sow		Any					**					** S, R, B	** S, R, B	L/M

Note: a = asterisks suggest suitability, and capital letters indicate likely combinations of establishment techniques. * = some suitability, ** = moderately suitable, and *** = very suitable. For example, rollers are moderately suitable for woody weeds such as gorse, but are very suitable for macerating logging slash. Likely combinations with other treatments are given using capital letters. For example, spraying for weeds (S) is often combined with other site preparation treatments; b = cost, where L = low cost (< US$300/ha), M = moderate cost ($US300–600/ha), H = high cost (>US$600/ha). The chemical cost of fertilizer or weedicide is not included; c = slope limitations: bulldozer – <25° degree slope; excavator – < 35° slope. Excavators are usually cheaper and do less soil damage; d= trees planted on mound; e = if there is heavy logging slash, there may also be a need for a V-rake or V-blade or similar. An alternative may be to use an excavator for spot cultivation; f = drainage is improved if hardpan is broken; g = including pampas grass (*Cortaderia* species).

Source: Based partly on Hall, 2005

- enable the soil to be cultivated and drained, etc.;
- overcome frost problems;
- are often cheaper than other alternatives;
- are safer for forest workers;
- require low manpower and enable large areas to be prepared quickly;
- assist with subsequent silviculture and might reduce other risks.

The disadvantages are that machines:

- have a high capital cost;
- are energy intensive;
- may be limited by terrain;
- are often limited by where and when they can be used (some mechanical methods are of less use following planting, and elsewhere they can be restricted by climatic, soil and topographic factors);
- require skilled operators;
- if incorrectly used and supervised may easily damage the site by compaction or the removal of topsoil, or cause offsite effects.

Furthermore, the forest manager is sometimes limited by the availability of a particular machine, or machine use may be limited by regulations or social values.

Machinery may be classified by the type of operation it performs and the site conditions to which it is suited (Table 8.3). The choice of machinery thus depends on an intimate knowledge of the site and on social and environmental regulations. The main site factors to consider are topography and the location of waterways and riparian buffers, soil types and their properties, the susceptibility to erosion, the type of vegetation or harvesting slash, pests, climate and the size of area to be treated. The main non-site factors are the availability of resources, including financial; surrounding ownership and crops; social and environmental sensitivities; and statutory and certification requirements.

The indicative costs for various machines versus other options (given in Table 8.3) are for individual operations. Thus the final cost of site preparation for a given site may often be substantially higher.

Energy analysis – where the energy return from growing trees, assessed at the end of the rotation, is compared with energy inputs – gives a measure of the efficiency of the use of fossil fuels (Mead and Pimentel, 2006). Cost and energy analysis results are not necessarily correlated. However, energy analysis has yet to be applied routinely in radiata pine plantation management.

Innovative practices developed or adapted for use in radiata pine plantation forests from the 1970s illustrate the potential for using mechanical techniques. In New Zealand, large gravity rollers were developed to crush dense, tall scrub regrowth on steep slopes (Everts, 1981). These rollers weighed about 10 tonnes and were controlled from tractors located on ridge tops using single or twin ropes. They were very effective in crushing material and were often used prior to burning. On flatter sites, towed rollers are preferred; in Australia, these are widely used after logging to mulch slash so as to avoid burning and to reduce the loss of nutrients (Box 8.1 and Figure 8.3).

Another development was the introduction of winged rippers for cultivating the soil to 0.5–1 m depth (Page, 1977; Hunter and Skinner, 1986). Winged rippers shatter the soil better than simpler tines and also use less energy. Ripping is often used on heavy soils, on shallow soils with a pan, and on sites compacted by machinery (Table 8.3), but not all sites respond to ripping (Mason, Cullen and Rjkse, 1988; Madgwick, 1994; Albaugh *et al.*, 2004). Ripping is usually undertaken in late summer or autumn when the soil is driest so as to shatter the soil rather than slice through it. Ripping may increase survival, root growth, tree stability and stand uniformity and on some sites it may result in large long-term, diverging growth responses (Mason, 2004). On some sites, ripping can also reduce weed competition, leading to better tree growth (Sands *et al.*, 2007).

