5 Growth characteristics, wood properties and end-use

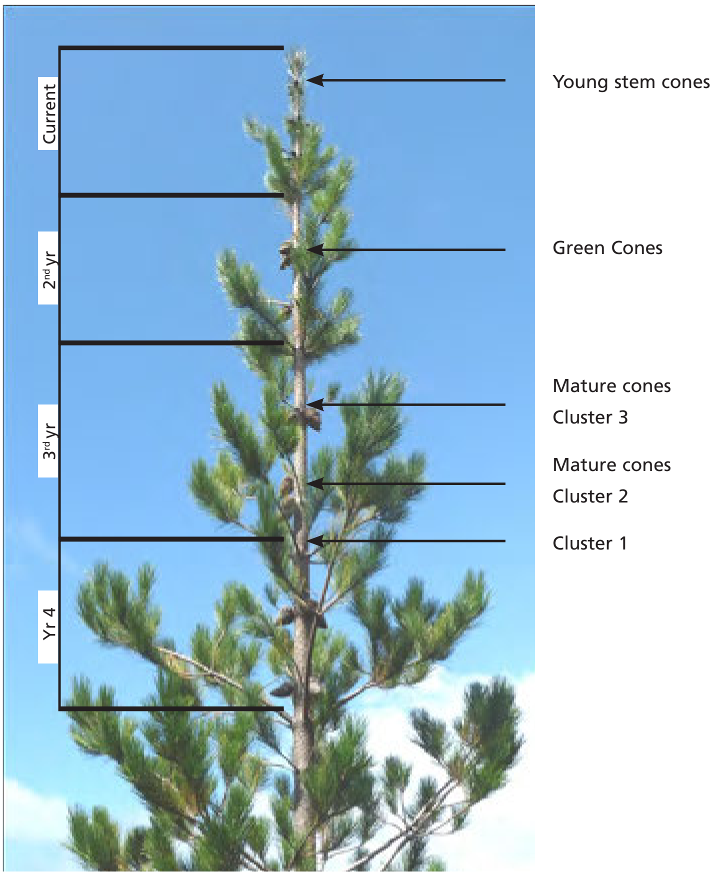
This chapter describes the underlying growth patterns, wood properties and end-uses of radiata pine. Understanding all three aspects is vital for designing robust silvicultural practices.

RADIATA PINE GROWTH

Growth habit

Radiata pine's growth habit is under strong genetic control but can be modified by environmental factors and silviculture. The species, like many conifers and some hardwoods, has an excurrent growth habit (Oliver and Larson, 1990). In excurrent trees, the strong apical control of the terminal bud determines the development of the lateral shoots below, giving the typical pyramid shape to the crown (Figure 5.1). Foresters often describe this phenomenon as strong apical dominance. Many trees, such as oaks, have weak apical control, which leads to a spreading decurrent growth

FIGURE 5.1
Radiata pine shoot showing annual polycyclic growth pattern



Note: The last four years of leader growth are marked and within each annual growth there are three cycles of growth. Stem cones have not formed in the first cycle. Note how cones grow and mature over three years. This tree is under phosphorus stress and is shedding three-year-old foliage.

form, while palms, with their one prime meristematic terminal, have a columnar habit.

There is considerable variation in apical control. Tree vigour, including nutritional status and tree age, may also influence the degree of control and hence crown form and development. Genetic differences in radiata pine are most readily seen in young plants growing on high-fertility sites. Under these conditions, some trees will show a retarded leader syndrome (or lammas shoots) in which the main terminal bud is outgrown by the more vigorous upper laterals. As radiata pine ages, this feature becomes less marked. Genetically improved trees and trees grown from physiologically aged cuttings show a stronger excurrent habit. In very old radiata pine trees, height growth slows and the crowns take on a rounded top (Figure 1.2), but they seldom completely lose their excurrent pattern. These patterns are not the same in all conifers. A classic example is kauri (*Agathis australis*), whose excurrent growth in youth gives way, when older, to decurrent growth and a spreading crown.

Nutrition has a powerful effect on crown shape. Trees under nitrogen and phosphorus stress, for example, have narrower crowns because the branches do not develop to the same extent (Table 2.2). The upper-mid-crown yellowing syndrome, ascribed to magnesium deficiency, often results in reduced branch development in the mid crown; it also has a strong genetic basis (Beets *et al.*, 2004). Other deficiencies, as well as pests and diseases (Chapter 4) and climate (Chapter 2), can lead to the death of branch and leader buds.

Additional factors affecting the crown shape of radiata pine are:

- Gravimorphic tendencies, which cause lower branches in the crown to grow at flatter angles compared to upper branches. This also results in edge trees leaning outward because of unequal crown development.
- Stand density, which influences the light reaching the crown and also determines whether there is abrasion of one tree on the next. Both abrasion and the incidence of light alter branch development in the lower crown, and ultimately control crown length.
- Both wind and salt spray influence branch development and can sculpt the tree crown. They can also result in leaning trees.

Shoot development

Like other pines, radiata pine forms two types of auxiliary bud in the axil of scale leaves (Bollmann and Sweet, 1977; Madgwick, 1994). One type develops into long shoots that can differentiate into branches or female cones, while the other forms short shoots or needle fascicles. In radiata pine, fascicles usually have three needles, although the range is from two to six. Under some conditions, such as following the removal of a high proportion of the green crown by pruning, short shoots may develop further, giving rise to adventitious (epicormic) branches, particularly on the sunny side of the tree (Figure 5.2).

Annual shoot growth in radiata pine tends to be polycyclic, which gives rise to several clusters of branches and/or cones each year (Figure 5.1; Jacobs, 1937; Bollmann and Sweet, 1977). In the leading shoots of non-juvenile radiata pines, the resting phase is marked by a close-spaced, sterile, scale-leaf region. The first-formed long shoots, which usually only form branches, will normally develop into the largest branches in that season's growth. The buds of these shoots are initiated late in the previous season; morphologically, each cluster is subterminal and belongs to the internode below it. Under some conditions this lower whorl may begin to grow in late autumn, giving rise to distinct "candles", sometimes with the terminal resting bud remaining dormant. The first cycle of growth is longer than subsequent cycles, with more needle fascicles (short shoots). These patterns may be used to determine retrospectively where the annual height growth ceased.

The number of cycles and clusters per cycle varies with genotype. In extreme cases,

FIGURE 5.2
Epicormic shoots forming on a pruned radiata pine tree, where the stem needles (short shoots) have not been removed

Note the region where there are no short shoots and how the leaf scars are closer together where the stem growth slowed in winter.

seen most frequently in warmer climates, there may be no branch whorls for up to 6 m, giving the appearance of a foxtail (the "foxtailed" effect; Rook and Whitehead, 1979). One cycle per year gives rise to a "uninodal" habit and typically produces trees with long internodes from which can be cut short-length clears. Polycyclic or "multinodal" trees can have up to six cycles per year. The number of cycles is also affected by climatic conditions – shorter growing seasons or drought can result in fewer cycles (Burdon, 2001) – and by latitude and altitude (there are fewer cycles and shorter internodes at higher latitudes and altitudes). The shoot length of each cycle is influenced strongly by environmental factors such as temperature, although the number of scale leaves for any particular genotype is less affected. A study in three New Zealand North Island forests found that internode length ranged from 0.04 m to 2.38 m and averaged 0.55 m (Woollons, Haywood and McNickle, 2002). In these 20-year-old trees, internode length was greatest at about one-third of tree height.

The number of branch clusters increases with age up to about 20 years. In polycyclic trees, the number of clusters per metre is similar in the bottom two logs (12 m), as height growth also increases and cluster production is positively correlated with height (Carson and Inglis, 1988). This polycyclic pattern and lack of "deep" dormancy gives radiata pine flexibility to grow when conditions are favourable (Burdon, 2001). The downside is that trees can get caught out by unusual climatic events (see Chapter 2).

Branch angle and branch size are strongly influenced by genetics, with polycyclic trees tending to have smaller, flatter-angled branches compared with uninodal trees. Branch angle changes with the age of the branch, with older branches flatter than newer branches. It is also associated with the straightness of the trunk; trees with flat branch angles tend to be straighter. All these features have an impact on end-use. For example, the polycyclic tree with small, flat branches is desirable when cutting structural wood, where knot size is a limitation. On the other hand, it may be possible to cut short-length clears from long-internode trees.

