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Sustainable management of *Pinus radiata* plantations

Cover photos:
Left: High pruning of radiata pine, New Zealand (P. Wilks)
Centre: A combination of radiata pine plantations, other introduced trees, native areas and farming create attractive landscapes in New Zealand; the farming is on the better soils (D. Mead)
Right: Recreation in a mature radiata pine plantation near Nelson, New Zealand (D. Mead)

Sustainable management of *Pinus radiata* plantations

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by
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Foreword

Growing societal demand for forest products and services require an increase in efforts to establish new forests. Where appropriate, intensively managed forest plantations can supply local and global markets with wood while contributing significantly to rural and industrial development. One of the most successful forest plantation species is *Pinus radiata* – radiata pine.

FAO recognizes the need to back up any significant tree-planting with a deep understanding of all aspects of the species being planted. In 1960, FAO published a major review of radiata pine, written by C.W. Scott, which presented the state of knowledge at that time. After more than 50 years, FAO is pleased to present a comprehensive update of knowledge on radiata pine. While this new publication, by Dr Donald Mead, covers many aspects of the species – its discovery and domestication, site requirements, limitations, wood properties and end-uses, and its social and environmental roles – its focus is on the principles and practices of growing radiata pine sustainably. It also looks ahead to emerging challenges facing plantation forest management, such as the effects of climate change, new diseases and other threats, and how to manage plantation forests to meet changing product needs and societal demands. Thus, this book is relevant and helpful for growers of other tree species, and should also provide valuable insights to forestry students and a wide range of other people interested in forestry.

Globally, there are just over 4 million ha of radiata pine plantations, mainly in Australia, Chile, New Zealand and Spain, making this species the most widely planted introduced conifer. As a plantation species, radiata pine has been a spectacular success, becoming the basis of strong wood-using industries in those countries and producing about 60 million cubic metres of wood per year. Even so, radiata pine provides only slightly more than four percent of the output of all planted forests.

Dr Mead, a New Zealander, has been involved in forestry research and teaching about radiata pine for more than 50 years. He wanted FAO to publish this review of radiata pine management as a means to ensuring its wide dissemination. For FAO, this publication is a way of educating professionals and others on the importance of long-term sustainable plantation forest management based on a profound knowledge of the biology, silviculture and use of a species. I congratulate Dr Mead for this outstanding contribution to global knowledge on plantation forest management and recommend the work to the global forestry community.

Eduardo Rojas-Briales
Assistant Director-General
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I also sincerely thank Alvaro Sotomayor, Rowland Burdon, Euan Mason, Lisa Langer, Mike Carson, Eric Appleton, Robin Trewin, Piers Maclaren, Jose Prado, Tat Smith and Philip West, all of whom reviewed parts of this book. Rowland Burdon actively cooperated by providing background information on radiata pine history and status; he has been involved with a book on the domestication of the species. Jim Carle provided insightful comments on the entire book based on his wide experience with FAO and as a forest manager. Walter Kollert is also thanked for his support after Jim Carle retired. Rosamund Arthur assisted by reading the manuscript from a non-forester's viewpoint. I thank the editorial staff at FAO – Giulia Muir, Alastair Sarre and Patricia Tendi – and designer Roberto Cenciarelli for their excellent work.

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Dedication

This book is dedicated to Dr Gonzalo Paredes Veloso, who died at Valdivia, Chile, in October 2012. Gonzalo was a forest engineer who did his PhD in forest economics at Corvallis, Oregon, United States of America, from 1984 to 1986. He was Dean of the Faculty of Forestry and Natural Resources, Universidad Austral de Chile in Valdivia, for two periods of his career, and for a time he was the Vice Chancellor of Finance and Administrative Support. He was a major leader in the development of the Chilean radiata pine simulator and actively supported forestry research in Chile. Between 1997 and 2000 he was director of Instituto Forestal, the Chilean government forest research organization.

Gonzalo, an academic leader and a critical thinker, was a strong supporter of this book project. He was a dedicated family man and a good friend to many, including the author.