BOX 8.1

Managing available moisture for optimum growth of radiata pine in South Australia

Site-specific establishment is practised in the radiata pine plantations near Mount Gambier, which are on relatively flat, podzolic sands of aeolion origin. Average annual rainfall is about 750 mm, with evapotranspiration exceeding precipitation for 5–6 months of the year. The soils have good water-storage capacity but only get recharged following logging. There are, however, large differences in fertility, drainage characteristics and weeds, so foresters use soil and other maps for planning, site inspections and monitoring. Researchers are also involved in decision-making, as current practices have evolved on the basis of considerable basic and applied research. Research followed site-quality decline in the second rotation, which was due to the loss of organic matter and nutrients from burning slash and soil moisture competition from weeds (O'Hehir and Nambiar, 2010).

The low-residue logging debris uses towed chopper-rollers to maintain organic matter and nutrients. This partially incorporates the material in the soil, where it acts as mulch and reduces evaporation. This operation also provides mechanical woody weed control for eucalypt coppice and pine wildings. To optimize soil moisture conditions, ripping, bedding, ploughing or spot cultivation follows, based on topography and soil conditions. Bedding, for example, is used in wetter areas.

Chemical weed control is vital for maintaining soil moisture, reducing nutrient competition and ensuring good survival and initial growth rates. Weed species, environmental and operational restrictions and soil type are all important in the choice of method. Expensive or high application rates are minimized, as long as good weed control results. In environmentally sensitive areas, chemicals and application methods are used based on research, human safety, buffer requirements and other factors, while second-year applications may be omitted. For FSC-certified plantations, atrazine and some other chemicals cannot be used.

In ForestrySA-managed plantations, weed control begins prior to logging with the spraying of understorey woody weeds and radiata pine wildings using a sprayer mounted on a skidder. The chemicals used vary with the season but always include metsulfuron-methyl. This treatment reduces weed seed loads and makes subsequent treatment easier. It also reduces possible off-site effects.

After logging and chopper-rolling, the weeds at each site within compartments are mapped. The chemicals used in this pre-plant operation depend on the species present, although chemicals with a residual action are preferred. Aerial applications are timed so that they will be most effective and also to prevent the weeds from setting seed. Soil cultivation is avoided for six weeks following spraying so that weedicide action has maximum effect. A second-year weed-control treatment is usually required with radiata pine, but this is minimized by the use of residual-action chemicals.

Trees are planted deep with spades to ensure maximum survival. Fertilizer is delayed until age 2.5–3 years, as the nutrient supply from the decaying slash is adequate. If fertilizer is applied earlier it can result in excessively vigorous top growth and subsequent toppling.

Mounding or bedding, often with rippers, is another widely used technique for radiata pine establishment and is generally better than ripping (Figure 8.4). This machinery was initially developed in the United States. It can be used to improve drainage, assist in the control of weeds, and reduce the damage from frost (Mason, Cullen and Rijkse, 1988). Mounding also concentrates the topsoil close to the young trees and contour mounding may assist water retention on dry sites. Typically, mounds are 30–40 cm high and without large clods. An hourglass-shaped roller is sometimes

FIGURE 8.3

Site preparation in South Australia using towed rollers. The resulting mulch assists with moisture conservation, conserves nutrients and makes planting easier.

towed behind the ripper–mounder. It may also have fertilizer applicators so that fertilizers can be incorporated at the same time as the ripping or mounding is done. On steeper sites, ripper–mounders may be attached to excavators (Hall, 2005).

The use of mounding and ripping may result in large diverging growth responses. For example, on a poorly drained site in South Africa, radiata pine planted into pits

FIGURE 8.4

Mounding and ripping provide an excellent cultivated planting site, concentrate nutrients and reduce weed competition.

FIGURE 8.5
Windrows made using a backhoe with a root-rake attachment. Note that there is some soil disturbance.

and on 30 cm-high beds had, at age 8.5 years, survival rates of 74 and 96 percent and stand volumes of 25 and 83 m^3 per ha, respectively (Zwolinski, Johnson and Kotze, 2002). In this study, hand-made mounds proved less effective than beds. Other studies have achieved less dramatic results (e.g. Mason, Cullen and Rijkse, 1988; Albaugh *et al.*, 2004).

Small V-blades have been used to make furrow-lines on drought-prone sand sites in Western Australia. These create a weed-free furrow, which also tends to accumulate moisture, thereby improving survival and tree growth. In New Zealand, larger V-blades or line rakes on crawler tractors (120 kW) have been used to make planting lanes through heavy cutover or wind-blow debris and also to create small mounds on which to plant in frost-prone or boggy areas (Hall, 2005). These techniques redistribute nutrients in the slash and topsoil.