Long shoots may differentiate into female cones rather than branches (Figure 5.1). However, those initiated late in the growing season usually abort, so most of the female cones on the leading shoot occur in the second or third clusters (Madgwick, 1994). The number of cone-bearing clusters on the leading shoot is, on average, two less than the total number of clusters per year, so uninodal trees do not have stem cones. The importance of female stem cones, apart from their reproductive function, is their impact on wood quality. The cone stalk goes through the cambial layer; as the tree grows in diameter and the cone sitting on the bark is pushed out, it leaves a hole about 1 cm in diameter in the wood behind it, which is often filled with resin. Female flowers can occur from about age four years but generally start about age eight years. Cones are also found on branches.

The number of branches per cluster is variable but usually between five and eight. It appears to be influenced more by genetics than by environmental factors, except perhaps shading (Madgwick, 1994).

Branches themselves tend to be monocyclic, particularly as they become older. Male pollen strobili develop from short shoots on lower crown branches and it has been found that 13 percent of potential foliage can be diverted to their formation (Cremer, 1992). Annual growth by weight of male and female reproductive structures was 10 percent of stem growth in 10–14-year-old radiata pine. Fielding (1960) suggested a figure of 16 percent over a rotation. However, Cremer (1992) concluded that it was unclear if reproductive growth had a large effect on vegetative growth.

In summary, once the juvenile phase is passed, the number of branch clusters on an annual shoot of radiata pine is positively correlated with:

- number of cones produced
- flatter angle of branches
- straightness of the trunk
- lack of forking
- evenness of taper of the trunk
- tree growth rate
- higher crown classes (i.e. dominant trees).

It is inversely correlated with:

- internode length
- branch diameter.

Growth stages

Radiata pine goes through various maturation stages (Jacobs, 1937; Bannister, 1962; Wilkes, 1987; Lewis and Ferguson, 1993). These include:

- Juvenile, to age three years (five years on poor sites)
  - no resting buds
  - slow growth rates
  - tendency to be monocyclic
  - thin bark
  - crown to ground level
  - high taper
  - high carbon allocation to foliage and fine roots
  - short tracheids, high microfibril angle and low density.
- Adolescent, age 4–8 years
  - true bud formation
  - increase in branch clusters
  - fast height growth
  - thicker bark
  - possible crown closure

  – start of butt swell and high taper
  – peak foliage biomass.

- Adult, from adolescent to 20–40 years
  – true bud formation
  – often polycyclic
  – cones become common
  – thick fissured bark on lower stem
  – rise of base of green crown (in stands)
  – decrease in taper below green crown
  – increase in carbon allocation to stems
  – formation of mature wood
  – heartwood formation (after age 14 years).
- Mature: older than 20–40 years
  – slowing in height growth
  – decrease in distance between clusters
  – possible decrease in the number of clusters
  – rounding of crown
  – respiration progressively more important
  – greater proportion of higher density, longer-tracheid wood.

Note that the branching characteristics of the first two stages will affect the most valuable logs in the tree. Bark development is important to minimize animal damage and for fire resistance. Changes in wood characteristics affect wood quality and are discussed in greater depth later. In radiata pine, maturation effects remain when trees are propagated vegetatively, so that cuttings have more mature characteristics than seedlings. Other species of pine may have different growth habits that influence their silviculture.

Growth patterns

There has been considerable research into the growth patterns of radiata pine (e.g. Madgwick, 1994). This section highlights the most important aspects for silviculture.

Sunlight is a fundamental driver of tree growth because of photosynthesis. Mason, Methol and Cochrane (2011) replaced time with potentially useable radiation sums in a hybrid radiata pine growth model to good effect. The efficiency of light use is reduced by both water and nitrogen stress (Raison and Myers, 1992).

A tree's photosynthates are allocated to various uses in the following overlapping order (Oliver and Larson, 1990):

- the maintenance respiration of living tissue – this is temperature-dependent and occurs both day and night, and radiata pine growth is favoured by warm days and cool nights;
- the production of fine roots and leaves;
- flower and seed production;
- primary growth to terminals, lateral branches, root extension and renewal of phloem;
- diameter growth (xylem);
- the development of resistance to diseases and insects.

Photosynthesis is related to leaf area and hence crown size, while nutrient and water uptake is related to the surface area of fine roots. Respiration is linked to the volume of living tissue. The maximum leaf area index (LAI, one-sided foliage area per unit land area) in radiata pine is usually about six and in normally stocked stands on fertile sites occurs at age 4–6 years (Nambiar, 1990; Beets and Pollock, 1987; Grace, Jarvis and Norman, 1987). In closely planted experimental plots (40 000 stems per ha) covering a wide range of sites, maximum LAI, achieved at about age four years, averaged 6.5 ± 2.3 (Coker, 2006). In that study, LAI coupled with mean annual temperature explained

84 percent of stem volume, while fertilizer applications increased LAI by 5 percent. LAI was higher in cooler environments where soil moisture was abundant and light intensity was reduced (Coker, 2006). LAI can be estimated using airborne LiDAR (Light Detection and Ranging system), as can other stand attributes such as elevation, height and stocking (Adams *et al.*, 2011; Beets *et al.*, 2011). This is opening up new possibilities for forest mensuration and management.

Changes in photosynthate allocation also take place as a stand develops. Trees give a higher allocation to foliage and fine roots when young and to stem growth and branches when they are growing rapidly (Beets and Pollock, 1987; Beets and Whitehead, 1996; Raison and Myers, 1992). Thinning does not alter partitioning. By the end of the rotation, above-ground partitioning to leaves may be as low as 10 percent, while in highly stocked unthinned stands there can be reduced partitioning to branches. Thinning and high nitrogen fertility can also increase the allocation to branches, and fertilizer responses may be associated with lower allocation to fine roots. Irrigation may increase allocation to stems (Raison and Myers, 1992).

Seasonal growth

Seasonal growth patterns are important in that they can influence the timing of operations such as weed control, pruning and the application of fertilizer. Most shoot height growth occurs in spring and early summer, with a second smaller autumn peak on sites with adequate moisture supply.

The extension of current needles of radiata pine begins in early spring, with length increment reaching a peak in early summer (December/January in the Southern Hemisphere), by which time 90 percent of growth will have occurred (Raison, Myers and Benson, 1992). Needle weights follow a similar pattern, but weight often continues to accumulate slowly during winter and the following summer. Drought, nutrition and competition alter these patterns and the maximum size of needles; water stress is often the most frequent determining factor. Nutrient accumulation in needle fascicles tends to follow similar patterns. LAI peaks in late December in the Southern Hemisphere (Coker, 2006).

New foliage production is the major process affecting early canopy development and thus tree growth rate. New foliage growth occurs largely in spring and early summer. In radiata pine, foliage is retained on the trees for about four years, although this can be considerably shorter on drought-prone or nutrient-deficient sites. The shedding of older foliage tends to peak in summer or autumn, the timing partly affected by drought (Raison, Myers and Benson, 1992). Thus, the total amount of foliage on the tree fluctuates during the growing season and is usually at its peak in summer. Current foliage accounts for 30–75 percent of total foliage biomass or leaf area, depending on site conditions, with the lower end of the range associated with poorer conditions (Beets and Pollock, 1987; Raison and Myers, 1992).

Diameter or basal area increment at breast height can be highly variable, depending on moisture supply. On many sites, basal area maximum growth occurs in the summer–autumn period, but in areas subject to summer drought it may be greatest in spring or bimodal, with a smaller peak in autumn. The effect of irrigation is to even out the growth in spring, summer and autumn, leading to the development of more latewood (Raison and Myers, 1992). Basal area growth is always lowest in winter. Wood density is also influenced by the timing of basal area growth, with higher amounts of latewood producing higher wood densities.

Longer-term patterns

Biomass data for radiata pine generally indicate the following patterns (Madgwick, 1994; Bi *et al.*, 2010):

- Foliage mass increases until the trees close canopy and again after thinning, although the latter may not always reach the unthinned level.

- The maximum foliage weight (up to 20 tonnes per ha) is dependent on site.
- Foliage mass declines from a peak at about age 10 (during the adolescent phase), if the stands are unthinned, to about half the peak level. The timing of the peak is governed by stocking and site factors.
- Branch weight increases rapidly in the first ten years and has an upper limit of about 40 tonnes per ha, although higher figures have been measured on ex-pasture sites.
- Stem weight growth over time has a sigmoid shape.

