9 Tending established radiata pine stands

This chapter covers operations that take place after trees are established through to their harvest. It is closely linked with the establishment phase and with the end use of the stand (Figure 1.1). Initial stocking and thinning intensity are linked because they control inter-tree competition and timber characteristics. The breed selected and the establishment techniques used influence how the stand will develop and in turn will influence later tending decisions and final end use. It is important that forest managers avoid looking at later tending in isolation, but rather view it as a part of an overall programme to meet management objectives.

As a timber producer, radiata pine has proved to be silviculturally flexible, and the plantation resource can be managed using a wide range of strategies. Early in the twentieth century, spacing and thinning schedules adopted for radiata pine were conservative and cautious, with high stocking levels reflecting European philosophies. As familiarity with the species developed and its rapid growth rate became evident, stocking levels were reduced. Later, radiata pine plantations were subjected to a changing array of thinning practices, often dictated by market factors and current fashions. Some schedules were designed to emphasize a particular type of product (e.g. high-quality sawlogs, or pulpwood). The Western Australian "Silviculture 74" and some silvopastoral regimes (see Chapter 10), both of which advocated very low final crop stockings, were trends that were ultimately deemed unsatisfactory. Fortunately, due to the flexibility of the species, the earlier and often untended first-rotation plantations that were on suitable sites generally performed adequately (in terms of volume), although perhaps not optimally.

To put tending into a forest management context, the largest economic decision a manager will make is where, what and how much to plant. Only then does the actual regime assume importance.

CHOICE OF TENDING SCHEDULES

The range of silvicultural schedules or regimes being practised can be bewildering initially. The optimum schedule for radiata pine depends largely on context. As Maclaren and Knowles (2005a) emphasized, the demand for "off-the-shelf regimes" should be resisted.

A silvicultural schedule that is appropriate for one grower may be inappropriate for another. The factors that are usually considered in making such decisions are:

- the owner's mission (related to the type of investor, such as public or private enterprise, smallholder, community or investment fund);
- specific management objectives (e.g. quality sawlogs or shelter);
- social, cultural, environmental and political conditions;
- physical site conditions;
- location and infrastructure;
- financial aspects, including return on investment and cash-flow bottlenecks;
- the complexity and costs and benefits associated with multi-products;
- vulnerabilities, and tolerance of risks;
- management ability and constraints.

There are many facets to risk, including biotic, abotic, financial and market-related. For some managers, long-term silvicultural flexibility is rated highly because of uncertainty about how stands will be used.

The usual approach, after weighing these factors, is to develop silvicultural regimes for specific sites. These usually prescribe how the stands should be grown and include factors such as planting stock, stand density control, whether and how the stand should be thinned and pruned, and how long it will be grown. Another related approach is to prescribe the ideal stand attributes being sought for particular site conditions. The advantage of this approach is that it gives a simple picture or set of criteria that should be aimed for and allows the manager to monitor success.

Most large-scale plantation managers rely on computer models to develop schedules for given sites (Maclaren and Knowles, 2005a; West, 2005). Since the optimal performance of a specific site depends on multiple variables (see Chapter 2), silviculture needs to be site-specific (Toro, 2004). Recently developed techniques using remote sensing and other technologies now allow managers of larger plantations to measure stand growth and other attributes during the rotation relatively easily and inexpensively.

An increasing number of management tools are available to help in developing optimum schedules and for managing plantation forests (see discussion below). For example, the New Zealand Forest Research Institute (now Scion) has developed a number of plantation management aids, which are available under the ATLAS label. Increased computing power and information storage is allowing more complex scenarios to be modelled and facilitating the management of plantations in finer detail.

Schedule evaluation

Evaluation techniques have developed rapidly and have been important in the success of plantation forests, including radiata pine. New concepts and modelling systems allow management alternatives to be considered that would not have been possible 40 years ago. When evaluating schedules, the following need to be considered: management objectives and economic factors (Chapter 3); wood quality and stand growth (Chapter 5); and site factors and biological feasibility (Chapter 2).

In economic evaluations it is the norm to compare various alternative schedules, initially at the stand level and later using estate models for a more refined assessment. The usual method uses discounted cash-flow analysis, although for some enterprises where finance is critical it is also important to consider the cash flow on a year-to-year basis.

To perform a discounted cash-flow analysis for a commercial crop requires:

- accurate yield tables of specified products for production thinnings and optional clearfelling ages. These are often obtained from models that estimate, over time, recoverable log volumes and grades, including aspects affecting log quality, the cost of land and operations, and the year the operations are carried out;
- annual overhead costs to cover administration, fire control, land taxes, insurance, etc.;
- current revenues at the price point for the products specified in the yield table;
- an acceptable discount rate.

For wood production it is necessary to decide at which point along the production cycle the evaluation ought to take place. The usual choices are: on stump (before logging); on ride (e.g. log grades after logging); at mill door or the wharf (logging including transport); and after conversion into the final saleable products. In the future, ecosystem services (see Chapter 3) are likely to be included in schedule evaluations. For carbon sequestration and some other ecosystem services, a longer-term horizon and selection of discount rates needs to be considered.

The main factors that usually alter comparisons between wood-production schedules are:

- discount rate;
- location and infrastructure;
- growth rate and factors influencing log quality;
- site factors such as weeds, topography and soil constraints that will influence establishment and other tending costs;
- size of operation, which can reflect itself in overheads and logging costs;
- logging costs, which are strongly affected by topography;
- the intensity of management and silvicultural choices, including stock quality, initial and final stocking, timing of pruning and thinning, rotation length, etc.;
- biotic and abiotic risk factors;
- relative product values.

Of these, discount rate, because of its inherent exponential nature, is the most important factor affecting economic evaluation (Maclaren and Knowles, 2005a). Most economic analyses should be viewed with a certain amount of scepticism since they usually involve many assumptions and imperfections. For example, errors associated with volume estimates are seldom considered and models are often incomplete. However, ranking alternative schedules is usually reasonable, particularly when differences are large. Sensitivity analyses, where factors are altered by set amounts, can help clarify the important factors influencing profitability.

Wood quality is discussed in greater detail in Chapter 5. An evaluation of wood quality and product outturn requires the development of models grounded in good databases, with the results linked to manufacturing and marketing options. If predictions of wood quality and product outturn from models or actual stand data are unavailable the evaluation must use simpler approaches, such as attempting to match anticipated characteristics with future markets.

Any devised schedule must be biologically acceptable for the site conditions and associated biotic and abiotic risks. Sustainability issues should also be thought through (see Chapter 11). Is the schedule going to lead to reduced growth from one rotation to the next because of a reduction in the site's nutrient capital? If this is likely, how can the risk be ameliorated? The cost of ensuring long-term sustainability should normally be included in any evaluation. Other sustainability issues might concern the risk of disease, insects or fire, erosion, biodiversity, energy and material inputs, the carbon balance and social acceptability. The use of energy analysis, although still uncommon, has been advocated as an additional criterion for selecting silvicultural schedules (Mead and Pimentel, 2006).

It is also important to be aware that schedules with low stockings (relative to tree size) may lead to incomplete occupation of the site (Box 9.1 and Chapter 5). This will not only influence stand productivity in terms of wood volume but alter timber quality and the potential provision of other services. More than 20 percent of timber volume can be lost, and reduced wood quality is of particular concern on fertile sites. Together, the reduction in wood volume and quality could result in low revenues – this has particularly been a problem in Australasia. Part of this adverse outcome resulted from the use of incomplete models that did not evaluate the effects of low stockings on intrinsic corewood properties (see Chapter 5). Furthermore, the extra light reaching the forest floor may allow the development of either useful plants or weeds and alter stand biodiversity.

The forest manager needs to consider these issues when determining which schedule to implement. Some are not explicit in current decision-support systems, although with time they are likely to be included.

BOX 9.1

Effect of silviculture on a fertile farm site in New Zealand

The 93 ha Tikitere agroforestry experiment near Rotorua, New Zealand, was established on a fertile farm site (site index of about 33 m and 300 index of about 33 m^3 per ha per year). Since the final crop stocking ranged from 50 to 400 stems per ha, the experiment has provided insight into the effect of stocking on growth rates and timber yield.

Radiata pine seedlings (GF 13) were planted at five times their final crop stocking. They were pruned to 6 m in 4–5 lifts and thinned to waste twice in the first eight years (10 m height). Pastures under the trees were grazed.

Low stockings substantially reduced height, so that at age 20 years the site index ranged from 25.4 m at 50 stems per ha to 33.5 m at 400 stems per ha. Height growth was strongly influenced by stocking.

Final stems/ha	Height* at 25 yrs (m)	Mean dbh at 25 yrs (cm)	Basal area at 25 yrs (m^2/ha)	Volume at 25 yrs (m^3/ha)	CAI at 25 yrs (m^3/ha/yr)	MAI at 25 yrs (m^3/ha/yr)
50	31.1	81.1	24.2	213.0	11.9	8.5
100	33.1	75.1	42.1	400.1	19.0	16.0
200	36.6	60.7	55.0	604.4	17.9	24.2
400	39.6	50.4	74.3	935.3	21.7	37.4

* = Mean top height.

At low stockings, mean diameter was substantially higher than at high stockings, but the basal area and total stem volumes were much lower. At age 25 years, CAI was higher than MAI for some stockings, indicating that the site was still not fully occupied. Further, the low CAIs reflect that year's drought.