Twenty-tonne excavators are often preferred to tractors for windrowing to improve access to the site for planting (Figure 8.5; Hall, 1995; Hall, 2005). Windrowing can easily lead to topsoil removal, but the use of excavators reduces this risk. However, windrowing and heaping inevitably result in the redistribution of nutrients in the slash and may also increase pest problems. Excavators can also be used for spot mounding.

Fire

Broadcast burning of the site prior to planting was once a common technique employed to reduce the amount of vegetation and debris after logging, but its use has declined substantially in the last 30 years. The burning of windrows or slash-heaps has also declined, although it is still employed in Western Australia (Figure 8.6). In New Zealand, windrow-burning is now a method of last resort or is used to train fire-fighters (Hall, 2005).

For a good broadcast burn it is important that woody vegetation is killed and allowed to dry and is reasonably compact. Lighting the burn needs to be done with care to ensure the safety of the ground crew, minimize the risk of burning surrounding areas and achieve a good burn. Firebreaks should be constructed and fire equipment should be deployed during the burn and until the site is completely safe. Planning and

FIGURE 8.6
The heaping of slash, and then burning the heaps, clears the site but runs the risk of nutrient loss and creating uneven growth in the compartment.

good supervision are essential and permission from authorities must be obtained.

The general advantages of burning as a site preparation method are that it:

- is an efficient and inexpensive method of biomass removal where large areas are involved, although costs can vary widely (Table 8.3);
- is suitable for a wide range of terrain;
- improves access;
- may reduce subsequent weed growth (including unwanted wildings of radiata pine) by killing plants and seed, although for some hard-seeded species (e.g. some legume weeds such as *Ulex* and *Acacia*) it may stimulate germination;
- provides a good seedbed for the establishment of cover crops;
- reduces the fire risk to the subsequent stand;
- releases nutrients tied up in the biomass, which can sometimes benefit the trees;
- results in a black colour, which may reduce frost problems.

However, there are also many disadvantages. For example:

- There is a danger to the forest or other adjoining landowners if the burn gets out of control – in some situations, material may smoulder unnoticed for a long time.
- To get a good burn the weather and the condition of the material must be satisfactory, and in some places this can be very restrictive or unreliable (see Hall, 2005, for further details).
- Major losses of volatile nutrients such as nitrogen and sulphur can occur in a hot burn, and burning is incompatible with the retention of slash as mulch.
- On some sites, a burn can be a prelude to soil erosion or excessive nutrient runoff.
- Creating a bare surface sometimes facilitates invasion by wind-blown seeds, such as those of pampas grasses (*Cortaderia* species).
- Burning is considered by many to be an environmentally poor practice – communities often object to the smoke, the blackened sites and CO_2 emissions.
- The creation of firebreaks often results in topsoil removal.
- Good supervision, crews and equipment are required.

Nutrient loss, low community acceptance and risk to adjacent properties are the major reasons for a decline in the use of fire (García *et al.*, 2000; Hall, 2005). Burning is also an expensive option when the areas involved are small.

The effects of site-preparation fires on wildlife can be positive or negative. In some situations, pests are reduced when their habitats or breeding niches are destroyed, but sometimes preferred species may also be affected adversely. In other situations the fire may promote additional feed and so encourage wildlife. Similarly, the effects of fire on plant species composition may be either good or bad, depending on the ecosystem and the species present.

Chemicals

Chemicals are most commonly employed to control vegetation, although sometimes they are also used against insects or other pests (see Chapter 4). Weedicides are often a component of successful establishment regimes (Box 8.1), and they have been widely employed in the last 50 years in radiata pine plantation forests. Prior to the widespread use of weedicides, most weed control in radiata pine plantations was performed by a combination of hand and mechanical methods, sometimes in association with fire (Little *et al.*, 2006). Weedicides are not commonly used in Spanish plantations (Fernández and Sarmiento, 2004).