Tree growth commonly has a sigmoid or S shape pattern over time. Trees grow quickly in the early years into the available growing space. Once the site is fully occupied, individual tree volume or biomass growth tends to slow, although total gross growth per unit area may continue. At a very old age, total growth on the site decreases. This causes a flattening off of the growth curve, although this may not be marked at normal radiata pine rotation ages.

The shape of these growth patterns is influenced by genetics and site and the effect of other biotic agents as well as internal factors. There are two opposing trends – the propensity of a tree or stand to expand in an exponential fashion within the limits of its potential and site, and the restraints on this propensity imposed by external factors, such as competition and site limitations, and internal factors, such as physiology and age (Zeide, 1993). West (2006) discusses some physiological theories on the factors that limit tree growth.

Natural mortality occurs when smaller, weak, suppressed trees die because they can no longer fix enough carbon to meet their requirements for respiration and the renewal of leaves and roots. Eventual death, however, may result from a pest or disease or other abiotic factors.

Height growth also follows a sigmoid pattern, with CAI increasing exponentially in young trees and reaching a peak at the early adult stage (i.e. 6–15 years) and then slowly declining. Site and establishment techniques influence the shape of the early part of this growth curve. The very fast period of height growth, which can exceed 2 m per year on good sites, occurs when many pruning and early thinning operations are occurring.

Basal area, which again follows a sigmoid-shaped curve over time, is influenced strongly by stocking (including thinning) and site. Basal area growth (CAI) reaches a peak quite early in unthinned radiata pine stands, often about age 7–10 years. High stocking and fertility reduce the age of the peak, while early thinning will tend to delay it. From a silvicultural viewpoint, understanding basal area growth is important because it is sometimes used to decide thinning intensities and because it is affected by pruning and fertilizer treatments. Individual tree basal area (or diameter) can be used as an indicator of the size and value of a butt log, although it is not sufficient by itself.

Relating basal area to height trends will remove some of the sigmoid shape, at least until severe competition begins to occur. Some growth models follow a similar procedure, using top height as the main variable for setting trends in growth over time and relating changes in basal area to changes in height (Beekhuis, 1966; Garcia, 1988).

Basal area and height are related to tree and stand volume via form factors that take into account the shape of the stem and, for merchantable volume, losses due to harvesting practices. Over long periods, volume will tend to follow a sigmoid-shaped curve, with the shape of the curve being site-dependent. The maximum mean annual volume increment in unthinned stands often occurs at about age 20, but there is considerable variation (Shula, 1989). Thinning delays and flattens the peak MAI (Lewis and Ferguson, 1993). In a South African spacing study on a less fertile site, net volume MAI peaked at age 21–23 for unthinned stands (2 965 stems per ha) and at age 31–32 years in stands with a final crop stocking of 124 stems per ha (van Laar, 1982).

Productivity rating systems

For radiata pine stands, site index (mean top height at age 20 years) has frequently been used as a measure of productivity (Goulding, 2005). In New Zealand, mean top height is predicted from height:diameter at breast height (dbh) curves and is the height of the quadratic mean diameter of the 100 largest trees per ha. Predominant mean height has also been used. This is defined as the average height of the tallest non-malformed tree in each 0.01 ha; it is closely related to mean top height. In Australia, the mean of the tallest 75 trees has often been used (Lewis and Ferguson, 1993). One argument for using height as a measure of productivity is that it is less influenced by stand density, although this is not always true (see Chapter 9; Kimberley *et al.*, 2005). A major disadvantage of a height index is that it does not adequately represent the growth of basal area or volume on different sites.

Basal area indices have not been used widely in the past, although attempts were incorporated into some models using simple "fertility levels". More recently, a basal area model has been developed based on a function that predicts basal area growth on the basis of age, stocking, site index and a basal area index (Kimberley *et al.*, 2005). This basal area function uses age from breast height, rather than planting, and allows for the effects of pruning by an age-shift technique, driven essentially by crown length and pruned height. It is built into the volume-based 300 index model (described below).

The maximum MAI of a stand is a more direct measure of stand wood productivity. This maximum is also affected by site and stand silviculture. The culmination of MAI to a given small-end log diameter (e.g. 7–10 cm), has been used frequently in Australia (Lewis and Ferguson, 1993). The range of these MAI values may be divided into yield classes. This approach is best suited to fully stocked schedules and, in parts of Australia, stands are often assessed for management purposes prior to first thinning to determine their yield class. Note that harvesting volumes may be 25–30 percent less than the volume increment (Lewis and Ferguson, 1993).

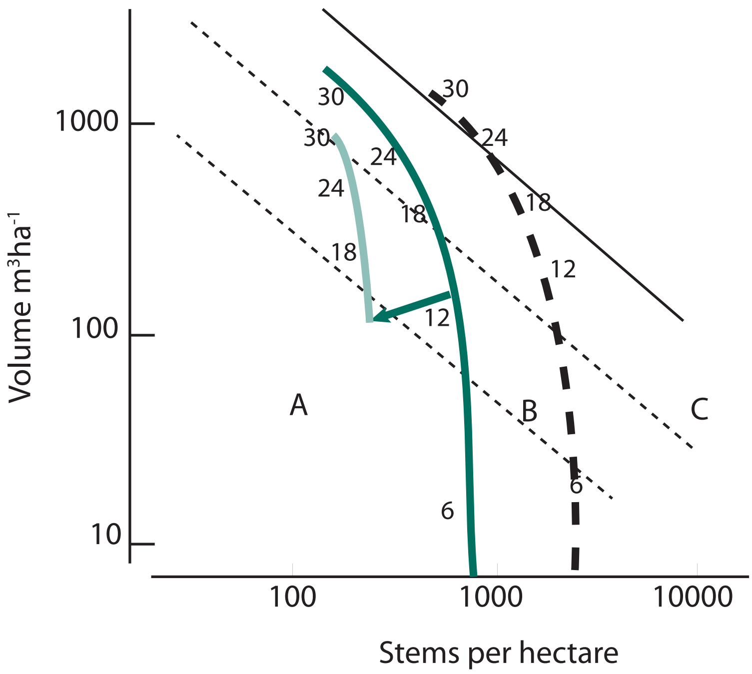
In New Zealand, the 300 index has recently been incorporated into simulation models and is also used to classify and map sites (Kimberley *et al.*, 2005; Watt *et al.*, 2010). The 300 index is based on the stem volume growth (MAI in m^3 per ha per year) of 30-year-old stands growing at 300 stems per ha and pruned to 6 m. The calculation of the index involves a stand-level basal area model (discussed above), a height–age model, a mortality function, a stand-level volume function, and a thinning function that predicts basal area following thinning. The 300 index model can be viewed both as a growth model and as an algorithm for predicting the site productivity index (Kimberley *et al.*, 2005). It has been used in simulation programmes for scheduling and evaluating silvicultural operations (Chapter 9). It is said to be a robust model, particularly after age 15, and applicable outside New Zealand, although a study supporting the latter claim is yet to be published.

Stocking and stand density

Stand growth rate is influenced by stocking. This is illustrated in Figure 5.3, which shows the growth of three stands of varying densities on the same site over time. At early ages and wide spacings, the trees do not fully occupy the site, and hence volume growth per ha is less than it might be (Long, Dean and Roberts, 2004; West, 2006; see zone A in Figure 5.3). At the low tree densities in zone A, the growth of an individual tree is maximized because its leaf area is not limited by inter-tree competition, but site occupancy is below its potential. Trees spend longer in zone A when planted at lower stockings. Moisture and nutrient status may also alter the ability of trees to occupy a site and the rate at which full site occupancy is reached. Competition by understorey plants for moisture and nutrients can be important on some sites.