The assessment of log quality at age 21 years (see below) found substantial differences in the volumes of pruned logs, small branched logs (<7 cm), large branched logs (>7 cm) and pulpwood, and in total recoverable volume.

Final stems/ha	Pruned logs (m^3/ha)	Small branched logs (m^3/ha)	Large branched logs (m^3/ha)	Pulp logs (m^3/ha)	Merchantable volume (m^3/ha)	% pulp logs
50	69.6	1.3	15.1	42.1	128	33
100	128.5	1.7	57.8	81.3	269	30
200	182.6	21.5	135.7	67.2	407	17
400	210.7	186.6	224.1	46.5	668	7

The 400 stems per ha treatment produced greater volumes of higher-quality logs and only a small proportion of pulp logs. It also produced five times more wood than the 50 stems per ha treatment. A stocking of 200 stems per ha reduced merchantable volume by almost 40 percent.

Sources: Maclaren and Knowles, 1999; Hawke, 2011

PRINCIPLES OF STAND DENSITY CONTROL

A basic law of stand development and silviculture is that as even-aged stands or groups of trees develop, there is a gradual diminution in tree numbers (see Chapter 5). In untended stands, this is caused by inter-tree competition; with tended stands, stand density is controlled by the forest manager.

Stand density control influences the degree of site use, the rate of tree and stand growth and the shape and length of crowns. This ultimately has large effects on wood quality, end-use potential and value. Thus, stand density influences stem slenderness, which in turn affects wood stiffness. It also influences tree selection during thinning and other factors such as tree stability and disease spread. Most decisions on initial spacing and timing and the intensity of thinnings, once implemented, cannot easily be reversed.

Stand density decisions are usually central to developing silvicultural schedules. Initial spacing, natural mortality and thinnings lead to one of the most important stand attributes – the final stocking at harvest. They are thus closely interlinked with other silvicultural operations.

Stand density management is thus a combination of the following choices:

- initial stocking and spacing;
- the state of the plantation at the end of the establishment phase;
- the timing of thinnings;
- the type of thinning (low, crown, etc.);
- production vs non-production from thinnings;
- the criteria for selecting trees during thinning;
- the intensity of thinnings;
- the final crop stocking;
- the rotation length;
- abotic and biotic factors.

Initial stocking

The choice of initial stocking (stems per ha) depends on the:

- quality of the planting stock, particularly its genetic improvement;
- presence of weeds;
- selection required – i.e. the ratio of planted trees to final crop trees;
- final crop stocking;
- need for mutual protection against wind and perhaps snow;
- minimizing natural mortality from competition before first thinning or harvesting;
- rapidity required to occupy the site;
- requirements for production thinning in terms of out-rows and volume requirements;
- requirements for aspects of wood quality, such as corewood properties and branch control;
- establishment and tending costs.

The tree improvement programme and, to a lesser extent, better nursery and establishment practices have had a large impact on initial stockings. This is evident when comparing past Australasian selection ratios with present-day ratios. In the 1960s, selection ratios with unimproved trees were typically 5:1 or higher, with typical planting densities of 1 600 stems per ha or higher and final crop stockings of 300–350 stems per ha. Today, selection ratios can be as low as 2:1 to 3:1, particularly for non-production thinning schedules. The very best genetic material has been planted at less than a 2:1 ratio, although this may be risky, because unless there is full establishment there may be canopy gaps and incomplete site use. It is also likely that, over time, managers have become more stringent in their requirements for acceptable trees. Interestingly, in Spain, radiata pine is still planted at a high stocking, typically with a selection ratio of 4.5:1 (Rodríguez *et al.*, 2002a).

Table 6.3 suggests that unimproved seed generates about 45 percent acceptable trees and the best genetic material about 80 percent. Cuttings from aged parents also improve the proportion of straight trees (Menzies *et al.*, 1989). These changes have driven the reduction in selection ratios. But if 80 percent of trees have acceptable form, why still plant at a 1:2 ratio or even more? There are several reasons for this:

- Many forest managers tend to be risk-averse, adopting a safety margin.
- Despite better establishment techniques, there are still occasional deaths, and

blanking has proved to be an unsatisfactory option except where there have been large-area failures. The additional numbers help ensure a reasonable stocking (sometimes called a stocking reserve).

- The acceptability estimates made by tree-breeders in New Zealand at age 5–10 years uses simple acceptable/not acceptable criteria. This may not reflect how trees develop. Furthermore, these trials are usually made on average forest sites and may not be directly transferable to very fertile farm sites or to sites where the trees are stressed for nutrients or moisture.
- Mutual protection and effects on height growth development require a minimum stocking of 600 stems per ha (Maclaren and Knowles, 2005a).
- Stocking needs to be sufficient to allow for selection during thinning and pruning operations. Trees can be damaged between operations, or their social status might change, particularly during the formative stages of the stand. There is evidence to suggest that selection in typical radiata pine stands before age seven years is of limited benefit (Maclaren and Knowles, 2005a).
- A relatively high initial stocking can help to improve the corewood quality or to get branch size control in the lower part of the stem.
- Some growers aim for maximum production and/or plan to have production thinnings. For the latter to be economic it is usually necessary to extract more than 50 m^3 per ha and if there are insufficient trees this may not be obtained.

An experiment performed in New Zealand that compared selection ratios of 1–6 with open-pollinated seed orchard stock on a good site found that stem form and merchantable volume improved with increasing selection ratio (Maclaren and Kimberley, 1991). It also found the proportion of straight, round, good pruned logs increased from 74 percent to 94 percent while good unpruned logs rose from 70 percent to 90 percent as the selection ratio increased from 1 to 6. Mean top height, total volume and pruned log volume were all improved by higher selection ratios, although mean diameter was not altered. However, the optimum economic selection ratio depended on the discount rate; at 5, 8 and 10 percent, the optimum selection ratio was 6:1, 4:1 and 1:1, respectively. These economic analyses need to be treated with caution because of cost and revenue assumptions. In the same trial, tree-breeding (GF 3 compared to GF 13) increased the proportion of good stem-formed trees by 17–20 percent.

There are situations where different approaches may be suitable. Some trials and small growers have shown that it is possible to get away with low ratios when growing on pruned clearwood schedules. Designer clonal trees are another option for overcome the problem of low-quality corewood. There are also situations where the stands can be left unthinned and where stem straightness is of lower priority; pulpwood schedules, for example. Some growers in Australia and Chile have also been known to plant at higher stockings on their fastest-growing sites, and some specialist crops like poles and Christmas trees often require higher stockings.

THINNING OBJECTIVES

The main reason for thinning is to ensure that only trees of good form and vigour will be left to grow on to become valuable, final crop trees. Thinning essentially concentrates the growth potential of the site onto the crop trees. Large trees are usually of greater value than small ones (of the same quality) because large trees are usually cheaper to harvest and use than the same volume of smaller material and have greater end-use potential and flexibility. If the stand is being pruned at a young age, larger trees have the advantage of producing a greater amount of clearwood.

Other objectives may be to:

- prevent natural mortality, and if production thinning is used, to use this wood;
- improve stand health by removing weaker trees and allowing greater air movement in the stand;

- achieve greater stand stability (resulting from early thinning);
- provide intermediate income between planting and final felling;
- provide certain products (e.g. pulpwood, posts or poles) required by the market.

Generally there is a need for at least one thinning with radiata pine (Maclaren and Knowles, 2005a). In New Zealand, one or two thinnings are common in non-commercial thinning schedules and, where it is applied, there is only one commercial thinning (Tables 9.1 and 9.2). Two (sometimes three) production thinnings are common in Australia, Chile, South Africa and Spain (Lewis and Ferguson, 1993; Fernández

TABLE 9.1
The current range of typical radiata pine thinning schedules in non-pruned stands

Region, Site index (SI), topography and other limitations	Operation	Age (yrs)	Height* (m)	Stocking (stems/ ha)	Predominant output
South Australia:[a] SI 26–29; gentle; sands; moisture	Planting	0	0	1 600	
	Production thinning	10–13	15–22	700	Chip, pulp
	Production thinning	17–22	23–31	450	Pulp, sawlogs
	Production thinning	24–31	29–36	250	Sawlogs
	Clearfelling	32–37	32–39	0	Sawlogs
Western Australia[b] SI 27–28; flat; sands	Planting	0	0	1550	
	Production thinning	15–16	22	600	Chip, posts
	Production thinning	22–23	31	300	Chip, sawlogs
	Clearfelling	30	34	0	Poles, sawlogs
Auckland, New Zealand[c] SI 25; gentle; coastal sands	.Planting	0	0	1 000	
	Production thinning	10–12	15	350	Posts and poles
	Clearfelling	27–28	30	0	Sawlogs
Nelson, New Zealand[d] SI 27; Steep; infertile; weedy	Planting	0	0	800–1 000	
	Thin to waste	7–9	10–14	500	Nil
	Clearfelling	27–30		0	Sawlogs
Chile[e] SI 25; Steep	Planting	0	0	1 600	
	Clearfelling	15–18	18–21	0	Chip

Note: * = Predominant mean height or similar.