When using chemicals for weed control:

- It is important to clearly identify the problem caused by the weeds.
- Identifying the weed(s) to be controlled is essential. Often, it is not necessary or even desirable to completely eliminate all weeds. Plants differ in their competitive abilities; many grasses and woody weeds compete strongly with newly planted radiata pine, whereas some short-lived annuals are much less competitive. In many situations, weeds play a valuable role in preventing erosion and the leaching of nutrients. However, in drought-prone areas or where frost is a problem, a high degree of weed control may be necessary.
- It is useful to know the ecology of weed species, including their growth habits, flowering, seed dispersal and storage organs. Species successions may occur and could be altered by weed-control methods.
- Careful evaluation of the site is recommended. The coverage of different weeds, their size, extent of hindrance, the topography and other relevant physical features, as well as limitations related to surrounding land uses, need to be assessed. The likelihood of weed invasion from surrounding areas, or the germination of seeds dormant in the soil, should also be taken into account.
- Awareness of the chemicals to be used – their formulation and mode of action, application rates, the use of diluents or additives, environmental hazards, health and safety, and regulations restricting or governing their use – is extremely important. The application method should be chosen carefully.
- Finally, using well-designed checklists, and ensuring that all involved are aware of their roles in the case of emergency, is vital to successful chemical weed control.

The use of weedicides in South Australia highlights these principles and how they are part of good establishment planning (Box 8.1). A number of guides are available on the use of weedicides and other chemicals (e.g. García *et al.*, 2000; Gous, 2005; Gous and Richardson, 2007). More recently, computer-based systems have been developed to assist radiata pine plantation managers in their choices, sometimes incorporating more than weedicides (Richardson *et al.*, 1997; Tapia and Cepeda, 2005; Richardson *et al.*, 2006). However, these systems are not always employed routinely by managers.

There are ongoing changes in weedicide practices in radiata pine plantations. Phenoxy weedicides were phased out in the 1980s and replaced by less toxic compounds such as glyphosate. At the same time, triazines (e.g. hexazinone) were introduced, along with surfactants such as organosilicone. Rates of application have also been reduced as methods of application have improved. Certification and other environmental issues are adding additional pressure to change weed-control methods (Little *et al.*, 2006; Ronaldo, Watt and Zabkiewicz, 2011). Currently, the most commonly used weedicides in radiata pine plantations are glyphosate, hexazinone, metsulfuron methyl, terbuthylazine, atazine and simazine, but others are also employed.

Weedicide use in radiata pine plantations usually results in short-term tree-growth responses followed by parallel growth trends, with typical gains of 1–2 years but occasionally more (Wagner *et al.*, 2006; Mason, 2006; Mead, 2005a; Rubilar *et al.*, 2008). Uncontrolled weeds reduce tree growth mainly because of competition for moisture and nutrients, but shading may also be a factor with taller woody weeds. Unless the site is severely nutrient-deficient, the dense radiata pine crowns usually dominate the understorey after a few years.

There have been studies on the cost-effectiveness of varying sizes of weed-free zones. In one study on stony soils in Canterbury, New Zealand, where weed control ranged from nil to 100 percent, it was found that the best growth was achieved with complete weed control, but at age three years spots 0.5 m in radius were most cost-effective, compared with other treatments (Balneaves and Henley, 1992). However, by age seven, a 2 m wide strip was the most cost-effective treatment. The general conclusion is that responses are related to the degree of weed control but, in practice, the size of the response has to be offset by cost, environmental impacts and other negative effects such as increased tree-toppling.

Health and safety issues and other social concerns are very important when considering the use of chemicals in forests, as they are often perceived poorly by the general public.

Other weed-control methods

A number of other techniques may be effective in controlling competition during the early life of a stand. Grazing animals are sometimes used, both when establishing trees on pasture and where there are other palatable weeds (West and Dean, 1990). A common practice prior to planting is to graze heavily with sheep, goats or cattle. In the case of pasture, sheep are preferred over cattle because they graze closer to the ground. Pampas grass is a major weed in some Australasian plantations; where it is present, cattle are the preferred grazing animal because pampas is less palatable to sheep. Similarly, it is possible to get some short-term control over gorse (*Ulex europaeus*) and blackberry (*Rubus fruticosus*) through intensive grazing by goats. Animals need to be carefully controlled, which requires special management skills and inputs; the active involvement of farmers may be beneficial. The critical period for tree damage by grazing animals is the first years after planting (see Chapter 10). It may be necessary, therefore, either before or after planting, to complement an animal-grazing strategy with spot or strip spraying of weedicides to reduce competition. Goats cannot be reintroduced to the plantation after planting until the bark of the radiata pine plants has become thick and corky because they are palatable when young.