When the canopy is complete and the trees fully occupy a site, inter-tree competition occurs (zone B, Figure 5.3). At this stage, stand growth rates are highest,

FIGURE 5.3
Generalized (not to scale) relationship between stocking, age (years) and growth



Note: black dotted line represents trees planted at 2 200 stems per ha and unthinned; dark green line represents trees planted at 850 stems per ha and unthinned; light green line is this second stand thinned at age 12 years to 350 stems per ha. Zones A, B and C represent the zones of free growth, competition with full stocking, and self-thinning, respectively. The solid black line indicates maximum stand density. The numbers indicate age in years. Note that both stocking and volume are on logarithmic scales.

although individual tree growth rates are strongly influenced by stocking rate – higher stockings will produce trees with smaller crowns and lower leaf areas. At very high stockings, the live basal area or volume growth may be reduced by crown abrasion and as suppressed trees stagnate or die.This C zone is where self-thinning occurs. Figure 5.3 shows that stands enter the competition and self-thinning zones earlier when planted at higher stockings. Thinning, illustrated in Figure 5.3, reduces this mortality loss in the self-thinning zone and at the same time promotes the growth of the crop trees. Nevertheless, total volume production is reduced by thinning because leaf area is reduced and it takes time for the remaining trees to fully re-occupy the site (Long, Dean and Roberts, 2004). According to Lewis and Ferguson (1993), the Australian multiple thinning schedules aim to achieve about 80 percent or more of maximum increment for the site by growing stands predominantly in the B zone.

Another approach to describing the effects of stocking on basal area growth is to divide the total increment into two components, a time-dependent or base increment (associated with the age of the stand) and a competition-dependent increment (Horne and Robinson, 1988). Related to this is the recognition that stands can be divided into diameter class groups, for example the largest 100 or 200 stems per ha. The base increment for a given stocking is the growth of these trees in an unthinned stand, while the response increment is the additional response to thinning.

New Zealand radiata pine studies have shown that individual tree diameters are unrelated to stocking (up to 12 000 stems per ha) up to age four years, but thereafter stocking levels affect diameter (Mason, 1992). However, a South African study found decreased growth before age three years (Craib, 1947). In older stands, higher stockings have major effects on diameter, average taper and crown dimensions (Table 5.1). There is less of an effect on height, although some studies have found reduced height at low stockings (Cremer *et al.*, 1982; Maclaren *et al.*, 1995; Mason, 1992; Kimberley *et al.*, 2005). Other studies are less conclusive (Table 5.1) or show the opposite effects (Craib, 1947). There are suggestions that exposure to wind may be implicated.

Vanclay (2009) found that, for plantations, the arithmetic mean dbh is a constant proportion of predominant mean height divided by the logarithm of stand density. Conventional thinning caused small, transient perturbations. Such relationships may be useful where data are scarce.

Crown growth

In open-grown trees, crown diameter and stem diameter are linearly or almost linearly related. This has been found to be true for many species, including radiata pine (Leech, 1984). The relation for radiata pine is:

$$\text{Crown width (m)} = 0.75 + 0.2073 \text{ dbh (cm)}$$

This relationship could be used to indicate where crown interference is likely.

With continued growth after canopy closure, the lower branches die because of a lack of light and also, particularly in older stands, due to abrasion with adjacent trees. In turn, the base of the green crown begins to rise. This can be delayed by wider initial spacing (Table 5.1) and thinning.

The rise in the green crown is important for two reasons. The death of the branches sets a limit to their size and after they die they give rise to bark-encased rather than intergrown knots. Thus, knowledge of green crown dynamics is a biological characteristic that has considerable bearing on both tree growth and end-use. One of the most comprehensive studies was by Beekhuis (1965), who concluded that for non-pruning schedules there is less scope to control the rise in green crown than was previously thought. Diseases such as dothistroma needle blight can also influence the green crown level.

TABLE 5.1

The influence of stocking on tree size, green crown height, height-to-diameter ratio and stiffness (MoE) for the outer wood: results from a 17 year-old radiata pine Nelder spacing trial in New Zealand

Initial stocking (stems/ha)	Height (m)	Diameter (cm)	Height:diameter ratio	Green crown height (m)	MoE (GPa)
209	16.6	36.6	46	1.8	5.4
275	17.5	34.7	51	2.7	5.7
364	17.7	35.0	51	3.4	5.9
481	18.4	31.8	59	5.4	6.6
635	18.0	28.6	64	6.8	6.7
835	17.7	24.9	74	7.8	7.2
1111	17.8	24.0	77	8.8	7.1
1457	17.6	21.9	84	9.3	7.1
1924	16.8	18.9	95	9.4	7.6
2551	17.3	17.7	103	10.2	7.5

Source: Waghorn, Mason and Watt, 2007a,b

Branch development

Branch diameter is particularly important as it affects strength, appearance and timber grade outturns and in clearwood regimes it can also influence the effectiveness and cost of pruning. In some quarters, radiata pine has a reputation as a coarse-branched species, although tree-breeding has improved this image. The reputation is certainly true with respect to open-grown trees and high-fertility sites (Madgwick, 1994). Coarse-branched stems, however, are not found in slower-grown stands where moisture and fertility are limiting; environment is probably of greater importance than genetics.

Branch size and tree size are closely correlated, and growth conditions that promote tree diameter growth also promote branch growth. Spacing and thinning can substantially influence branch size in the upper bole. In Nelder spacing trials, where spacing and tree diameter were found to be closely related (e.g. Table 5.1), branch diameter was related to tree diameter (e.g. Waghorn, Mason and Watt, 2007b); other studies support this finding (Madgwick, 1994). Sutton (1970) found that rectangular spacing had little influence on branch diameter between and within rows and also reported that subdominant trees had smaller branches than dominants or co-dominants. Under most thinning regimes, major responses in branch growth are usually confined to the actively growing upper crown (Siemon, Wood and Forrest, 1976). Branch diameter is negatively correlated to the number of branch clusters in the annual shoot (Fielding, 1960).

Inter-tree competition and mortality

As stands develop and inter-tree competition intensifies, some trees become suppressed and may die, while others become more dominant. Stands differentiate into crown classes, depending on their degree of suppression (Lewis and Ferguson, 1993). Early in the life of a radiata pine stand there may be some movement between crown classes (Sutton, 1973), but this probably decreases in older stands.

The causes of mortality may be classified broadly as either competition or catastrophe, although there is an obvious overlap. So-called natural or competition-based mortality is often due to suppression, perhaps assisted by adverse conditions such as drought or by disease or insects attacking weakened trees. Light is the dominant competitive process (West, Jackett and Borough, 1989). West (2006) described how growth, mortality and branch development are related to stand density.

Thus, the onset of self-thinning means that any additional increase in mean tree size is associated with a decrease in stand density (Figure 5.3). For a given species, the maximum size–density relationship adheres to the following relationship, where n is stocking and α is a constant for a species:

$$\log n + \alpha \log(\text{tree size}) = \text{constant}$$

Reineke's (1933) density index uses quadratic mean diameter as the measure of tree size; α is about 1.6. The maximum stand density diameter index is about 1 200 for radiata pine; for schedules that emphasize volume production, with a minimal risk of tree mortality, thinning should be timed to maintain a Reineke's density index value of 0.35–0.55 (Mason, 2012). Beekhuis (1966) used relative spacing (average spacing divided by height), implying that $\alpha = 2$ for predominant mean height.

The "3/2 self-thinning law" uses mean tree mass, usually approximated by stem volume; here, α is given a value of 1.5 when using natural logarithms. This was first described in the context of radiata pine in a seminal paper by Drew and Flewelling (1977). Later research suggested that it may best apply to the more dominant element (West and Borough, 1983). There are examples where self-thinning in radiata pine has been less marked, usually on poorer sites (Lavery, 1986). Similarly, Bi (2001) has described the dynamic interplay of site quality on the self-thinning law for radiata pine and concluded that individual stands seldom travel along their self-thinning frontiers but converge toward them during the self-thinning phase. Long-term (50–100 years) data for radiata pine plots in New Zealand indicate that self-thinning stands tend toward a lower live stocking asymptote of 200–250 stems per ha (Woollons and Manley, 2011).

Curtis (1982) modified the Reineke model for Douglas fir and defined relative density in terms of basal area (in m^2 per ha) and mean tree diameter (in cm) so that:

$$\text{Relative density} = \text{basal area} \div \sqrt{\text{tree diameter}}$$

Reid (2006) applied this to radiata pine and suggested that the maximum relative density (self-thinning line) for this species was 16 and that lower relative densities could be used to guide thinning schedules. Reid also proposed that the ratio of diameter (cm) to basal area was a useful stand density guide and that for pruned radiata pine stands this should be about 1 and should not be greater than 1.5.

There is considerable controversy about such relationships, particularly the "3/2 self-thinning law" (e.g. Lewis and Ferguson, 1993), but they do illustrate how stands react to competition (West, 2006). Garcia (1993) developed a more generalized concept that uses a complex three-dimensional surface to explain wider variations in stocking.