Sources: a = Lewis and Ferguson, 1993, G. Brooks, personal communication, 2012; b = I. Dumbrell, personal communication, 2012; c = P. Houston, personal communication, 2012; d = A. Karalus, personal communication, 2012; e = Mead, 2010a

TABLE 9.2
Current typical pruning schedules with radiata pine

Region and site Site index (SI), topography and other limitations	Operation	Age (yrs)	Height* and (crown length) (m)	Stocking** (stems/ha)	Predominant output
North Island, New Zealand[a] SI 30; Flat; sometimes frosty or compacted	Planting	0	0	1 000	
	Prune to 3.5 m	6	7.5 (4)	375	
	Prune to 5.6 m	7–8	10	375	
	Thin to waste	7–8	10 (4)	750–800	Nil
	Thin to waste***	10	14	375	
	Clearfell	29–32	40–44	0	Sawlogs, pulp
Chile[b] SI 31; easy	Planting	0	0	1 250+	
	Prune to 2.2 m	5	7–8 (4.5-7)	700	
	Prune to 4.0 m	8–9	9–11 (5-7)	450–500	
	Production thinning	8–10	11–13	600–700	Pulp
	Prune to 5.5 m	8–10	11–13 (5-7)	400	
	Prune to 7.9 m#	10	13 (5)	250	
	Production thinning	12–14	~22	400	Pulp
	Clearfell	24–25	~35	0	Sawlogs; pulp
Spain[c] SI 26	Planting	0	0	1 700	
	Prune to 2.6m	8	~10	1 360	Nil
	Production thinning	12	16	790	Small wood
	Prune to 5.6 m	15	~20	~450	
	Production thinning	20	26	446	Sawlogs; pulp
	Clearfell	30	32	0	Sawlogs

Note: * = Predominant mean height or similar, **Stocking after thinning or number of stems pruned,

*** This second thinning to waste may be replaced by production thinning at 11-12 years, # By some companies only.

Sources: a= D. Balfour, personal communication; b= Mead, 2010a, Sotomayor, Helmke and Garciá, 2002; c= Recent schedule for private plantations on better sites (Rodríguez *et al.*, 2002) and Sarmiento, 2004). The lower emphasis on production thinning in New Zealand is because of topography, the windy climate, a lack of markets, damage to stands during production thinning, reduced productivity of the final crop and higher costs (Maclaren and Knowles, 2005a).

The most common form of thinning in radiata pine plantations is low thinning, or thinning from below (Lewis and Ferguson, 1993). In this form of thinning, the lower crown classes are preferentially removed, with an emphasis on leaving the best-formed trees and, to a lesser extent, obtaining an even spacing. With production thinning it is common in Australia to take out every fifth row, known as out-rows, to aid access and to thin the areas between (known as bays) by low thinning. After a low thinning, the mean diameter, mean height and quality of the stand all increase. Crown thinnings (thinning from above) and selection thinnings are not practised regularly with radiata pine.

These days, radiata pine growers do not refer to traditional thinning grades, but usually define the intensity of thinning by prescribing the number of trees to leave. Occasionally, the residual basal area or relative spacing (spacing in relation to dominant height) is used.

Effect of stand density on stand characteristics

The dynamic nature of stand development has been described in Chapter 5 from the viewpoint of both individual trees and the stand. That chapter also gives an overview of wood properties and products.

Initial stand density, genetics, establishment practices and site factors all influence the timing of crown closure. The maximum crown closure in radiata pine stands is about 85 percent (Knowles *et al.*, 1999). As the crowns close, branch growth in the lower part of the tree crown slows down, controlling knot size, provided the stand is not thinned. This competition also reduces tree diameter growth. On impoverished or dry sites, crown closure may not occur, but if the site is very deficient in nitrogen or phosphorus, the lower crown may still die off as these mobile nutrients are retranslocated to the upper crown.

As the stand continues to grow taller, the lower branches die off, knots become bark-encased, and the base of the green crown begins to rise (Figure 9.1). Unlike some other species, radiata pine does not boast an efficient self-pruning mechanism. If the stand remains unthinned for a long time, the crowns become very narrow, with minimal branch interlocking (radiata pine has shy crowns), and natural tree mortality will occur.

In direct clearwood schedules, the maximum branch index in second logs decreases with increasing site index but increases with higher fertility, such as on ex-farm sites. Nevertheless, the relationship between tree diameter and branch index is relatively constant.

From a silvicultural point of view, controlling stand density provides a method for controlling knot size and type, at least to some extent, and hence for influencing timber grades (Box 9.1). Branch index (see Chapter 5), or the diameter of the single largest branch (as used in the New Zealand log grades), has proved to be a useful way of relating stand silviculture to timber grades for structural wood. For example, a branch index of 4 cm will provide over 40 percent No 1 framing grade from 5–6 m logs exceeding 300 mm small-end diameter (Figure 5.5). Similarly, there may be branch size restrictions for logs sold in some markets.

Trees grown close together have lower taper; this improves corewood properties, particularly stiffness and wood shrinkage (see Chapter 5). Additionally, as the green crown rises, the lower bole tends to become more cylindrical below the green crown; growth rings will be narrower than where trees are given more space. With suppressed trees, growth at breast height may actually stop, although some diameter growth

FIGURE 9.1
The rise of green crowns results in the development of bark-encased knots after branches die

may continue to occur further up the tree. This is because trees first allocate their photosynthates to crown growth and respiration before assigning them to stem growth.

Other biotic and abotic factors

Thinning and pruning are often advocated to reduce the impact of diseases and pests (see Chapter 4). Keeping trees vigorous is a major way of keeping stands healthy.

Tree stability is also a major consideration when thinning. Juvenile instability or toppling is discussed in Chapter 8. Juvenile instability is largely associated with the establishment process and part of its importance is its effect on wood quality and the need to allow for culling the worst-affected trees.

In addition to juvenile instability, thinning very tight stands can lead to trees bending over, breaking or falling. Wind damage is generally confined to the first few years after thinning – until the trees have time to rebuild crowns and increase in diameter. Thinning also changes the wind turbulence characteristics over the stand, leading to potentially greater forces on the trees.

There are several suggestions for minimizing wind damage in established stands. Somerville (1989) argued that, in wind-prone areas, it is probably best to aim for a smooth canopy (to reduce turbulence) and close relative spacing so that individual tree crowns remain relatively small. Somerville (1989) cited several examples where higher stockings had led to greater stability but noted that there were exceptions.

Management criteria that have been used to reduce the risk of wind damage in radiata pine stands include (Cremer *et al.*, 1982; Lewis and Ferguson, 1993):

- using a height:diameter ratio (sometimes called the slenderness ratio) of the largest 200 trees per ha. Where this is less than 70, stands are relatively safe, although this rule is not absolute;
- minimum average growing space (m^2) equal to the dominant height (m);
- avoiding thinnings after subjectively defined critical heights. For example, in Canterbury, New Zealand, which is subject to extremely strong winds, thinning stands over 15–17 m high is not recommended. On less windy sites, some managers do not thin after stands reach 20 m in height;
- improving or avoiding soils that severely restrict root development.

Potential damage by snow is also a factor. Much like wind damage, keeping a height:diameter ratio of less than 70 has been found to reduce the risk of snow damage, and thinning before the stand reaches 20 m in height is also recommended (Cremer, Carter and Minco, 1983). In Spain, a slenderness ratio of less than 85 (for all trees) is used for both windthrow and snow (Rodríguez *et al.*, 2002a). However, where snow is a major risk, selection of snow-tolerant species may prove to be a better solution.

Final crop stocking

The final crop stocking, often achieved through thinning, is closely tied to rotation length and final log size. There has been considerable debate in the past 40 years about the ideal final crop stockings for radiata pine. Most of the debate was generated by the introduction of the direct sawlog or clearwood schedules, which did not envisage late thinnings. However, in a broader context, it is governed by the same factors as those discussed above.

With clearwood schedules using non-commercial thinning, the tradeoffs are between total stand volumes, the size and value of the pruned butt logs, the quality of the upper logs and the optimum financial rotation. In recent years, the quality aspects of the corewood have also become important (see Chapter 5). Part of the debate has focused on the timing at which managers should achieve the final crop stocking, including risks from windthrow, and the optimum length of the rotation. In terms of profitability, there is often a wide range of acceptable final crop stockings because volume is traded off against log size and wood quality.

There have been some interesting trends in final crop stockings in actively managed radiata pine stands. Before the development of the "direct" schedules in New Zealand, which use non-commercial thinning, most growers considered that a reasonable final crop stocking for sawlogs was about 350 stems per ha. It was lower than this in the managed 40+ year rotation stands in Australia (Lewis and Ferguson, 1993). However, introduction of the integrated stand modelling system SILMOD (and later STANDPAK) by the New Zealand Forest Research Institute in the early 1980s suggested that these stockings were much too high: "Extensive use of SILMOD has shown that maximum volume production, which requires high stockings, is incompatible with maximum profitability" (Whiteside and Sutton, 1986). There was, therefore, a trend among many growers in New Zealand and Australia to reduce final crop stockings to about 200 stems per ha, and even lower where silvopastoral systems were being advocated.

However, this trend has now been reversed, for three major reasons. First, it was found that the models upon which these recommendations were based were inaccurate at such low stockings; these older models were superseded by models that gave better predictions of growth (see modelling systems below). Second, it was found that on very fertile sites, wood properties were less favourable. Finally, the trend reversed because there was a lower volume of production (Maclaren, 2005; Box 9.1). Thus, for typical forest sites of average-to-good fertility, many forest growers use final crop stockings in the range of 250–350 stems per ha for rotations of 25–35 years (Tables 9.1 and 9.2). Final crop stockings tend to be higher in Spain (Rodríguez *et al.*, 2002a).