Cover crops are a form of biological control of weeds in which grasses and/or legumes are over-sown to compete against problem weeds and to reduce the need for chemical weed control (Hall, 2005). Cover crops may also reduce erosion, improve aesthetics, provide a palatable species for grazing and, in the case of legumes, improve the nitrogen status of the site. The choice of cover crop is critical, as it should not compete strongly with the trees but should make it difficult for other weeds to establish. The cover crop should not itself become a pest. Cover crops have been used after logging. Although the results of cover cropping have been mixed for radiata pine plantations, the concept is well established in rubber and oil-palm plantations in the tropics.

Other biological control methods for important introduced weeds are being researched in a number of countries, including in radiata pine plantations. There are two main approaches. The first is to introduce an insect or microbe to attack the weed. The control agent needs to be species-specific so that it does not cause wider problems. An example of this approach has been the introduction of the seed weevil, spider mite and other insects in New Zealand to control gorse, although the results have been modest (Hill, Gourlay and Fowler, 2000). A weevil has also been introduced to control buddleja (*Buddleja davidii*) in New Zealand (Watson *et al.*, 2011).

The second approach is to make use of already existing organisms in the ecosystem; bioweedicides are an example of this approach. The objective is to overwhelm the weed with a biological agent, either killing it outright or weakening its competitive edge. In radiata pine plantations, it may be possible to use this approach on broom and gorse using fungi such as *Fusarium tumidum* (Frölich *et al.*, 2000).

In all these examples, biological control should be viewed as a part of an integrated weed management regime.

Mulching using weed mats is a rarely used technique to control weeds in radiata pine plantations, although roller-chopping debris at clearfelling is now recognized as a useful method for conserving moisture and nutrients while reducing some weeds (Box 8.1). Although weed mats do reduce weed competition, they may not be as effective as weedicides and are much more expensive (Mason, 2006; Ronaldo, Watt and Zabkiewicz, 2011).

PLANTING

Being a temperate species that prefers wet winters and dry summers, radiata pine is invariably planted between late autumn and early spring. Only as a last resort should summer planting be practised.

Radiata pine planting will have high survival, fast early growth and tree stability if the following four points are attended to (Trewin and Cullen, 1985):

- obtaining good stock that meet proven quality criteria (see Chapter 7);
- reducing the planting shock caused by the stress placed on the plant in lifting and transport, plus the difficulty of getting good soil–root contact;
- placing the tree roots where they will have good access to soil moisture – on drier soils, radiata pine can be planted so that one-third or even more of the foliage is buried;
- ensuring that trees will remain stable – in particular, a good distribution of roots in the soil is necessary, as twisted or tangled roots often lead to toppling and a weak stem–root junction.

Juvenile instability or the toppling of young trees usually occurs in the second or third winter after planting and is greater on windy, wet and highly fertile sites (Moore *et al.*, 2008). High fertility leads to larger bushy tops, thereby increasing wind interception, although evidence for this is conflicting. Opening a good hole, planting deep (>15 cm of stem buried for bare-rooted stock) and using a positive-pull-up technique have been recommended to reduce toppling (Trewin, 2005). Crown lightening and the use of mature cuttings have also been advocated (Davies-Colley and Turner, 2001; Trewin, 2005; Moore *et al.*, 2008). Wind-proofing by crown lightening is a low-cost, effective practice and does not reduce growth rates. However, it needs to be performed before the trees are vulnerable to toppling. In South Australia, fertilizer applications are delayed to reduce this risk (Box 8.1). However, the complex mix of factors involved has made it difficult to predict when toppling will occur.

Trewin (2005) noted that cuttings grown in containers can develop poor root systems if they are placed too deep in the containers. Additionally, container plants should be planted so that there is about 5 cm of soil over the top of the plug, again to reduce toppling and to ensure adequate soil moisture (Figure 8.7).

Most growers use spades for planting both bare-rooted and container stock. On cultivated sites, if the soil is too loose it may be necessary to compact the soil by foot

FIGURE 8.7
Container-planted seedling, illustrating the regeneration of new roots four months after planting. Note that part of the foliage had been deliberately buried.

before planting. On friable soils, a well-trained worker can plant about 240 trees per hour but on heavy clay soils or in difficult conditions, such as planting through logging slash, the target could be as low as 90 trees per hour (Trewin, 2005). Machine planting is less common than it was in the past because it is unsuitable for logged sites without extensive windrowing or similar operations.