Acronyms and abbreviations

B	boron
BA	basal area
C	carbon
Ca	calcium
CAI	current annual increment
CO^2	carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
Cu	copper
D	diameter
dbh	diameter at breast height
DCF	discounted cash flow
DDC	diameter of the defect core in the centre of a pruned log
DOO	diameter over occlusion
DOS	maximum stem diameter over branch stubs after pruning
DRIS	Diagnosis and Recommendation Integrated System
FAO	Food and Agriculture Organization of the United Nations
Fe	iron
FRI	Forest Research Institute (New Zealand), now Scion
FSC	Forest Stewardship Council
G	genetic gain
H	tree height
H^2	broad-sense heritability
INFOR	Instituto Forestal (Chile)
IRR	internal rate of return
LAI	leaf area index
LEV	land expectation value
LiDAR	light detection and ranging
LSW	log sweep
MAI	mean annual increment since establishment
Mg	magnesium
Mn	manganese
MoE	modulus of elasticity
N	nitrogen
n	stocking
NPW	net present worth
P	phosphorus
PEFC	Programme for the Endorsement of Forest Certification
PMAI	periodic mean annual increment
RD	relative density
REDD+	reducing emissions from deforestation and forest degradation
S	sulphur
SI	site index
V	variance
Zn	zinc

1 Overview

This book is about how to grow *Pinus radiata* (radiata pine) forest plantations. Radiata pine is a versatile, fast-growing, medium-density softwood, very suitable for a wide range of end-uses. Its silviculture is highly developed, being built on a firm foundation of over a century of research, observation and practice. It is often considered a model for growers of other plantation species. This book explores current knowledge and experience with radiata pine forest plantation management and examines its long-term sustainability.

Forest plantations are stands of trees established by planting or artificial seeding. Silviculture is the art and science of controlling the establishment, growth, health and quality of forest stands to sustainably meet the needs of owners and society. For radiata pine forest plantations, commercial objectives for the production of wood, fibre and fuel generally dominate, but the forester should always take into account wider societal values. Forest plantations can enhance landscapes, reduce erosion, improve water quality, sequester and store carbon, harbour biodiversity and produce a range of ecosystem services that provide other direct and indirect benefits. Plantations can also have adverse impacts, and have sometimes gained a negative image when these have been ignored. The forest manager needs to adapt forest plantation management to ensure that the wider benefits of plantations are maintained and that negative features are minimized. Society today expects foresters to manage plantations to balance social, cultural, environmental and economic values.

Silviculture is an applied science, built on basic science and ecology, and it is also an art. Shepherd (1986) interpreted the art of silviculture as the imaginative skill of the practitioner in interpreting scientific knowledge for a particular situation. However, art is also the conscious use of skill, taste and creative imagination in the practical production of beauty. Thus, silviculturalists should aim to create beauty in the landscape or an individual stand while ensuring that the plantation achieves its other objectives. The silviculture of radiata pine is not static. Biotechnology, ecophysiology and computer applications are helping to refine management practices, and managers must also respond to emerging challenges such as climate change and changing perceptions of sustainability.

GENERAL APPROACH

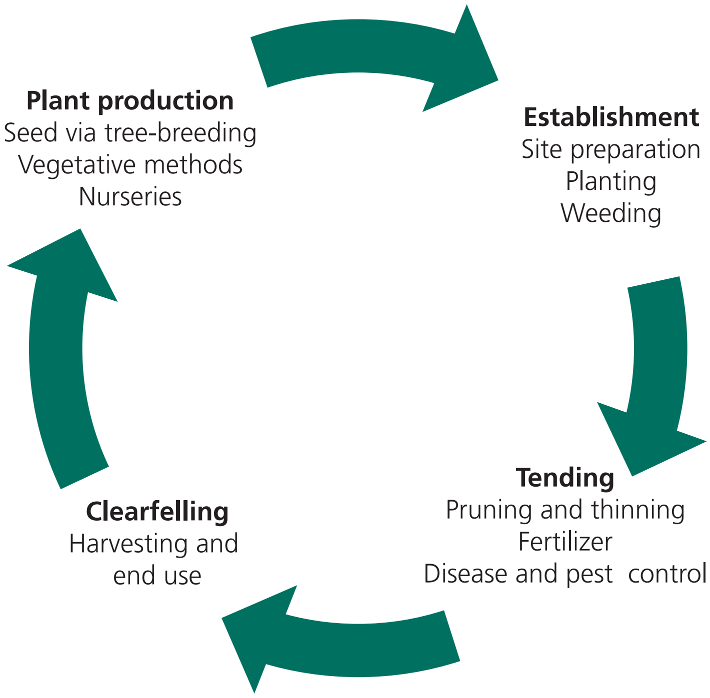
Radiata pine management must integrate the biological aspects of growing trees with socio-economics, management objectives, practical considerations and other constraints and opportunities. Although stands of radiata pine may appear simple, they are quite complex ecosystems – they contain large, long-lived trees that change considerably over time and interact in changing ways with the environment and other organisms. A plantation forest is even more complex, being made up of stands of differing sizes and ages, sometimes adjoining one another and often on differing sites. For a plantation to be sustainable, its biological requirements are paramount, because the trees must survive and the ecosystem must be stable. However, silvicultural decisions are easier and clearer when they are related to management objectives. Economic, environmental, cultural and social factors are also important when setting the principal plantation management objectives. Powerful tools, including economic analysis, are available to assist decision-making (see Chapter 3).