Rotation length

Rotation lengths in radiata pine typically range from 18 to 40 years (Table 1.4). Several criteria can be used to assist this decision, which may be grouped into five categories:

- biophysical reasons;
- technical optima based on end use, wood industries' technology, wood quality and market constraints;
- optimizing volume out-turn or biomass;
- optimizing economics;
- other management constraints or opportunities.

The biophysical impacts on rotation length can be quite varied. In the broad sense, this includes the rate of growth of a species, its growth pattern, onset of decay, stand breakdown from various causes, reproduction, and even perhaps arguments about biodiversity. For example, an ecologist's optimum may comprise the complete cycle of growth, maturity, death and decay, while for production plantations the latter part of the cycle is unimportant.

However, for radiata pine, the main biological constraints are risk from windthrow, and harvesting impacts. In windy climates, long rotations may pose too great a risk. In some parts of New Zealand, managers have reduced rotations of radiata pine by a few years because of this risk. Harvesting trees at very frequent intervals (short rotations) can sometimes be detrimental to site productivity, although the methods used in harvesting, and the parts of the tree that are removed from the site, can be even more important (see Chapter 11).

Wood quality and end use are often important criteria and are themselves associated with end-use potential and market requirements. Wood quality varies with stand age and can influence rotation length (see Chapter 5). For example, the rotation age for high-quality poles must allow sufficient time for high-density outerwood to form in order to give the pole sufficient strength. Generally, this would require a rotation of at least 20 years, even though the same-dimension material could be grown more quickly. Similar arguments can be put forth for not growing sawlogs on very short rotations, while for mechanical pulps there are some advantages in producing young material. Sometimes the market or sawmills place constraints (both small and large) on piece size, and this too is partly tied to tree age. Very large logs, for example, may be too large for debarking or for saws. Rotation length is also strongly tailored for the production of Christmas trees, which are usually grown to about 3 m in 4–5 years (their growth being slower because the trees are pruned to give them a bushy appearance).

A traditional method for setting rotation length has been to optimize the MAI of harvested volume from the site. This occurs when the merchantable CAI equals the MAI. Regenerating at this point maximizes the productivity of the site, although the timing has wide latitude because change can be quite slow. Today, this method of setting a rotation length is seldom used for radiata pine plantations.

Financial methods for setting rotation lengths are generally considered much more suitable than using maximum MAI (see Chapter 3). Financial analysis takes account of different product values, trends in real prices, the value of money (discount rate), the value of land and risk. The recommended procedure is to base the rotation length on the maximum net present value or IRR; these will be shorter than the maximum productivity rotation length. The higher the discount rate, the shorter the rotation will be. The choice of discount rate is therefore very important and is likely to vary by owner. Other factors such as site and stocking will also influence rotation length.

Rotation lengths are often affected by other management factors. For a large enterprise these might include considerations such as the requirement of wood for a manufacturing plant, the impact of imbalances in age classes, the investment profile and strategic goals. For a small owner, other factors may influence the decision, such as cash flow, taxes and market opportunities.

Radiata pine is almost always grown in even-aged stands. However, in North Canterbury, New Zealand, John Wardle, a farmer with a 30 ha radiata pine plantation, is attempting to regenerate stands by each year removing selected trees with a diameter of over 60 cm (see also Chapter 8). Although he has obtained groups of radiata pine regeneration, the long-term viability of this approach is yet to be proven. This selection (or "continuous canopy") system would probably only be suitable in unique situations.

NON-PRUNING TENDING SCHEDULES

The control of branch size is part of the rationale behind the structural, non-pruning, structural sawlog schedules widely used in Australia and New Zealand (Table 9.1). In the Australian production thinning schedules, the first thinning does not occur until the green crowns have started to rise (Figure 9.1). Subsequent production thinnings gradually reduce this stocking in such a way as to ensure small knots.

The Australian examples in Table 9.1 have two or three production thinnings because they are on easy country conducive to production thinning and have industries that can use chip or pulp logs and/or posts, as well as small sawlogs to provide timber for the domestic housing market. Both the South Australian and Western Australian examples employ sophisticated harvesters and forwarding systems (Figure 9.2) and take out every fifth row to aid access and reduce tree damage. In Western Australia, there is currently a market for valuable large poles, so between 6 and 15 trees per ha

FIGURE 9.2
Mechanized thinning in South Australia

are harvested separately at clearfelling for this market. The New Zealand example of production thinning in unpruned stands is also on easy topography and supplies a local post and pole market. In this case, the initial stockings are lower, with trees planted at 5 × 2 m spacing to aid access, and there is only one thinning. On all these sites, tree form is good and corewood properties are reasonable, due to climate and nutrient and/or moisture stress. Thinning heights are also chosen to reduce wind problems.

In New Zealand, unpruned sawlog structural schedules were developed that do not include production thinnings (so-called "direct" schedules). Again, consideration was given to controlling branch size to meet market expectations for house-framing timber (Fenton, 1971). This early version recommended planting at about 2 500 stems per ha and a single thinning to 350 stems per ha at a top height of 18 m. This height was chosen to control the branch size in the bottom two logs, which are the most valuable logs in the tree. This schedule aimed for a tree diameter of about 45 cm on a 30-year rotation and gave a good return on investment. Fenton and Tennent (1976) argued that a similar schedule, with lower initial stockings (1 530 stems per ha) and a single thinning to waste at 11 m – to 370 stems per ha – could profitably be used for the log export trade.

In the current version used in New Zealand, the initial stockings have been reduced further because of improved genetic material and establishment practices. Thinning to waste occurs at 10–14 m height (Table 9.1, Nelson example). The use of highly improved planting stock on low-to-medium fertility, weedy sites ensures that branch size and wood quality are reasonable. The sites are often steep and unsuitable for production thinning. On very fertile sites, such schedules may run a risk of overlarge branches. Another reason for the earlier thinning is to avoid wind and snow damage.

Schedules designed to produce structural wood need to take into account stiffness (MoE) and the poor quality of the corewood in many radiata pine trees (Walker and Butterfield, 1995; Moore, 2012; see Chapter 5). A structural wood index, yet to be developed, would assist managers to grow these stands correctly (Mason, 2012).

Up to 10 percent of stands grown by large pulpwood companies in Chile are managed on non-thinned, short-rotation pulpwood schedules (Table 9.1; Sotomayor, Helmke and Garcia, 2002; Mead, 2010a). The stands tend to be on steep, lower-quality sites, where production thinning is less attractive. In the example given in Table 9.1, trees are planted at relatively high stockings and clearfelled at 15–18 years of age. Using a lower initial stocking of 1 250 stems per ha, the optimum rotation length is 20–25 years (Sotomayor, Helmke and Garcia, 2002).

Similar non-thinning schedules may be appropriate for post and pole schedules on some sites, although earlier research, with less improved genetic material, suggested that light thinning may be beneficial (Manley and Calderon, 1982). As the production of high-quality pole material requires meeting specifications for size, straightness, branch size and number of rings, keeping stands tight is important. One difficulty with pole-only schedules is that the diameter size distribution may provide difficulties in meeting pole specifications. Site selection should also be considered, because medium-to-low fertility sites in areas of high wood density and strength give added advantages. Calderon and Maclaren (1988) also suggested that pruning may be beneficial.

Features of post and pole schedules are:

- high initial stockings;
- light thinning and perhaps pruning;
- final crop of 600+ stems per ha;
- rotations of 18–30 years, with longer rotations including sawlogs;
- small final-crop mean diameters.

Pole schedules are seldom used because of market risk. Further, they can be produced, if required, in some structural sawlog regimes, as they are in Western Australia (Table 9.1).

Thinning techniques

For waste thinning, chainsaws are the most common tool used, although other tools such as axes and scrub-cutters (brush saws) are used occasionally with natural regeneration. Labour requirements for power-saw thinning vary with site conditions, the size of trees, the numbers thinned per ha and operator skill – typically it will take an operator 6–12 hours to thin out 400 trees per ha (Maclaren, 1993). With waste thinning, trained workers usually perform the tree selection, but where this skill is lacking the trees can be marked by a supervisor. If waste thinning is associated with pruning it is best that the pruning is done first and selection is carried out by these workers. There are several reasons for this:

- pruners, partly for safety reasons, are in a better position to inspect the surrounding trees and choose the best;
- there is less of a problem with slash hindering movement from tree to tree;
- thinning is more final (if a pruner finds that the selected tree is unsatisfactory, another can be chosen);
- quality control is easier.

Pruners should be motivated to select the best-formed and most vigorous trees for retention. There may be a bias towards lightly branched or less vigorous trees. On the other hand, thinners are likely to be biased towards leaving the largest trees, despite their form.

Maclaren (1993) stated that the criteria, in order of importance, for radiata pine tree selection should be:

- the best formed trees. This involves rejecting malformed trees where the stem at any point passes outside an imaginary line between the midpoint of the stump (0.3 m) and the tip. Double and multiple leaders are also rejected. It is important to keep in mind that the most valuable part of the tree is the bottom log;
- vigour (i.e. thin from below);
- condition of the leader;
- spacing.

The technique of poison-thinning is seldom employed today, although it was common shortly after the Second World War and is still used to kill woody weeds and radiata pine wildings. There were several reasons why this technique was discarded in tended stands:

- The poison-thinning of young stands required more or less the same effort as using power-saws and sometimes the tree was not killed.
- The stands were unsightly.
- Trees decayed slowly, which potentially posed a hazard for subsequent workers.
- There was the risk, particularly in older stands of some species, that the poison would affect adjacent crop trees because of root grafting.
- Fire risk was perhaps slightly greater.