Quality control of planting operations is critical, particularly because inexperienced workers are often used due to the seasonal nature of the work (Trewin, 2005). Worker training, assessing the quality of planting by supervisors, and the use of checklists and quality assurance indicator plots are all ways of ensuring good planting practices. Monitoring tree health after planting is also critical to catch unforeseen problems and to integrate the planting operation with subsequent weed and pest control operations.

Survival and replacements

Good practices should lead to high survival rates (>90 percent) so it should not be necessary to replace dead trees (Menzies, Holden and Klomp, 2001). A survival assessment is usually made towards the end of the first growing season, noting whether the survival pattern shows groupings of dead trees. With radiata pine, there is no advantage in filling gaps of less than 100 m^2, as they will not affect the growth of surrounding trees, and replacement trees seldom perform well (Figure 8.8; Chavasse, Balneaves and Bowles, 1981). In large gaps it is usually sufficient to plant a few trees; they should be looked after carefully to ensure fast growth. On difficult sites, the assessment can be made earlier and trees planted in large gaps in the spring following the initial planting (A.R.D. Trewin, personal communication, 2012).

FIGURE 8.8
Trees replaced in gaps seldom keep up with those planted earlier. The large trees are three years old.

DIRECT SEEDING AND NATURAL REGENERATION

Direct seeding, either broadcast or by drill sowing, has been used in the past, particularly in New Zealand between 1926 and 1930 (Kennedy, 1957). However, it fell out of favour because of its high seed use and the difficulty of achieving a uniform crop.

Natural pine regeneration occurs but is rarely employed systematically in plantations (Lewis and Ferguson, 1993; Burdon, 2001). This is because of:

- the need to use improved genetic material, which necessitates planting;
- the variability associated with natural regeneration;
- predation of seeds by birds and mice when natural regeneration is used on a large scale;
- the cost of handling high-density regeneration – thinning regeneration with slashers or brush cutters can take 2–5 man-days per ha (Minko, 1985).

In the 1960s, the aerial sowing of radiata pine seed at a rate of 2.24 kg per ha was used in conjunction with natural regeneration in Kaingaroa forest, New Zealand, but was subsequently discontinued (Levack, 1973).

Radiata pine is also known to regenerate under a sparse overwood in its native habitat and elsewhere (Lewis and Ferguson, 1993). In the mid twentieth century, trials were undertaken with traditional shelterwood systems in South Australia and the Central North Island region of New Zealand. The strip system was also attempted in New Zealand. Australia's experiments with shelterwood systems found that the best natural regeneration was achieved with 100 stems per ha using a uniform shelterwood system rather than a group shelterwood system (Lewis and Ferguson, 1993). In North Canterbury, New Zealand, a farmer, John Wardle, is currently using a form of shelterwood to regenerate stands by frequent removal of selected large trees. This has resulted in groups of regeneration, but it is too soon to know if the system is viable. Damage from logging, to both the remaining trees and regeneration, plus additional wind damage, are causes of concern. Shelterwood systems are unlikely to be used widely with radiata pine; indeed, advanced regeneration in South Australia is usually eliminated (Box 8.1).

FERTILIZER AT ESTABLISHMENT

Fast exponential growth following planting may be limited if there are inadequate nutrients. Nutrient demand from the soil follows this exponential pattern until about age five years, when in radiata pine the nutrient cycle from litter fall reduces the demand on soil reserves. This pattern of nutrient uptake is also a function of root surface area, which expands rapidly in the establishment phase. Nutrient uptake is also governed by soil characteristics (including nutrient and moisture availability and physical features), soil processes (such as mineralization, immobilization and leaching), climate, site preparation and competition from other plants. Fertilizers are potentially valuable where the roots are unable to acquire sufficient nutrients from the soil to meet the trees' demands. However, the response may be poor if uptake is restricted by a lack of moisture, severe competition, root disease, root death due to fertilizer "burn", the unavailability of the added nutrient, or an imbalance in supply. Further details pertaining to these underlying processes can be found in Bowen and Nambiar (1984), Madgwick (1994) and May *et al.* (2009a).