While different chapters of this book deal with different aspects of silviculture, for example establishment and thinning, we are actually dealing with a continuum in the life of a stand (Figure 1.1). After a stand is harvested, the cycle begins anew, but the removal of mature trees causes dramatic changes to the microclimate. The new planting site may differ from the previous rotation because of harvesting impacts and changing weed and pest spectra. Such changes will influence silvicultural practices. The cyclic continuum shown in Figure 1.1 is an example of a systems approach; the individual operations should be viewed as part of an integrated system rather than as subjects in their own right. One way of ensuring this integration is to define the desired state that will achieve the management objectives. It is also important to use an adaptive management approach in which the plantations are monitored and management is altered as needed.

This book describes the underlying biological mechanisms or processes that occur in trees and stands, thus enabling the plantation manager to determine appropriate management responses in differing situations. However, as this is not a physiological text, that aspect is covered only lightly.

The book places considerable emphasis on principles, as this enables knowledge to be applied to different situations. Technology is constantly changing: the weed-control techniques used today are quite different from those of only 30 years ago and no doubt will continue to change, but the principles behind weed control are likely to endure. The book illustrates these principles through examples that show how various forest managers have approached their specific situations and requirements.

FIGURE 1.1
The plantation cycle, with major operations related to the planting stock production, establishment, stand tending and clearfelling of the crop



HISTORICAL PERSPECTIVE

Pinus radiata D. Don, without doubt the best-known expatriate of the North American conifers, is the world's most extensively planted exotic softwood. The specific name, radiata, comes from its radiating cone scales. In early literature the species was often called *P. insignis* Doug., as it was separately described a little later by Douglas (Bannister, 1954; Lavery and Mead, 1998). The almost universal common name for the species and the timber is radiata pine (or pino radiata in Spanish), but it is still referred to as Monterey pine in the United States of America and some other English-speaking countries, or as *pino insigne* or *pino de Monterrey* in some Spanish-speaking areas. Insignis (or *insigne* in Spanish) can be translated as "remarkable", a term that the species lives up to.

Radiata pine was first formally described by David Don, Professor of Botany at Kings College, London, to the Linnean Society on 2 June 1835, from specimens collected in 1829 or 1830 by Dr Coulter (Don, 1836; Bannister, 1954). However, the species was apparently first collected and taken to Europe in 1787 by the La Pérouse expedition, and there are much earlier reports of the species in its native habitat and its use as timber (Bannister, 1954; Contesse, 1987; Libby, 1997). Radiata pine at Monterey was noted in Spanish records, perhaps as early as 1542, and was used in the Carmel Mission in 1769 (Contesse, 1987). In 1833, the Scot, David Douglas (of Douglas fir fame), apparently was responsible for the earliest successful introduction of the species to England, from seed collected in 1830. This appears to have been the first planting of radiata pine outside its native habitat.

The introduction of radiata pine to Australia may have been as early as the 1840s, although the first record of seed was in 1857 for the Melbourne and Sydney botanic gardens.[1] It is also recorded as being in cultivation in Hobart in the same year. From 1859, seedlings from this collection were distributed widely in Victoria and later in other states. Two 3-year-old plants from Sydney were planted in 1859 by J.B.A. Acland at Mt. Peel in South Canterbury, New Zealand; this is the first recorded planting of radiata pine in that country (Figure 1.2), although there are unconfirmed suggestions of earlier plantings in Canterbury and Auckland. The earliest confirmed milling of radiata pine was by Duncan Rutherford at Culverdon, Canterbury, in 1893, the timber being used for farm buildings. During the 1860s there were further introductions to both Australia and New Zealand, including a few larger importations of seed direct from California to New Zealand between

FIGURE 1.2
The Mt Peel radiata pine in Canterbury, New Zealand, planted in 1859 as a three-year-old seedling

Note: The tree is 3.1 m in diameter and almost 50 m tall; photograph taken in 2010.