From the point of view of sustainable silviculture, the forest manager should aim to keep trees healthy and to prevent mortality. Thus, while there may be a need to estimate mortality in growth models, this is less critical than estimating the growth rates of well-managed stands.

WOOD PROPERTIES AND END-USE

The systematic variation in wood properties in the stems of radiata pine has a considerable bearing on end-use and indirectly on the species' silviculture. More detailed descriptions of radiata pine wood properties and uses can be found in Wilkes (1987) and Cown (1999). On the basis of its wood anatomy, radiata pine is placed in the ponderosa group, which includes, among others, *Pinus contorta*, *P. patula*, *P. pinaster* and *P. ponderosa*. Radiata pine tends to have lower stiffness than many of its competitors in the structural wood market (Moore, 2012).

Cambial activity and differentiation

On many sites, cambial activity in radiata pine never ceases, although mid-winter is the month of least activity. The maximum rate of cell production is January–April in the Southern Hemisphere, which is later than the height–growth pattern. Most of the time the cambium is dividing off new tracheids towards the inside of the tree, and this forms the xylem or wood. In radiata pine, 95 percent of the wood is tracheids. Light-coloured, thin-walled earlywood cells are formed early in the growing season, followed by a narrower zone of darker, longer, thick-walled latewood cells. Resin canals are most frequent in the transition zone between latewood and earlywood. The proportion of latewood ranges from 10 percent near the pith to 50 percent in the outerwood of mature trees (Cown, 1999). For radiata pine, the difference in density between latewood and earlywood is 1.6:1, which is similar to sitka spruce but lower than the southern pines, ponderosa pine and Douglas fir. Thus, radiata pine is easier to machine and veneer, wears more evenly and takes paint and glue better than, say, Douglas fir, which has a density ratio of 2.3:1.

The tracheids laid down close to the pith (and also when the tree is young) are shorter and have a larger diameter and thinner walls than those laid down further from the pith. The longest tracheids are found in the outerwood at about 50 percent of tree height. Root wood tends to have longer tracheids than stem wood.

The shorter, thin-walled tracheids close to the pith have higher microfibril angles and this has been identified as a major cause of the weaker structural strength and greater longitudinal shrinkage of wood in this zone (Walker and Butterfield, 1995). The microfibril angle is the angle at which cellulose microfibrils in the S2 layer of the cell walls wind around the cell.

Water and nutrients from tree roots are conducted upward through the sapwood by tensions created in the crown. Most of this transport is in the earlywood rather than the latewood. Latewood tracheids become filled with gas bubbles so that latewood is drier than earlywood and can no longer transport water. Tree physiologists talk of the "pipe theory" because they have found there is a good relationship between the cross-sectional sapwood area and leaf area (Waring, Schroeder and Oren, 1982). Interestingly, Leonardo da Vinci (ca. 1500) suggested that the sum of the branch cross-sectional areas above a point in the crown should be the same as the stem cross-sectional area at that point. Madgwick (1994) reviewed radiata pine data, where some variation was noted, and suggested that under-bark measurements may be preferable to over-bark diameters. As water is conducted in the earlywood, the area of earlywood would be more appropriate, but this has not been tested. O'Hara *et al.* (1998) found that, as a surrogate for leaf area, sapwood area at the base of the crown was better than crown length for predicting basal area growth in radiata pine.

The cambium also divides off cells towards the outside of the tree to form the phloem. These cells are different from the xylem tracheids and are largely living sieve cells. Food in the form of sugars, synthesized in the leaves, is transported through this living inner bark to where cell division takes place in the cambium and meristems. Sugars are also conducted radially and stored, mostly as starch, in the horizontal rays of the wood.

The thin cylinder of vascular cambium is initially derived in the apex of the elongating primary shoot (terminal bud) from procambial strands that link up into a circular sheath. In doing so, they enclose a central core of primary parenchymatous tissue, which becomes the dark-coloured pith about 10 mm wide. The bark is formed from zones of cell development within the phloem or the cortex (the primary ground tissue outside the phloem). These cells become suberized and die.

Mature functional tracheids in the sapwood ultimately die and form heartwood. Heartwood formation is the consequence of aging wood, or more accurately of the failure and senescence of the xylem function of water conduction and water and food storage. Heartwood cells contain more resins and tannins than sapwood, but in radiata pine these are insufficient for the wood to be called durable. Resinification of the heartwood is an ongoing process, with resin content increasing over time.

In radiata pine, heartwood develops from age 12–14 years and progresses at a rate of about half a ring width per year, the rate apparently varying with site and genotype (Cown and McConchie, 1992). The proportion of heartwood increases with age, from nil at about 12 years to 10 percent at 20 years, 20 percent at 30 years and 30 percent at 40 years (Cown, 1999).

Corewood properties

Radiata pine wood laid down by cambial cells under a certain age has intrinsic characteristics that differ markedly from the remainder of the wood. This corewood is often taken as ten growth rings from the pith but in reality there is a gradual change and there are variations up the tree as well. As far as sawnwood is concerned, the first 3–5 annual rings from the pith are the worst.

Compared to more mature outerwood, the corewood of conifers is generally characterized by:

- wider rings
- lower wood density
- lower tangential shrinkage
- higher longitudinal shrinkage (influences drying of the first three growth layers)
- lower stiffness (modulus of elasticity, or MoE) due to the high microfibril angle
- more compression wood
- higher spiral grain

- higher moisture content
- shorter, thinner-walled tracheids
- lower cellulose but higher lignin content
- a dull and lifeless appearance.

For radiata pine and most other fast-growing conifers, the corewood's low stiffness (MoE), greater longitudinal shrinkage and low hardness, in contrast to mature wood, are the most important properties (Moore, 2012). The effect of a wide, poor-quality corewood is exacerbated when radiata pine is grown in rotations of less than 25 years, because the proportion of sawnwood that contains some corewood is higher. However, matters become complicated when butt logs are compared with logs higher in the tree (Box 5.1). Where early growth is restricted, for example by pruning, this may restrict the size of the corewood (Wilkes, 1987). Research on corewood properties and ways to overcome the problems with corewood in sawnwood production has focused on tree-breeding, initial stockings and stem slenderness (Walker and Butterfield, 1995; Mason, 2008; Watt *et al.*, 2009a). However, as pointed out by Mason (2008), the underlying reasons for focusing on stem slenderness are unknown and it is not always a good predictor of stiffness. The influence of these properties on reconstituted products is discussed later.

Thinning and fertilizer treatments that increase the radial growth rate have small effects on wood properties and so are generally of little consequence for wood use (Cown, 1999). However, higher final tree stockings produce a higher proportion of harvested corewood (Moore, 2012).

Heartwood compared with sapwood

The heartwood of radiata pine is only marginally more durable than the sapwood, but sapwood is considerably more permeable and thus easier to treat with preservatives and other chemicals. Green sapwood has a higher moisture content than heartwood but contains fewer extractives and resins (Cown, 1999). Shrinkage is slightly greater in sapwood than heartwood. Heartwood is not as readily digested in chemical pulping processes because of its higher content of extractives, and the tall oil yield is increased. In mechanical pulping, high heartwood content can give rise to pitch problems. Knots also have a higher extractive content.

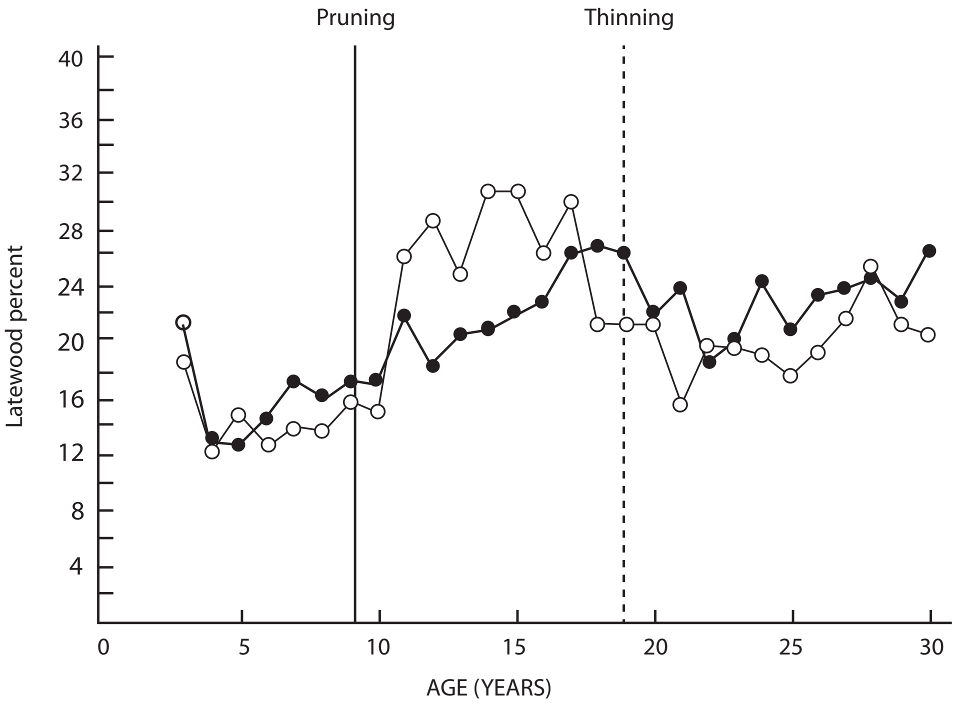
Bleeding or exudation of resin on the surface of sawn radiata pine is generally confined to heartwood and knots. As with other conifers, this resin can cause problems in wood use and is exacerbated by dark stains or paints that increase wood temperature when exposed to sunlight.