However, a trial involving radiata pine under current management regimes did not find that poison-thinning posed a risk of damage to crop trees or that slow decay was a threat (Maclaren *et al.*, 1999). Nevertheless, chemical thinning was not recommended, except in special situations such as to control wilding spread or perhaps to control natural regeneration within a plantation (see also Chapter 8). Where wildings are being removed, the slow decay of standing trees from poisoning may be an advantage over felling the trees as it would minimize damage to other vegetation.

Production thinning is often restricted to easy topography, as this allows the use of machines. Therefore, some enterprises will have separate schedules depending on topography. Nevertheless, production thinning is still carried out in steep country, particularly where labour costs are low.

A wide range of equipment can be used for production thinning of radiata pine, depending on social conditions, available capital, the skill of workers and the size of

FIGURE 9.3

Stands of radiata pine with too high a height-diameter ratio can have stability problems

operations. Options range from hand or animal-assisted extraction of small material to the use of sophisticated machines that fell, delimb and bunch logs (Figure 9.2).

Production thinning with machines usually requires a minimum harvestable volume of 50–70 m^3 per ha to be economically viable, although there can be exceptions to this rule. The use of machines may require the removal of rows to aid access. Nevertheless, damage to remaining trees may occur.

The type of material extracted in production thinning is usually of lower value than at clearfelling, often with a high proportion of chip or pulpwood; less frequently there is a market for post and pole material (Table 9.1). Although the extraction of some small sawlogs may be possible before age 20 years, these will suffer from having a large proportion of lower-density corewood and produce low-grade sawn timber. Typically 30–45 percent will end up as box grade. Markets for smallwood from thinnings often fluctuate, unless the plantation is supplying a large industry. The biggest silvicultural danger is waiting for a market to develop or for market prices to increase and delaying thinning as a result. This delay increases the risk of windblow, as late-thinned stands often have stability problems (Figure 9.3).

PRINCIPLES OF PRUNING

Radiata pine does not readily self-prune within normal rotation lengths. In this it is similar to many other important plantation trees, such as Douglas fir and Sitka spruce. Many species do self-prune more readily, including southern pines and some of the eucalypts. However, even for these species it is sometimes advantageous to assist the stands by artificial pruning, particularly if branch size is relatively large.

In one sense, pruning a forest tree is no different from pruning a horticultural or ornamental tree. In all cases, the branching habit of the tree is being altered to suit a particular end. In horticulture, the aim may be to maximize fruit production; with ornamental trees it may be to control growth and improve aesthetic qualities. For forest trees there are other motives. In all cases, pruning is based on an understanding of the basic biology of the tree and how it will respond to the operation. While the techniques for pruning radiata pine are not necessarily directly applicable to other tree species, some general concepts and ideas may be so.

Pruning objectives

There are a number of objectives for the pruning of forest trees, and sometimes one will strongly outweigh another. For radiata pine and many other plantation species, objectives may include:

- improving access to the stand;
- reducing the danger of crown fire;
- improving stand health;
- improving stand aesthetics;
- reducing degrade of timber from knots;
- producing clearwood.

The most demanding of these objectives is to produce clearwood (Figure 9.4). Pruning for clearwood production, while not a new concept, was intensively researched and developed in New Zealand, beginning in the 1960s. The concept of the direct clearwood schedule was first published by Fenton and Sutton in 1968. Many concepts were researched in New Zealand during the period of the Radiata Pine Task Force (1978–1981) and have been refined since.

Clearwood production is achieved by pruning off branches and allowing subsequent diameter growth to first occlude over the branch stubs and then to produce a clearwood sheath. The occlusion process occurs relatively rapidly in radiata pine because of its fast diameter growth, and if green branches are removed there is usually little danger of pathogen infection, although this can occur (see Chapter 4). During the occlusion process a small amount of bark and gum is incorporated into the wood. The depth

FIGURE 9.4
Ladder high pruning of radiata pine in New Zealand

of this occlusion defect is about 1.5 cm and is larger with large branches. It is also influenced by the pruning method.

The defect core is defined as the cylinder inside a pruned log that contains the pith, knots and occlusion defect. The diameter of this defect core (DDC) is primarily influenced by the maximum size of the diameter over stubs (DOS) in the log. With each pruning lift there will be a whorl of branches that defines the maximum DOS for that lift. As the DOS can vary between lifts, it is the largest that will have the greatest influence on long-length clear boards and clear veneers.

The diameter over occlusions (DOO) for a given DOS is given by the following equation, where all measurements are in mm (Park, 1980):

$$\text{DOO} = 32.36 + (1.01 \times \text{DOS}) + (0.032 \times \text{maximum branch size})$$

The straightness of the stem is also important. Log sweep (LSW) and sinuosity will both increase the size of the defect core. Thus, for 4.9–5.5 m sawlogs, the size of defect core is (where DDC and DOO are in mm and LSW is in mm/m):

$$\text{DDC} = 46.0 + (0.95 \times \text{DOO}) + (0.003 \times \text{LSW}^2)$$

As a rule of thumb, the diameter of the defect core is about 6 cm greater than the diameter over stubs for "straight logs". Thus, if the maximum diameter over stubs is 18 cm, the diameter of the defect core is about 24 cm. If the objective is to grow a band of clearwood 13 cm in width, then the small-end diameter (inside bark) will need to be about 50 cm. Such a tree would have a dbh of about 63 cm and would yield 68 percent of its sawn output as clearwood.

The DOS is an easy measurement to make in stands at pruning time. For the first lift it normally occurs close to stump height and for other lifts the lowest whorl is usually the largest. It can also be predicted from knowledge of early stand development.

Park (1980) developed a pruned grade index to assist in evaluating the effectiveness of pruning for clearwood. The three factors that influence grade index are dbh, DDC and sawing conversion factor, as shown in the following equation (where dbh and DDC are in the same units):

$$\text{Grade index (GI)} = \frac{\text{dbh} \times \text{log conversion}}{\text{DDC}}$$

The tree described above with a defect core of 24 cm and a final diameter of 63 cm, and assuming a 0.55 conversion factor, would have a GI of about 1.4. Park (1980), who developed this index, gave indicative ratings for GI from which to judge the effectiveness of pruning:

- 0.8 = very poor
- 1.0 = unsatisfactory
- 1.4 = good
- 1.7 = very good.

GI helps relate pruning to potential wood value. A "pruned log index" and "clear veneer potential" for logs were later developed to assist the valuation of pruned logs and have been incorporated into some simulation models (Park, 1989; Park, 2005). For veneers, the extent to which the defect core is off-centre is also important. Because of tradeoffs between the schedule factors, it is best to use validated computer models rather than rely on simple calculations when assessing regimes.

Pruning off live branches reduces the amount of foliage on the tree and slows growth rate (Madgwick, 1994; Neilsen and Pinkard, 2003). The removal of a small amount of green crown usually does not have a big effect, particularly if the lower crown foliage is partially shaded. For more aggressive pruning of radiata pine trees (e.g. > 45 percent of tree height or leaving less than 6 m crown length), the reduction in basal area growth is more marked than height growth. The effect is greater with selectively pruned trees because of competition with the unpruned element. Growth rate recovers as the trees rebuild their crowns, which takes time because it is largely dependent on height growth. With severe pruning, the time taken for basal area growth to recover can be five years or longer. In New Zealand's EARLY growth model for radiata pine, this effect was accounted for by using crown length (km per ha) as the driving force for basal area growth (West, Knowles and Koehler, 1982; West, Eggleston and McLanachan, 1987; O'Hara *et al.*, 1998). The crown length model had an overall error for predicting basal area within ±15 percent, and crown closure occurred when the total crown length was 4–6 km per ha. However, crown length did not directly account for how site influences leaf area. Subsequently, O'Hara *et al.* (1998) explored the use of sapwood area at the base of the crown as a surrogate for leaf area; this improved the prediction of basal area increment. The recent 300 index model for radiata pine follows a slightly different approach by slowing growth after pruning using an age-shift technique, driven by crown length, and can also allow for site differences (Kimberley *et al.*, 2005; see Chapter 5).

There are, therefore, tradeoffs between growth reduction, the size of the defect core, and the number of pruning lifts. However, a large number of studies have found that there is more flexibility than previously thought because effects tend to offset each other. In general, the target DOS, which varies with site, cost and revenue assumptions, usually lies in the range 13–19 cm (Maclaren, 1993; Dean, 2005). Smaller DOSs are associated with low stem taper, such as on sites of low fertility, high site index or high stockings. In general, pruning is most profitable on high-fertility sites.

The rate of height and diameter growth of radiata pine is usually very fast, and because of this it is important to time pruning within a few months if a specified DOS is to be obtained. Each additional cm of DOS is associated with about 67 cm of height growth, which can be one-third of the annual height growth (Sutton and Crowe, 1975). Another objective is to obtain an even-sized defect core within the tree, so pruning lifts need to be timed carefully in relation to one another. A common problem is that the second or third lift is delayed and the defect core is larger than desired. Furthermore, pruning to a fixed height results in some trees being overpruned and others underpruned. The difference in green crown also results in different growth rates after pruning. Variable height pruning overcomes this problem; the objective should be to leave the same length of green crown on each tree. Models such as the Radiata Pine Calculator and Scheduler, which has superseded STANDPAK in New Zealand, assist managers in timing this correctly and specifying the green-crown length, although stand pre-assessment is also recommended (Maclaren, 1993). In New Zealand, typically 3–4 m of crown is left, while in Chile the length of green crown remaining is usually 5.5–7 m (Table 9.2; Maclaren, 1993; Sotomayor, Helmke and García, 2002; Mead, 2010a).