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[1] This discussion on the introduction of radiata pine to countries is based on Contesse, 1987; Libby, 1997; Lavery and Mead, 1998; Burdon and Miller, 1992; Shepherd, 1990; Wu *et al.*, 2007; Johnson *et al.*, 2008.

the late 1860s and the early 1880s. It appears that most of the latter importations came from the Año Nuevo area near San Fransisco (Burdon, 2001).

The first commercial plantation of radiata pine in Australia was in 1876 at Bundaleer in South Australia. In the same year the species was also planted on coastal sand-dunes near Bunbury in Western Australia, but that planting was a failure. The first plantations in New South Wales and Victoria were established in 1878 and 1880, respectively. Even though the New South Wales stands were milled in 1908, the first commercial radiata pine plantation in New South Wales was planted in 1912. The first recorded use of radiata pine wood in Australia – for apple crates – was in 1902 at Wirrabara in South Australia. The following year the South Australian Woods and Forests Department established its own sawmill.

In New Zealand the potential of radiata pine was also quickly recognized, and by the mid 1870s it was being planted extensively for shelterbelts and woodlots, particularly in Canterbury. In 1881 there were reported to be 3 284 hectares (ha) of radiata pine plantations in Canterbury. The plantings made up to the 1880s were presumably the seed source for the major plantings that took place in New Zealand in the 1920s and early 1930s.

A few specimens of radiata pine were introduced unintentionally to Chile in 1886 or perhaps a few years earlier, but the first plantation of 10 ha was planted near Concepción in 1893 (Contesse, 1987). In the early 1900s the Government of Chile hired a German forester, Federico Albert, who recommended planting radiata pine and eucalypts to control severe soil erosion; this led to the beginnings of a plantation programme in 1910, although major plantings of radiata pine did not begin until about 1935. Following the implementation of government subsidies to private growers in 1974, there was a large increase in new radiata pine plantations.

In Uruguay, radiata pine was introduced in 1871 and was planted in the 1940s and 1950s, but most of those plantations were abandoned as the species proved unsuitable. In Ecuador, radiata pine was introduced in 1905, with the first recorded plot planted in 1925 at an altitude of 3 350 m (Miller, 1974; Garrison and Pita, 1992). Radiata pine was planted between 3 000 m and 3 800 m from the 1960s, with a total of 20 000 ha established by 1990.

Radiata pine was perhaps introduced to South Africa in about 1850, although the records are poor. The first plantation near Cape Town dates from 1885 (Donald, 1993). Interestingly, the first recorded diseases of radiata pine were recorded there in 1893 (Lundquist, 1987).

In Spain, the first recorded planting of radiata pine was in 1840 in a botanical garden near Lekeitio (Goldazarena, Romón and López, 2012). The species was not planted widely until the 1950s.

Finally, as recently as 1990, radiata pine was introduced to Sichuan Province, China, as a reforestation species (Hui-quan *et al.*, 2003).

The planting of radiata pine as an exotic gave the species a new lease of life. Before that, it was a relict species in its natural habitat, covering about 10 000 ha within 5 km of the coast; it was able to survive against more long-lived species such as Douglas fir because of its resilience to fire and the climatic niche. Today, the area of radiata pine with a natural understorey (Figure 1.3) in California is about 5 300 ha, and there are another 4 500 ha in developed areas with varying canopy cover (Zander Associates, 2002). However, estimates of the current area of radiata pine vary widely, partly because of this urbanization. For example, Rogers (2004) estimated the current area of natural forest to be between 4 300 and 7 700 ha, of which only 1 353 ha were fully protected, while Burdon (2001) suggested an intermediate figure. There are 130 ha of radiata pine remaining on Cedros Island and only 220 trees on Gaudalupe Island (Rogers, 2004). In California, the species is considered an amenity tree rather than a timber species (McDonald and Laacke, 1990).

Radiata pine belongs to the closed-cone pine group (subsection Attenuatae) that also includes *P. muricata* and *P. attenuata*. Five provenances are recognized, with three taxonomic varieties. The three mainland provenances (Año Nuevo, Monterey and Cambria, which are between latitudes 35.5°N and 37°N) belong to var. radiata. Most plantations are derived from the Año Nuevo and Monterey seed sources. The var. binata comes from Guadalupe Island (latitude 29°N) and var. cedrosensis from Cedros Island (latitude 28°N). Both these varieties have paired needles and tend to have

FIGURE 1.3

Natural radiata pine stand at Monterey, California

persistent thin, smooth bark. More information on the natural stands and their ecology can be found in McDonald and Laacke (1990).