Basic density

Basic wood density (kg per m^3) – dry and distinct from green density – is important because it is associated with the strength of clear sawnwood and with pulping characteristics, including pulp yield. For sawnwood, tracheid microfibril angle is of greater importance than density (Box 5.1; Walker and Butterfield, 1995). For some pulping processes, such as mechanical pulping, low wood density is advantageous as it can reduce power demand by as much as 30 percent. This does not apply to kraft pulping, where high wood density is an advantage.

The corewood also has lower density than the outerwood; typically, the corewood has a basic density of 300–350 kg per m^3, while the basic density of outerwood is usually 400–450 kg per m^3. Basic density also varies with altitude and latitude and is generally lowest at high latitudes and altitudes (Cown and McConchie, 1983; Wilkes, 1987). Density decreases as mean annual temperature decreases with increasing altitude and latitude; Cown and McConchie (1983) found a significant relationship between density and mean annual temperature with an r^2 of 0.49 for outerwood and 0.31 for corewood. There is also evidence that rainfall is positively correlated with wood

FIGURE 5.4
The effects of pruning and thinning on latewood percentage in South Africa



Note: the pruned trees (circles) were pruned in one lift at age nine years (12 m height) leaving 4 m crown length, and this increased the latewood percentage. Unpruned trees are filled circles. The stand was thinned again at about age 18 years and this decreased the amount of latewood.
Source: From Gerischer and De Villiers (1963)

density, with winter rainfall being particularly important. Seasonal drought can cause a temporary reduction in growth and result in false rings.

The effects of silvicultural treatments on wood density generally show that when individual tree growth increases substantially, for example after thinning, there is a small reduction in wood density (Wilkes, 1987; Cown, 1999). The addition of fertilizers on nutrient-deficient sites tends to restore density to normality. Green-crown pruning increases density due to greater latewood percentages, while thinning reduces latewood (Figure 5.4; Gerischer and de Villers, 1963). These density changes with pruning and thinning support the pipe-model theory, described earlier, that links leaf area to the amount of earlywood. Such changes are small compared to age effects and have little impact on use.

Tracheids

Tracheid length affects the strength, surface and bonding properties of fibre products. Long tracheids shrink less longitudinally than short tracheids during drying. Tracheid length is also correlated positively with mean annual temperature and mean minimum air temperature as well as with tree slenderness; some sites have longer tracheids than others (Wilkes, 1987; Cown, 1999; Watt *et al.*, 2008c). Silvicultural treatments that increase individual tree growth can also reduce tracheid length by up to 20 percent. Such differences can be important for pulp and paper making but are unlikely to influence sawlog quality.

The microfibril angle of tracheids has major effects on wood strength and is the subject of research that aims to reduce its impact on wood quality (Box 5.1; Walker and Butterfield, 1995; Mason, 2008). At low initial stockings, the stiffness of wood can be reduced by as much as 40 percent (see MoE in Table 5.1; Lasserre, Mason and Watt, 2004). Studies have shown that this is related more to microfibril angle than wood density (Mason, 2008; Lasserre *et al.*, 2009) and that microbifril angle is related

BOX 5.1

The effects of radiata pine wood density and stiffness on structural timber grades

The key attribute for high-quality structural timber is high stiffness and structural timber grades based on mechanical stress grading uses this as a quality measure. For example, in the Australian standards, the MoE ranges from 4.5 GPa for F2 grade to 6.9 PGa for F5 to between 9.1 and 12 GPa for F8 to F14 grades. This study compared 25 year-old radiata pine grown on a site with low strength properties in Canterbury with an average New Zealand site (Nelson) and found that:

- The Nelson trees provided 56 percent of high-grade wood (F8 and higher), compared with 12 percent from the Canterbury trees. Only 14 percent of the wood produced in Nelson was F4 grade or lower, compared with 54 percent from Canterbury.
- The butt logs in Nelson provided a lower volume of higher grades than the toplogs. This surprising result is presumably because the juvenile trees had particularly low-strength wood; the corewood of the upper logs is better than that of the butt logs.
- On both sites the boards cut close to the pith provided only very poor wood of ≤F5 grade.
- In Canterbury the outermost boards provided 68 percent of good grades, compared with 100 percent in Nelson.
- The average MoE and basic wood density of Nelson trees were 9.9 GPa and 495 kg per m^3, compared with 6.8 GPa and 475 kg per m^3 for Canterbury trees, respectively.
- For the butt logs, MoE was a better predictor of strength and grade outturn than wood density (see also Walker and Butterfield, 1995).
- Sorting logs on skid sites for stiffness would be an advantage.
- To improve sawlogs through tree-breeding, stiffness of the corewood, rather than wood density, could be used as the selection or screening trait.

Source: Tsehaye, Buchanan and Walker, 2000

to stem slenderness. Higher stockings and pruning also increase trachied length, cell-wall thickness and latewood percentage (Lasserre *et al.*, 2009; Gerischer and de Villers, 1963).

MoE can readily be measured in standing trees and logs using sonics. It is easier than measuring tracheid properties, and by extension is a useful measure of corewood properties. MoE is also used in machine stress grading. A recent nationwide study in New Zealand in radiata pine stands at age six years found that MoE was most closely related to stem slenderness, which explained 71 percent of the variation (Watt *et al.*, 2009a). Furthermore, sites with warm air temperatures, or those that were infertile or had a high weed competition tended to have slender trees with higher MoEs. Apparently, tall woody weeds have a greater effect than herbaceous weeds. However, the contrasting results reported by Mason (2008) indicate that more research is required.

Breeding for low microfibril angle in the corewood is being undertaken as a way of improving the poor outturn of good structural wood (see Chapter 6). Apparently, there is no genotype x stocking interaction (Lasserre *et al.*, 2009).

The relationship of MoE to the machine stress grading of structural timber is discussed by Moore (2012). The average MoE for radiata pine in Australia, Chile, New Zealand and South Africa is 10.7, 8.8, 8.2 and 12.9 GPa, respectively (Cown, 1999).

Grain orientation and spiral grain

Wood in which the grain or alignment of tracheids is at an angle to its longitudinal surfaces frequently behaves abnormally. Deviations in the direction of the grain from the plane of the sawnwood can arise from three sources:

- sawing at an angle to the grain;
- inclination around knots;
- spiral growth patterns in the tree.

Sawing at an angle to the grain is unavoidable when sawlogs have sweep or high taper. Sloping grain produced by a knot affects the region adjacent to the knot and increases the effective area of the knot as a strength-degrading factor. Sloping grain causes reductions in strength characteristics, particularly bending strength. Spiral grain refers to the alignment of tracheids at an angle to the stem axis.

In radiata pine, spiral grain is not severe in the first ring from the pith, develops to a peak at about the third ring from the pith, and then gradually decreases in severity, until by the tenth ring it is less obvious. Spiral grain is therefore essentially a feature of the central corewood zone of the tree and causes drying degrade when in excess of five degrees (Cown, 1999). It is a highly heritable characteristic. Its main result is to cause sawn timber or veneers to twist on drying. Problems associated with spiral grain are exacerbated by short rotations and are more common in toplogs and logs derived from thinnings. Walker and Butterfield (1995) argued that the focus for structural wood should be on microfibril angle rather than spiral grain.