For inexperienced workers it is easier to prune off all branches up to a certain diameter on the stem instead of guessing this for each tree. This "calliper diameter", as it is called, is based on the average taper of the trees in the stand. Again, this value can be predicted from models or it can be determined by measuring some trees. In New Zealand, the calliper size ranges from 7 cm to 12 cm, with 9–10 cm being most common (Maclaren, 1993). Site differences are important, since crown shape, foliage mass and tree taper vary with site. With this approach, the amount of foliage left on each crown will be similar (O'Hara *et al.*, 1998).

The number of lifts and the final height of pruning are also important considerations, and the latter should be related to the potential end use of the logs. Logs tend to be traded in at 5.5–6 m or longer lengths and the stump height and any trimming need to be added to this to get the pruned height. Peeler bolts can be shorter, but as this market is not always available there may be an additional risk associated with restricting pruning to less than the standard log lengths. With extra high pruning above about 7 m, it may be difficult to control the DOS and uneconomic to prune. The usual final pruning height in most countries is 4.5–8.5 m (Maclaren, 1993; Mead, 2010a).

With radiata pine, three lifts are often required to obtain a 5.5–6.5 m pruned log. However, more lifts may be required on sites with high fertility (e.g. ex-pasture sites) or on slow height-growth sites, and only one or two may be required on some high-site-index sites with fast height growth, low-fertility sites, and sites with high stocking (Maclaren, 1993; Dean, 2005). When using variable height pruning, a final catch-up prune may also be required on trees that have not yet been pruned to the desired height.

A decision to prune only selected trees in a stand can result in those trees falling behind the unpruned trees (sometimes called "followers") in their growth. Sutton and Crowe (1975) found that a nominal 20 percent of the green crown removal (actually closer to 40 percent) did not influence tree dominance but that heavier pruning resulted in many more trees losing dominance. It is usual, therefore, to thin at the time of pruning or to thin out less-pruned crop trees before they are greatly suppressed. Early thinning in conjunction with pruning also promotes diameter growth, which assists in obtaining large diameters more quickly, although this needs to be balanced against poorer intrinsic corewood properties (see Chapter 5).

Sometimes, leaving unpruned trees within a stand can be advantageous, although it should be done with care. Additional trees may allow for a production thinning and can also help restrict branch growth in the final crop trees above the pruned zone. However, there is a danger that thinning may be left too long, resulting in a suboptimal final crop. In Chile, the retention of long green crowns (>6 m length) on pruned trees avoids this suppression risk (Table 9.2).

Pruning may also result in the formation of adventitious or epicormic shoots that develop from needle fascicles (Figure 5.4). Live stem needles on the pruned part of the stem are usually removed at the time of pruning (Maclaren, 1993; Dean, 2005). Generally, adventitious shoots develop more when heavy pruning is done, where there is strong side light (perhaps as a result of thinning), and where site fertility is high.

Pruning stands for clearwood has the disadvantage of increasing management costs, which may or may not be recovered decades later, depending on market conditions. It also increases the number of products being harvested and marketed, both of which increase harvesting complexity and overall cost.

Pruning, along with thinning, is known to be beneficial in the control of dothistroma needle blight (see Chapter 4). However, pruning wounds may lead to infection with other diseases, particularly *Neonectria fuckeliana* (Figure 4.4). This is most likely to occur when large branches are removed and the severity of pruning is high.

Variations in the standard pruning technique have been suggested for radiata pine. With form pruning, the objective is to ensure a single straight leader by removing large ramicorn branches and additional leaders. This would result in a higher number of acceptable stems. It has been employed at age three years in Chile to overcome the damaging effect of the pine shoot moth on leader development (Sotomayor, Helmke and García, 2002). Occasionally, lightening the crown by removing some larger branches is used to reduce tree toppling (see Chapter 8).

Sometimes an owner may not prune with the production of clearwood in mind but rather with the aim of preventing degradation by excessively large knots. For example, trees on the edges of compartments or next to large gaps may be pruned high. Berg (1973) recommended high pruning of edge trees because their larger size should provide good clearwood yields and also reduce fire risk, aid vehicle access down the edge of stands and improve aesthetics.

Pruning, preferably higher than 2 m, reduces the danger of crown fires. However, an entire stand may not need to be pruned for this purpose because fires usually start at plantation edges. Limited pruning may be required to allow better access to the centre of stands. In South Australia and Western Australia, for example, the policy is to high-prune strategic areas such as along some roads.

Pruning is also used in shaping and developing bushy Christmas trees (Sonogan, 2006). The objective is to produce a narrow, tapered, relatively dense crown, with the bottom 15–20 cm of the stem free of branches, straight and ready to place in water. Good planting and, if necessary, tree straightening is critical. The basal whorl is usually 30–35 cm above the ground. The bushy condition is achieved by controlling leader growth and shaping the trees by shearing branches to get the right crown taper (Figure 9.5). Detailed instructions are given by Sonogan (2006).

Pruning for purely aesthetic reasons does not require adherence to a clearwood schedule. In this case, pruned height depends on the desired effect.

PRUNING SCHEDULES

Most current pruning schedules put an emphasis on improving the value of the lower part of the tree and to a lesser extent on other objectives such as fire control and aesthetics. The examples in Table 9.2 illustrate the range of pruning schedules.

In the example from New Zealand's Central North Island region, two pruning lifts are specified to achieve a final pruned height of 5.6 m (Table 9.2). The pruning objective is to produce a DOS of less than 18 cm; with a final crop diameter of about 55 cm, this produces a very good pruned grade index. The schedule specifies two thinnings. The first is a light thinning to waste, which removes poor trees and natural regeneration. The final thinning occurs a year or so after the second pruning to ensure some branch control on the unpruned section of the stem but is performed before the tree reaches a height of 20 m to avoid wind damage. This second thinning can be either non-commercial or commercial.

FIGURE 9.5
Christmas trees trimmed to create dense, conical crowns

A similar schedule, but with 3–4 variable pruning lifts to 6.4 m, has been advocated for fertile farm forestry sites in Tasmania (Private Forests Tasmania, 2004). It is similar to schedules once commonly used by small growers in New Zealand (Maclaren, 1993) but differs by including a light form pruning at age three years and delaying the single thinning-to-waste to age ten years in order to control branch size. The grade index is expected to be good.

The Chilean schedules emphasize volume production and have higher stockings, two production thinnings and three less aggressive pruning lifts that leave long green crowns (Table 9.2; Mead, 2010a). Only some trees are pruned, but this method minimizes the danger of suppression of those trees (Figure 9.6). Pruning is normally carried out to 5.5 m but occasionally higher pruning is performed. The pruned grade index is low with these schedules, partly because final tree size is lower than in the New Zealand example, often being about 40 cm.

A study of pruned log index (see Park, 1989) in Chile of trees taken from pruned stands found a wide range in this index (Meneses and Guzman, 2000). It confirmed that pruning should be confined to higher site indices (>29 m) and that to get a high pruned log index it was important to have early pruning (ages five, six and seven years) and thinning (second thinning at age ten), with a final stocking of 300–350 stems per ha. The Chilean schedule in Table 9.2 does not meet these criteria.

Pruning has also been recommended in Spain. Current schedules on communal land use either only low pruning or two prunings (to about 5.5 m) and two production thinnings with a rotation of 35 years (Rodríguez *et al.*, 2002b; Fernández and Sarmiento, 2004). On more fertile private plantation sites there is usually only one single thinning and the rotation is about 25 years, although Table 9.2 presents a more

FIGURE 9.6
Long crowns left after pruning in Chile avoid suppression of the pruned trees by non-pruned trees

recently developed schedule with lower stockings and a longer (30-year) rotation. The pruning operations do not appear to be scheduled to ensure a good pruned grade index. IRRs, excluding land costs, have been estimated at 7–9 percent (Rodríguez *et al.*, 2002b).

As with the non-pruning schedules given in Table 9.1, the differences in these schedules reflect particular contexts and management needs. They therefore should not be used elsewhere without a detailed evaluation.

Pruning techniques

The most common pruning tools are shears and saws, with various types and lengths of ladder used for the higher lifts (Figure 9.4; Dean, 2005). On steeper terrain, clip-on ladders are easier to use than ladders that lean on the tree. Electric shears are used in *Pinus taeda* stands and have been tested in radiata pine stands (McWilliam, 2004). Long-handled saws are still used on occasion for higher pruning, and small chainsaws are used for low pruning. Knifes are used to remove epicormics. Axes are not recommended because they may damage the branch collar. Appropriate safety equipment should be used.

The labour requirements for pruning vary with the number of trees being pruned, site conditions, and whether the pruning is being done largely from the ground or from long ladders. The skill and fitness of the pruner will also greatly influence productivity. Typical productivity for average site conditions is 20–25 trees per hour, but depending on site conditions may decrease or increase by up to 30 percent. Dean (2005) gives detailed labour productivity estimates.