The efficient use of fertilizers in the establishment phase requires recognition that:

- Seedlings begin with a limited root area in poor contact with the soil.
- As root systems expand they will first tend to exploit moist, nutrient-rich, cultivated areas.
- Nutrient competition with other plants can occur and this will vary with species, their phase of growth and the methods used to control them.
- Trees require a balance of nutrients, but not all these need to be fully supplied in the fertilizer. However, nutrient interactions such as those between nitrogen and phosphorus are commonly observed (e.g. Hunter and Skinner, 1986).
- The availability of nutrients should follow the pattern of nutrient demand.
- Fertilizer properties, their reaction with the soil, and losses from the system need to be considered.
- Fertilizer burn due to excessive fertilizer salt levels in the rooting zone, or toxicity with boron fertilizers, needs to be avoided.
- Soil nutrient availability is likely to change over time.
- Application techniques must be planned and monitored carefully.

In addition, the costs and benefits of the operation, operational aspects and other factors such as toppling need to be considered. A number of approaches have been used to meet these biological–soil–fertilizer factors:

- Apply the fertilizer in increasing doses to meet tree demand. In this approach, fertilizer is initially applied in a small dose close to the tree shortly after planting and, if required, spread in higher amounts over larger areas at a later stage. Commonly a starter dose of fertilizer may be hand-applied into a slot 10–15 cm from the seedling shortly after planting, and this would be followed up with a heavier broadcast dressing (perhaps applied aerially) when the trees are beginning to dominate the site at age 2–4 years (Hunter and Skinner, 1986; García *et al.*, 2000; Mead, 2005b).
- Apply a larger broadcast or banded application of usually less soluble fertilizer at planting. With this method, the nutrients become increasingly available to the trees as the roots extend outward. This method is mainly applicable to fertilizers that are not readily leached. The application of rock or partially acidulated rock phosphate at 300 kg per ha is an example of this approach (Hunter and Skinner, 1986).
- Use weed control along with fertilizer applications to reduce competition – this has been found to be particularly important where nitrogenous fertilizers are used, or where phosphate is applied and there is competition from a legume.
- Apply fertilizer to reduce losses by volatilization, leaching, erosion or fixation and placing it where tree roots will intercept the increased nutrient levels.

Incorporating soluble fertilizer in slits close to the seedlings achieves this. Similarly, the band incorporation of fertilizer into the cultivated areas (such as when mounding) ensures that the fertilizer is placed where it will be close to roots and where there is less weed competition.
- Time the application of soluble fertilizer to avoid losses by leaching but when soils are moist enough to ensure uptake. Slow-release fertilizer formulations may also reduce leaching losses.
- Time the application and choice of nutrients to reduce frost damage or toppling.
- Avoid root burn by not placing soluble fertilizers into the planting hole – a soil barrier is usually required.
- Avoid toxicity with boron fertilizers by applying lower-solubility minerals and avoiding application rates that are too high.

The nutrient requirements for applications in the first year after planting radiata pine are often determined using soil analyses or on the basis of research and experience on similar soils (Mead, 2005b).

Hunter and Skinner (1986) showed that, on impoverished podzolic soils, starter doses would not supply the necessary nutrients for more than two years, with the young trees becoming deficient. Furthermore, on these soils, both site preparation with ripping and bedding and fertilizer applications were required.

The application of starter doses of fertilizer generally produces a short-term growth response, with a typical gain of 1–2 years (Mead, 2005a), although sometimes the response is only ephemeral (e.g. Mason, 2004; Albaugh *et al.*, 2004). Short-term responses are worth pursuing as part of an overall fertilizer management programme where sites are very deficient. However, where the sites are not so deficient in nutrients it is frequently not cost-effective to apply starter fertilizers. The use of heavier amounts of phosphate on deficient soils often provides a larger and longer-lasting effect with a diverging response pattern (Figure 8.2; Hunter and Skinner, 1986; Mead, 2005a).

Typical elemental rates of starter fertilizer are 10–20, 15, 20 and 1–2 grams per tree for nitrogen, phosphorus, potassium and boron, respectively (Table 9.3; Mead, 2005b). Banded or broadcast applications would supply 5–10 times these amounts.