Compression wood

Reaction wood in radiata pine – like in all conifers – occurs as compression wood on the lower or underside of leaning trees or on the leeward side of a stem subjected to strong prevailing winds. Compression wood can vary in intensity from isolated crescents of slightly darker-coloured wood to extensive areas involving many annual growth layers and covering one-quarter or more of the log's circumference. In extreme cases it can make up 45 percent of sawnwood outturn from an individual log. It is more common in corewood than mature wood.

The compression wood of radiata pine is weaker than normal wood in all strength properties except hardness, and its longitudinal shrinkage can be much greater, which can cause drying problems (Cown, 1999). In pulp-making, a high proportion of compression wood reduces yield and also results in reduced paper strength.

Knots and their link to grading systems

Four types of branch knots may be found within radiata pine trunks:

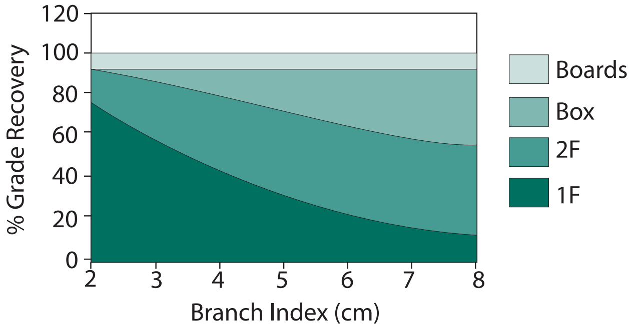
- Sound inter-grown knot: this forms when the branch is alive.
- Partially bark-encased knot: this is a variation of the sound inter-grown knot and results from a bark occlusion in the crotch (upper surface) of an acutely angled branch.
- Fully (bark) encased knot: this is formed where a dead branch is occluded in the expanding trunk. Fully encased knots can also be described according to whether they are firm, loose or decayed.
- "Black knots", as they are referred to in Australia: a knot where the surrounding bark layer has become dark because of heavy impregnation with resin.

Decayed knots have a far greater degrading effect than sound knots, especially for sawnwood graded on appearance. Early research in New South Wales clearly illustrated that bark-encased knots substantially reduced the value of logs (Humphreys, 1971).

Independent of appearance, knots are considered a defect of major importance because of their effect on strength reduction related to grain orientation. It is the disturbed grain around the knots that determines the strength of a piece of wood in bending tension. Larger branch diameters result in greater degrade.

Knots, therefore, have a major impact on lumber visual grading rules (Cown, 1999). They affect both full-length appearance grades (board grades) and strength grades (framing grades) as well as plywood. Knot size is more important in strength grades

FIGURE 5.5
The relationship of branch index to structural grades



Source: From Cown (1999)

than appearance grades. Grading rules also incorporate other defects, as appropriate, such as cone holes, pith and resin pockets for board grades, and pith, corewood and sloping grain for strength grading. The actual rules vary between countries.

A branch index (average diameter of largest branch in each of the four quadrants of a standard log length) was developed in New Zealand in the 1980s (Inglis and Cleland, 1982; Tombleson, Grace and Inglis, 1990). Studies found that branch index could be predicted with reasonable accuracy using the log height class and four stand parameters: site index, mean dbh of the stand at age 20 years, predominant mean height at the time of last thinning before branch measurement, and rotation age. Branch index has been used in models to predict the value of sawnwood output where it has been shown to have a major effect on outturn (Figure 5.5). However, a Chilean study found that branch index is a poor measure of log value when based on appearance grading (Alzamora and Apiolaza, 2010). The largest branches in radiata pine usually occur when height, diameter and foliage mass peak during the adolescence phase, and at 30–40 percent of total height in 20-year-old trees (Woollons, Haywood and McNickle, 2002). For practical reasons, the branch index was redefined for the log grading system as the diameter of the largest single branch in a log.

The second quality factor developed in New Zealand in the 1980s was an internode index. This index is obtained by adding the lengths of all internodes of 0.6 m or longer and expressing the sum as a proportion of the total 5–6 m log length (Carson and Inglis, 1988; Cown, 1999). This index recognizes that it is possible to cut short-length clears (known as clear-cuttings grade or factory grade) from between the knot clusters of many radiata pine trees. Clearcuttings increase with both log small-end diameter and internode index. For example, for logs of 250 mm small-end diameter with an internode index of 0 and 0.5 will produce 30 and 41 percent factory grade or better, respectively, while logs of 450 mm small-end diameter will produce 40 and 76 percent factory grade, respectively (Cown, 1999). Chilean studies also support the link between internode length and log outturn values (Alzamora and Apiolaza, 2010).

Meneses and Guzmán (2003) suggested an alternative index, base internode length, which is defined as the minimum internode index that is contained in 50 percent of the log length. This index may be more flexible because it indicates what might be manufactured from the log. Another suggested alternative is mean internode index (Watt, Turner and Mason, 2000). It should be noted that these branch or internode indices do not differentiate between knot types.

The log grades, developed in New Zealand, provide a uniform method of resource description that can be used for sale purposes and therefore are of value to both the seller and buyer (Whiteside and Manley, 1987). They can also provide a coherent link between forest planning, management and use. The log grades focus on key, readily assessed attributes that influence processed value, such as branch size, internode index, log small-end diameter, log sweep (see below) and whether the log had been pruned. They do not, however, take into account intrinsic wood properties, so logs may also need to be sorted on landings based on their stiffness measured with portable acoustic tools (Moore, 2012). Mason (2012) recommended that a structural log index that includes intrinsic wood properties should be developed to assist managers.

When knotty logs are pulped, the knots contribute a higher level of extractives and the compression wood surrounding the knots has higher lignin content. Knot wood also reduces pulp yield.

Experience has shown that radiata pine stems with fine branching can be produced on some soils by using high stockings. On the other hand, it can be difficult to contain branch size on very fertile sites. Tree-breeding has also reduced knot size and altered the internode length and may be used to improve intrinsic wood properties (see Chapter 6). Alternatively, the quality of the wood in the bottom log can be upgraded by judicious pruning.

Clearwood

Clearwood – wood free from defects such as knots, resin pockets and cone holes – is the most valuable wood and is useful for many purposes. The green branch pruning of radiata pine was introduced to South Africa and New Zealand and subsequently to other countries to increase the value of the butt logs. Straight, pruned logs should yield 50–60 percent or more of clear grades, provided that the defect core is kept small (e.g. 250 mm) and the small-end diameter of the logs is large enough (e.g. >500 mm) (Cown, 1999). A pruned log index has been developed in New Zealand that can be used to rank pruned logs for potential output on the basis of detailed log shape and defect core information (Park, 1989). The true clearwood potential of sawnwood and veneers also depends on other aspects such as resin blemishes and the position of the knotty core (Park, 2005). As noted above, short-length clears are also possible from between branch clusters.

Log size and sweep

The small-end diameter of logs has a major impact on timber recovery and hence on log value (Cown, 1999; Alzamora and Apiolaza, 2010). In addition to producing larger logs, longer rotations often result in improved wood properties. Log size and sweep also interact strongly (Figure 5.6). Sweep has been defined as the maximum deviation from the central log axis (i.e. the straight line between the mid-points of each end of the log) and the diameter at that point and is usually expressed as mm per m.

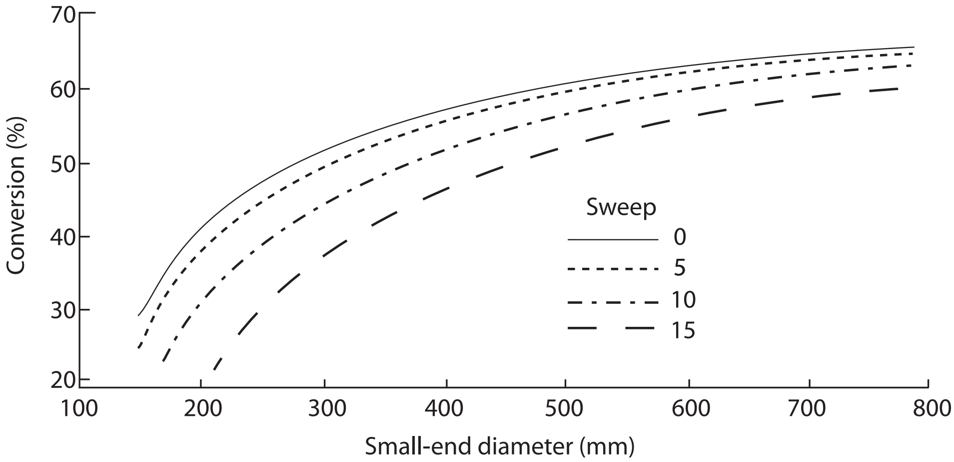
In addition to lower recoveries, sweep logs typically produce a higher proportion of lower grades. Recognition of the significance of sweep as a downgrading characteristic has led to a greater emphasis on lower bole straightness in the selection of stems for retention in waste thinning schedules in clearwood regimes.