Quality control of pruning operations will ensure that the work is of a good standard and can also provide information for use in management systems. The ATLAS suite of models includes a module that assists managers with quality control.

INTERRELATIONSHIPS AND FLEXIBILITY

Many decisions on initial stocking, thinning, pruning and rotation length are interrelated and will determine harvesting volumes and wood quality. Such decisions can be facilitated by analysis of the system using models.

Studies of schedules used in countries suggest that a wide variety of regimes is in use (Maclaren and Knowles, 2005a). The danger with presenting typical schedules is that they may imply – erroneously – that this is the way to grow radiata pine. This is not the purpose of tables 9.1 and 9.2; rather, they are intended to illustrate how different growers have resolved their constraints, opportunities and objectives depending on their specific contexts. Their decisions are frequently market-driven.

A useful application of models is to explore the most important aspects affecting economic returns and the flexibility of different schedules. Sensitivity analyses show that the choice of discount rate has the largest impact on returns to growers (Whiteside, West and Knowles, 1989; see Chapter 3). Currency exchange rates and timber prices also have major impacts on profitability, as do site index and topography. The silvicultural schedules themselves generally have lower impacts, although long rotations are less profitable, particularly at higher discount rates.

Modelling systems

In New Zealand, two main modelling systems are used widely to schedule thinning and pruning options and to explore the impacts of different schedules on wood outturn and profitability. The more comprehensive of the two is Forecaster, which is a module in the ATLAS system (Snook, 2010). The structure of the Forecaster model has not been published, but it is based on 40 years of research on radiata pine silviculture and wood properties and is a big improvement on earlier models (J.P. Maclaren, personal communication, 2012). Forecaster can predict the impacts of site, silviculture and genetics on tree and branch growth and wood properties and hence on wood value and economic return. For example, the model can use wood density, acoustic velocity and MoE models based on location and slenderness to predict the trees' suitability as structural wood. The second model is the Radiata Pine Calculator, which is simpler than Forecaster and is often used by small growers (Maclaren and Knowles, 2005b); it has also been used for research (e.g. Manley and Maclaren, 2009; 2010). Both models employ the empirical 300 index model to predict volume growth for different sites and thinning and pruning options (Kimberley *et al.*, 2005; see Chapter 5). They also calculate carbon storage using the "C_Change" model (Beets *et al.*, 1999).

South Australia developed a growth model that predicts volume directly rather than via height and basal area models (Leech, 2007). The Australian Plantation Yield and Regulation System, while primarily designed for yield regulation, can also be used to examine silvicultural schedules (Strandgard, Wild and Chong, 2002). South Australia has also developed a decision-support system for applying fertilizers after thinning (May *et al.*, 2009b). In Chile, RADIATA is the main stand-based simulation model; from 2005, this has been extended to include an individual tree model, INSIGNE.

In Spain, the last decade has seen a rapid expansion in forest modelling, including for radiata pine plantations (Bravo *et al.*, 2012). For example, Rodríguez *et al.* (2002a) documented a simulation model for Spanish conditions, which includes predictions of four log types, including pruned logs, and an economic evaluation. A stand density management diagram has also been produced for radiata pine based on other Spanish models (Castedo-Dorado *et al.*, 2009).

In addition to radiata pine empirical models, more complex growth models have been developed that are, at least in part, physiologically based (Rodríguez *et al.*, 2002b; Landsberg, Waring and Coops, 2003; Flores and Allen, 2004; Mason, 2005; Fernández *et al.*, 2011; Mason, Methol and Cochrane, 2011). The advantage of physiological-process models is that they should be more flexible and reliable in changing environments, although they have not yet been developed to the same extent as empirically based models. The flexible hybrid model developed by Mason, Methol and Cochrane (2011) deserves special mention because it replaces time with useable light sums.

Schedule flexibility

It is useful to consider how much flexibility there is to change management direction during a rotation. Uncertainty about future developments can sometimes drive managers to delay decisions on the stand-tending regime. On other occasions, managers may have good reasons for change – such as when market conditions change (e.g. a mill closes). Whether it is possible to change depends on the direction contemplated and the age and state of the stand. Change is usually easier in young stands before age 5–8 years if the decision concerns pruning, but other decisions, such as final crop stocking, thinning to waste versus production thinning, and rotation length, can be left until later in the rotation. For example, the introduction of carbon markets suggests that higher stockings and longer rotations may be most profitable, and shifting the regime in this direction may be possible in some stands (Manley and Maclaren, 2009). Again, models are useful in making such decisions.

USING RADIATA PINE IN MIXED SPECIES STANDS

Radiata pine is seldom used in mixtures; its ability to pioneer sites makes it well-suited to simple plantations where it is grown alone. There are occasions, however, when mixtures may be considered, and indeed second-growth, naturally regenerated stands in California can be observed in association with other conifers and *Quercus agrifolia* (Lindsay, 1932; Zander Associates, 2002). In Spain, there are 60 000 ha of mixed stands comprising radiata pine, other *Pinus* species, oaks and other hardwoods (MMAMRM, 2006; Lombardero, Vázquez-Mejuto and Ayres, 2008).

The main reasons for considering mixtures are:
- amenity factors;
- to overcome extremely heterogenous soils;
- to provide a nurse for other valuable, more shade-tolerant species;
- to provide a filler species;
- to promote self-thinning;
- as insurance against calamity.

Most of these reasons, apart from using radiata pine in an amenity situation, are not applicable on a large scale. Radiata pine would quickly dominate most other species and, because of its dense crown, it is likely to suppress slower-growing species. According to Burdon (2001), no other species has been found to be compatible with radiata pine on a large scale. Nor is there evidence that mixed-species stands would provide insurance against disease (Lombardero, Vázquez-Mejuto and Ayres, 2008), although it could conceivably help against extreme cold events.

The basic principles to consider when using mixtures are to:
- clearly identify the reason why a mixture is being considered;
- design the mixture to achieve this result;
- obtain information on relative growth rates, shade tolerances and other characteristics;
- keep them simple – complex plans developed on paper are seldom effective in practice.

FERTILIZERS

Nutrient deficiencies and their diagnosis are described in Chapter 2, and fertilizer use in the establishment phase is covered in Chapter 8. Fertilizers are also applied to established stands. The world's first aerial application of fertilizer was to phosphorus-deficient radiata pine in Riverhead Forest, New Zealand, in 1955, which produced a marked response (Conway, 1962). Since then, fertilizer has become an accepted management tool. For example, in Australia's softwood plantations, 3 260, 1 524 and 448 tonnes of nitrogen, phosphorus and potassium were applied annually by major growers in 2002–2004, of which the majority was applied to established plantations (May *et al.*, 2009a). Fertilizer use is lower in New Zealand, having diminished substantially since the mid 1980s, although the reasons for this are unclear (Payn, Skinner and Clinton, 1998). In Chile and Spain, fertilizer application to established radiata pine stands is less common than in Australasia.

There are three main reasons for applying fertilizer to established stands. The first is to correct deficiencies that will prevent a satisfactory crop (Figure 9.7). In these situations, fertilizer use needs to be considered as an essential cost in economic evaluations. This is illustrated by the unfortunate experience in Westland, New Zealand, where the termination of fertilizer use on very impoverished soils to reduce costs led to expensive wood-supply problems, aggravated in part by windthrow. Mead, Mew and Fitzgerald (1980) described the critical role of fertilizers in Westland. The second reason for using fertilizer is to improve the growth of crops that are considered adequate; here, the use of cost–benefit analysis is appropriate for evaluating fertilizer options. Finally, fertilizer may be required to maintain site sustainability (see Chapter 10). In such situations, forest managers need to include the cost of fertilizer in their economic analyses.

The key factors involved in decision-making by managers have been studied in Australia (May *et al.*, 2009a). For softwood plantations, the most important factors, on a scale of one to ten, were the amelioration of nutrient deficiencies and increasing profits (8), followed by increasing production and fertilizer costs (6). Wood price, environmental aspects, markets, wood quality and sustained yield were intermediate in

FIGURE 9.7

Phosphate fertilizer response on a deficient site: a site with fertilizer (left) and without (right)

importance (3–5), while land price was the least important consideration (2).

The correction of nutrient deficiencies has been widely studied. The most common limitation is phosphorus, and very marked sustained responses have often been described on infertile sites (Mead and Gadgil, 1978; Payn, de Ronde and Grey, 1988; Turner, Lambert and Humphreys, 2002). With phosphorus deficiency, the crowns are thin and the foliage is shed earlier than normal, so it takes a few years for the leaf area to increase and for the response to build up. Typical rates of phosphate applied to established stands are 35–110 kg of phosphorus per ha (Table 9.3). Today, the use of phosphate fertilizer in radiata pine plantations is often managed through regular foliage sampling, and the crowns are not allowed to deteriorate (Mead, 2005b; Payn *et al.*, 2000; May *et al.*, 2009a). The type of phosphate fertilizer most commonly used in Australia is diammonium phosphate, but in New Zealand other forms of phosphate are more common, including reactive-phosphate rock.