FIRST ROTATION FEATURES

Historically, there were five main vegetation types suitable for afforestation or reforestation with radiata pine. Some early plantations were established in areas of natural grasslands or scrub land, for example in New Zealand and South Africa. In Chile and more recently in Spain, the main areas often included degraded farmland. Poor natural forest or remnants of natural forest, perhaps having been degraded by logging or fire, were also planted in several countries. In New Zealand, large areas of moving sand dunes were planted after the Second World War, partly as erosion control measures. Considerable areas of marginal farmland were also planted, some of which were reverting to early-successional native species or introduced plants such as gorse that were filling the same niche. The final main vegetation type in New Zealand was pastures or eroding pasture hill country where grasses were dominant.

One of the features, therefore, of first rotations was that the weed associations were quite varied. Some vegetation types, such as natural grass and pastures, proved easy to handle, but others that featured woody weeds such as gorse, broom and wattles were more difficult. In Australia, the eucalypts often required methods for overcoming stump resprouting. In New Zealand, *Armillaria* damage was of concern where natural forest was being converted to plantation (see Chapter 4). On sand dunes, the moving sand initially had to be stabilized with marram grass (*Ammophila arenaria*) and lupins (*Lupinus arboreus*) before being planted with radiata pine.

Other site characteristics also varied greatly. Topography, altitude, climate and soils all affected the choice of site preparation and establishment techniques. Establishment thus became site specific.

LATER ROTATION FEATURES

All the main radiata pine-growing countries are predominantly re-establishing second or later rotations, and only relatively small areas of new plantations are being established (Table 1.2). This is posing a range of problems.

The spontaneous regeneration of radiata pine commonly occurs on re-establishment sites, but it is seldom used except on a small scale. Rather, such regeneration usually needs to be controlled to favour the newly planted radiata pine trees, which are generally of higher genetic quality (see, for example, Box 8.1).

For replanting after logging, the forest manager needs to consider the following.

- Interaction with harvesting. The harvesting method and degree of tree use has a considerable impact on the volume and distribution of slash and on soil disturbance and compaction. Hauler logging leaves the site with less tall debris, except in the vicinity of the hauler itself, and usually does less damage to soils (Figure 8.9). On the other hand, logging by skidder or tractor can create more difficult sites for re-establishment unless an effort is made to reduce the amount of larger slash.
- Season of harvesting. The time it takes for weeds to become established varies according to season, and the effects of harvesting on the compaction of skid tracks can also differ. Thus, the season of harvesting can alter establishment methods.
- Changing weed problems. In some places, spontaneously regenerating radiata pine seedlings can be a problem and have to be dealt with by physical or chemical methods (Box 8.1). Elsewhere, the types of weeds differ from those of the first rotation and sometimes these can be more difficult to control.
- Heavy slash. Planting is more difficult and subsequent seedling health is poorer when there is heavy slash. This can be overcome by crushing (Trewin and Kirk, 1992).
- Fire. Inside a forest, considerable caution is required when using fire to clear debris.
- The maintenance of site productivity. This is often of concern because of compaction and possible nutrient on-site redistribution or removal from the site (see Chapter 11).

FIGURE 8.9
Hauler logging leaves a clean site but redistributes nutrients.

SYNTHESIS AND TRENDS

Improved genetic and nursery plants, coupled with improved site preparation, weed control and planting techniques, have increased the survival of plantings and subsequent stand quality substantially in the last 40 years. This has allowed the reduction of initial stocking rates by half. Today, initial stocking rates for radiata pine range from 600 to 2 000 stems per ha. Chapter 9 discusses the choice of initial stocking rates.

There is growing awareness and application of site-specific establishment techniques, which often integrate a number of methods, including the use of clonal varieties. At the same time, managers are assessing success by looking at financial results over the whole of a rotation rather than using a single criterion, such as survival, soon after planting. This is helped by improved modelling systems that can evaluate the effects of establishment on long-term growth (Richardson *et al.*, 2006). Research that collects data over a longer proportion of the rotation, rather than the first 2–3 years, has also helped these efforts.

There is growing awareness of the need for, and pressure to use, more environmentally friendly techniques. Coupled with this, a higher proportion of radiata pine planting is now for re-establishment rather than planting new forests. As the availability of fossil fuels reduces, there will also be more efforts to use woody waste, so changing the planting site characteristics, and to carefully evaluate energy use in the establishment phase. These factors will impel further changes in establishment practices.