Other defects

There are a number of other potential defects of radiata pine, some of which can be important locally. These include resin pockets or other blemishes, thinning damage, non-centrally located pith, cone holes and needle traces.

Resin pockets or blemishes occur in many softwood species, particularly spruces and pines. They originate from tangential longitudinal splits in the cambial zone. New Zealand research suggests that several types occur in radiata pine and may cause large pockets or smaller blemishes (Cown, Donaldson and Downes, 2011). Strength characteristics are not affected significantly, but the occurrence of resin pockets can reduce the value of clearwood, particularly where it is used for veneer. It is possible to detect the presence of resin pockets, particularly the bigger types, on the bark and also

FIGURE 5.6
The impact of log small-end diameter and sweep on sawing recovery



Source: From Cown (1999)

to see them on the ends of freshly cut logs. As the number and type can be related to end-use, visual scoring may allow the screening of genotypes, site classification, tree selection at thinning, and log-sorting during the processing stage (Cown, Donaldson and Downes, 2011). However, a recent Chilean study found a weak relationship between external resin bleeding and resin pockets (Ananias *et al.*, 2010). Hotter, drier climates with water stress and exposure to gale-force winds appear to be implicated in the formation of large resin pockets, but such pockets occur at a low level in most pruned logs. One experiment showed that preventing tree sway reduced resin pockets, thus implicating wind as a stress factor (Watt *et al.*, 2009b). Damage by pests, thinning with machines, and lower stockings, also influence the occurrence of resin pockets, and there is also a genetic component.

Exposure to wind can cause the pith to be non-centrally located and the creation of substantial compression wood. Such trees cause difficulty when used as veneers because of the differences in wood properties.

Cone holes are relatively common in radiata pine wood, and they originate from persistent stem cones. The occurrence of this defect is largely confined to logs above the second log length. Its impact on strength characteristics of timber is minimal, but it does degrade appearance-grade timber.

The remnants of needle traces, the woody tissue that connects stem needles to stemwood, can be seen as small lenticular-shaped flecks in the innermost growth rings. They are of no consequence for the strength of timber, but they do indicate that the wood has properties associated with corewood. Occasionally these flecks are considered attractive.

Sapstain associated with fungi can degrade appearance grades (Cown, 1999). It can be caused by some pests and diseases (see Chapter 4), fire, windthrow, thinning and pruning damage and poor log handling, and also during processing. Freshly cut radiata pine wood is less susceptible to fungal attack than rubberwood but is more susceptible than Douglas fir. Anti-sapstain treatments and kiln drying are frequently used to control fungal problems during processing (Cown, 1999).

Pulpwood and reconstituted products

The various sources of chipwood in radiata pine plantations have differing properties that influence their potential use (Cown, 1999). Full-length, relatively young logs aged 10–20 years are produced in extraction thinnings and from pulpwood crops. Currently, large quantities of these logs are used in some states of Australia, in Chile and in parts of New Zealand. A second source of chipwood is toplogs from older trees. Toplogs, extraction thinnings and logs produced in pulpwood crops are relatively low in density and contain shorter trachieds; they are particularly suitable for reconstituted panel products such as medium-density fibreboard, oriented strandboard and particleboard, and for mechanical pulping. The third major source of chipwood is slabwood residues from sawlogs. These are usually higher in density with longer trachieds and are particularly suited for chemical pulping (Cown, 1999). However, as many pulp and paper grades need a blend of both pulp types, they are often segregated at the mill and blended in the proportions required. Similarly, between-site differences can be used to help control pulp quality. In general, radiata pine is very suited to panel and pulp products.

OVERVIEW OF RADIATA PINE END USE

Despite much early prejudice, radiata pine has proved to be a medium-density, even-textured, softwood of wide utility. It is possible to grow large logs in under 30 years, which is a significant advantage (Figure 5.7). The importance of these factors is outlined below:

- Wood density is a rough measure of timber strength and of yields that can be expected in reconstituted wood products. It also has relevance for properties such as machinability, paintability and so on. Radiata pine is considered average in this regard.
- The evenness of the texture of radiata pine is significant for most users. For pulping, it implies a relatively uniform type of fibre that is much less technically demanding, from fibre separation (whether chemical or mechanical) to the final stage of processing, when paper sheets are formed. It also makes first-class fibreboards. For machining solid timber, uniform cutting characteristics, uniform response to machining pressures and uniform resistance to tearing or plucking are great advantages. For veneer and plywood manufacture, evenness of cutting and

FIGURE 5.7
Large radiata pine logs arriving at the mill

relative uniformity of glue absorption and bonding are desirable features.
- Softwood tracheids are much longer than hardwood fibres. This increases their versatility for many reconstituted products.
- The utility of radiata pine is demonstrated by its wide range of uses and products, even if it may not be the preferred species for some end-users.

There are many specialty uses for which radiata pine is unsuited. Furthermore, it has some inherent characteristics that are sometimes undesirable such as wide ring widths, poor surface hardness, wide variation from pith to bark, large knots, poor natural durability, relatively poor figure and surface checking and resin bleeding in external applications. It also produces low-quality fuelwood or charcoal and is difficult to grow for high-quality poles.The lack of natural durability, moreover, means that radiata pine needs to be treated for use where moisture is present to prevent fungal or insect damage (Cown, 1999).

Radiata pine serves other end-uses apart from wood products. It is used as a Christmas tree, for example, both in California and in its adopted countries. It has proved a valuable species for shelter and in erosion control, and, less frequently, as an amenity tree. It is also important as a carbon sink and for biodiversity and other social services (see Chapter 3). It has been used on a small scale for resin-tapping in South America, while turpentine and tall oil are important byproducts of kraft pulping. The bark of radiata pine is widely used in horticulture, both as a mulch and in potting mixes (Figure 5.8). Edible mushrooms are collected from under radiata pine, especially in Chile.

The link between silviculture and end-use or outturn can be difficult for the forest manager, particularly where the grower is not part of a vertically integrated industry. There are two contrasting approaches to producing marketable products: forest-based and factory-based.

The forest-based approach is the more traditional approach. It involves the use of forest silviculture (e.g. genetic selection, stand density control and pruning) to grow

FIGURE 5.8
Radiata pine bark is widely used in horticulture

trees that will yield the required log qualities for desired products with straightforward processing. Often there are additional costs early in the rotation, thus incurring high compounded costs and greater risks, including market risks, particularly where longer rotations are needed to obtain the desired log quality. The adoption of pruned log schedules without production thinning in South Africa, New Zealand and elsewhere is a good example of the forest-based approach designed to address particular marketing problems and take advantage of perceived market opportunities.

The factory-based approach emphasizes the upgrading of wood products during the processing phase rather than the tree-growing phase. Logs are processed more intensively to produce specific products. For sawnwood, the processes currently used, apart from sawing and seasoning, include jointing, laminating and surfacing with other materials. In some cases, new products such as medium-density fibreboard and laminated veneer lumber have been developed that have replaced solid wood or plywood in some uses.

The availability and cost of energy are relevant considerations in this choice. For example, energy input (other than solar) to grow clearwood is low, while the factory-based approach to production through remanufacture is more energy-intensive. This also influences its carbon footprint.

However, there are limitations to such a simplistic view. Some end-uses, such as pulp and paper manufacture, do not fit neatly into either category. Furthermore, many intensive pruning schedules also produce lower-quality logs above the clearwood butt logs, and those need to be upgraded in the factory. Differing wood-using enterprises may have very differing objectives and strategies that influence their decisions on processing and adding value in the forest, and these strategies can change over time. Ultimately, the success of large-scale radiata pine plantations lies in the fact that that they have provided markets with valuable resources (Lavery and Mead, 1998). It is not exclusively an outcome of either a forest-based or factory-based approach.