Many marginally deficient established radiata pine stands will respond to nitrogen fertilizer, particularly if applied after thinning or pruning (Mead and Gadgil, 1978; Hunter *et al.*, 1986; May *et al.*, 2009a, 2009b). Very deficient stands are less common. Usually the responses last for 3–6 years in mid-rotation stands and result in about 30 percent additional growth. In New Zealand, the responses are limited to where total soil nitrogen is less than 0.2 percent, but this has not been found to be as useful in Australia. Sometimes responses last longer, particularly where composite fertilizers are applied, but in other studies on low-rainfall sites the response decreased over time (Woollons, Whyte and Mead, 1988; May *et al.*, 2009b). In South Australia, where multiple production thinnings are used, it may be necessary to reduce the interval between thinnings to prevent diminution of the nitrogen response (May *et al.*, 2009a, 2009b). Pre-thinning fertilizer applications have not proved effective.

On some soils it is important to apply phosphorus along with nitrogen, given the marked interaction between the two nutrients. Responses to nitrogen in New Zealand have been limited where soil Bray-2 levels are less than 10 ppm. While the optimum rate is about 200 kg of nitrogen per ha, managers often apply less than this rate. A survey of Australian softwood growers found that in young established stands, stands aged between 11 and 20 years, and stands aged over 20 years, the average rate of nitrogen applied was 63, 87 and 104 kg per ha, respectively (May *et al.*, 2009a). However, May *et al.* (2009a) warned that applying low rates of urea fertilizer can result in a higher proportion of the applied nitrogen being immobilized, while at higher rates more is lost by volatilization. The optimum application rate of 200 kg nitrogen per ha resulted in three times more nitrogen being available to the trees than an application rate of 100 kg nitrogen per ha. Urea has been the traditionally favoured form of nitrogen fertilizer for forestry because it is relatively low in cost per unit of nitrogen and because of its high nutrient concentration (Table 9.3). Unfortunately, however, volatilization can be

TABLE 9.3
Typical fertilizer types and rates used in radiata pine plantations

	Nutrient (%)				Rate of fertilizer	
Fertilizer	N	P	K	Other nutrients	At planting (g/tree)	Established stands (kg/ha)
Urea	46	0	0		25–60	250–450
S-coated urea	41				25–60	250–450
Ammonium sulphate	21	0	0	24S	60–180	500–950
Superphosphate	0	9	0	20 Ca; 11 S	60–200	300–1 200
Triple super	0	21	0	15 Ca; 1 S	40–100	150–600
Rock phosphates*	0	11–16	0	32–38 Ca	*	250–900
PAPR phosphate**	0	15–17	0	20 Ca	50–100	200–500
Diammonium phosphate	18	20	0	2 S	40–85	250–500
Potassium chloride	0	0	50		25–50	80–200
Potassium sulphate	0	0	41	18 S	50	85–250
Magnesium sulphate	0	0	0	10 Mg; 13 S	–	500–1 500
Kieserite	0	0	0	18 Mg: 23 S	–	250–800
Dolomite	0	0	0	11 Mg; 24 Ca	–	500–1 500
Calcined magnesite	0	0	0	50–55 Mg	–	100–300
Manganese sulphate	0	0	0	31 Mn; 18 S	30–45	20–45
Copper sulphate***	0	0	0	25 Cu; 13 S	2–4	20–60
Copper oxychloride	0	0	0	57 Cu	2	9
Zinc sulphate***	0	0	0	22 Zn; 11 S	2–25	10–30
Borax****	0	0	0	11 B	6–10	20–80
Ulexite	0	0	0	12–15 B; 10 Ca	6–30	20–70
Na borates	0	0	0	13–22 B	–	variable
Colemanite (Ca borate)	0	0	0	16 B; 20 Ca	6–30	25–70

Note: fertilizer mixes are also widely used; * = rock phosphate, perhaps in mixture with super, can be band or broadcast applied at establishment at 500–1000 kg/ha. Reactive phosphate rock is a non-granulated, slower-acting fertilizer, suitable for acid soils (<pH 6.0) and annual rainfall >800 mm; ** = PAPR is partially acidulated phosphate rock; *** = sometimes spray applied using 0.2% copper fertiliser or 2.5–5 percent zinc fertilizer; **** = sometimes added as boronated superphosphate.

Sources: Herbert and Schönau, 1989; Mead, 2005b; May *et al.*, 2009a.

very high when urea is applied to pine litter and the low unit cost can easily be offset by lower tree uptake (May *et al.*, 2009a). Volatilization can be reduced through the use of urease inhibitors, coated urea prills, applying urea immediately prior to rainfall, and using other nitrogen sources. Economic analyses suggest that nitrogen applications are most profitable if applied at mid-rotation or later (May *et al.*, 2009a).

Potassium deficiency is relatively uncommon in radiata pine plantations, but where it does occur it is readily corrected. In Australia, about 450 tonnes of potassium are applied annually in the form of potassium sulphate at a rate of about 35 kg of potassium per ha.

Boron deficiency is widespread in radiata pine plantations in Australia, Chile and New Zealand. This can be readily corrected; the most commonly used fertilizer is ulixite (applied at a rate of 8 kg of boron per ha), a slowly soluble form (Will, 1985; Mead, 2005b; May *et al.*, 2009a). Foliar analysis is used in the management of this deficiency, and it has been found that boron fertilizers raise foliage boron levels for five years (Knight, Jacks and Fitzgerald, 1983). Boron toxicity has occurred where soluble forms have been applied inadvertently at high rates.

Magnesium, zinc and copper deficiencies occur sporadically in Australasia, with the two micronutrients (zinc and copper) routinely corrected with the use of fertilizers (Table 9.3). Sulphur is also reported to be limited in some Australian plantations (Turner and Lambert, 1986). Manganese deficiency occurs on limited sites in South Africa and Australia and again has been corrected with fertilizers. Calcium deficiency is rare and because it is associated with very poor soils is usually corrected when phosphate is applied. Recently, calcium applications have been found to correct the effects of excessive nitrogen that results in stem sinuosity in loblolly pine (Espinosa *et al.*, 2012).

Because of the variability in the occurrence of nutrient deficiencies it is important to manage them on a site-specific basis (see Chapter 10; Herbert and Schönau, 1989; Turner *et al.*, 2001; Toro, 2004; May *et al.*, 2009a). In Australasia, growers are confident about their ability to diagnose responsive sites but there is apparently less confidence in South Africa, Spain and Chile. The use of nitrogen-fixing plants instead of nitrogen fertilizer should be considered by management (Mead, 2005b; May *et al.*, 2009a).

Most fertilizers are applied by air to established stands, although there is some ground application following production thinning where the topography is suitable. The use of guidance systems is recommended to assist with uniform spread. Application costs amount to 20–25 percent of the total cost of the operation (May *et al.*, 2009a).

SYNTHESIS AND TRENDS

There have been major structural changes within the plantation forestry industries in some major grower countries in the last decade and these, coupled with market aspects and innovations in technology, are changing radiata pine tending schedules. In Australia, where there has been a stable domestic market for structural timber, thinning schedules have not changed greatly in recent years, although new, technologically superior machinery has been introduced. For example, thinning may employ harvesters that process wood to market requirements and locate logs using geographic information systems. The harvested logs are picked up, in turn, by forwarders that also have access to this information.

In Chile, the large integrated pulp and paper companies have moved towards growing for maximum volume plus value, and this has led to thinning/pruning schedules like the one given in Table 9.2. While animals are still used in the harvesting of thinnings, mechanical harvesting has increased in recent years, particularly on more difficult topography.

In Spain, there has been a move away from smallwood schedules common in the 1960s to more intensive stand silviculture in their radiata pine plantations, often aimed at providing material for their sawmill and fibreboard industries (Rodríguez *et al.*, 2002a). This trend is likely to continue, particularly because Spanish research into radiata pine management is rapidly expanding. In New Zealand, there was once wide acceptance of direct clearwood schedules for better sites, including in the farm-forestry sector. However, the low price differential between pruned logs and good structural logs in the domestic market has prompted growers to question the value of pruning; the premium must pay for the additional cost, the loss of volume and sometimes the lower value of second logs. Part of the problem is that pruning must be paid for up to 20 years in advance of use and there is a risk associated with predicting future markets. The trend in recent years has been to shift away from pruning (see Chapter 1).

The low quality of wood generated from widely spaced trees on farm sites, coupled with the problem of low-quality corewood under recent schedules with low initial stockings (accentuated by tree-breeding), is also causing growers to rethink stocking schedules. There are two trends here. One is to increase initial stocking, and the second is to improve genetic wood quality (see Chapter 6). The outcome of these trends is yet to be seen, however. For regimes aimed at structural wood markets, the development of a structural index, similar in principle to the grade index for pruned logs, may be possible (Mason, 2012).

It is now accepted in New Zealand that the final crop stocking should be higher than was thought optimal 30 years ago. If carbon trading becomes embedded, this too will favour higher stockings and longer rotations (Manley and Maclaren, 2009, 2010), as would increased bioenergy production from radiata pine plantations. Long-term plot data suggest that radiata pine rotations could, if needed, be extended to 60 years or even longer without loss of tree vigour (Woollons and Manley, 2012), although wind damage may become limiting.

A possible trend is that there will be more emphasis on growing a uniform product that can be used by forest industry engineers in the manufacture of marketable products. This could also simplify supply chains to industries. Forest managers often see their stand manipulations as adding value and providing the products needed by the markets, whereas a move in this direction would be towards greater factory-based value adding.

Finally, the correction of nutrient deficiencies has become accepted practice, and there has been some interest in using fertilizers to boost the growth of marginally deficient stands. The further integration of fertilizers into silviculture is likely to occur, along with more site-specific management. This will be helped by improved land information planning tools.