THE FOUR PHASES OF RADIATA PINE PLANTATION DEVELOPMENT

The history of radiata pine – its discovery, introduction, domestication and development – is a fascinating story. It has been suggested that the development of radiata pine into the pre-eminent exotic plantation conifer is the forestry equivalent of the development of rice, wheat and maize during the Green Revolution (Bentley, 1997). Table 1.1 shows a timeline for key silvicultural and other technical developments. We can also divide this timeline into phases (Figure 1.4).

The "discovery" phase lasted from the eighteenth century through to the mid 1870s in New Zealand and Australia and even longer in other countries. In this phase, people started to become aware of the potential and limitations of radiata pine. There were early prophets, such as Baron Von Mueller in Australia but, at first, most people thought the species a curiosity (Box 1.1). By the end of this phase, however, its virtue of rapid growth, coupled with reasonably wide site tolerance, was starting to be recognized.

In the second, "acceptance", phase, perceptions evolved to the point where radiata pine was accepted as a prime candidate as a plantation species. While this could be seen as a natural progression, given its performance, for many people it required a major shift in thinking. The people promoting radiata pine had come from Europe, where they were accustomed to hardwoods like oaks and European beech and slower-growing conifers such as Baltic pine. Many such people grew up equating slow growth with high wood quality. It was therefore a considerable leap of faith to accept fast-growing radiata pine, a species unknown and unproven in its native country, as a prime candidate for timber supply. Europe is only now beginning to accept radiata pine timber for other than low-value uses.

Several conditions made the acceptance of radiata pine easier in the Southern Hemisphere. In parts of recently colonized countries, settlers needed to plant trees for

FIGURE 1.4

Phases in the development of radiata pine plantation forestry

TABLE 1.1

Timeline for the domestication of radiata pine and the development of silviculture

Year	Event	Country*	People or group*
1786–87	First seed collected	France	La Pérouse expedition
1833	First nursery plants	UK	D. Douglas (collected 1830)
1839	First rooted cuttings	Europe	Nurserymen
1840	Introduced to Spain	Spain	Carlos Adán de Yarza
<1850	First seed imported to Southern Hemisphere	SA	
1857	First confirmed seed import	Aus.	Botanical Gardens
1859	First confirmed planting in NZ	NZ	J.B.A. Acland, Mt Peel
1866	First commercial recommendation	Aus.	F. von Mueller
1870-80s	Shelter and first plantations	NZ/Aus.	
1880s	Introduced Chile	Chile	A. Junge
1913	Large-scale use recommended	NZ	Royal Commission
1920-30	High pruning used	SA[a]	
1925-35	First planting boom	NZ	State and private
1926	Wood properties	NZ	A.R. Entrican
1929	First newsprint used	NZ[b]	
1928-30	Biological control of Sirex	NZ[c]	Cawthron Institute/FRI
1939	First fertilizer trial results	Aus.	W.V. Ludbrook
1950s	Serious breeding begins	NZ/Aus./SA	Research institutes
1955	First aerial application of phosphate	NZ[d]	M.J. Conway
1957	First seed orchards	Aus./NZ	
1960s	Mill studies	NZ/SA	G.S. Brown and others
1965	First computer growth model	NZ/Aus.	J.W. Shirley
1968	Economic evaluation	NZ	R. Fenton & W.R.J. Sutton
1968	Nutrient cycling	NZ[e]	G.M. Will
1970s	Weedicides	NZ/Aus.	FRI, Aus. states
1970s	Intensive site preparation	NZ/Aus.	FRI, Aus. states
1970s	Intensive fertilizer research	NZ/Aus.	FRI, Aus. states, CSIRO
1970s	Improved nursery techniques	NZ/Aus.	FRI, Aus. states
1970s	Index selection in breeding	NZ	FRI, M. Wilcox
1975	First tissue culture plantlets	NZ	FRI, K.J. Horgan
1977	3/2 power law evaluated	NZ dataf	
1979-82	Radiata Pine Task-force	NZ	FRI; led by W.R.J. Sutton
1980	Grade index – pruned logs	NZ	J.C. Park
1980-2005	Silvopastoral studies	NZ/Aus./ Chile/Spain	FRI, Aus. states, Lincoln University, INFOR Chile
1985	Somatic embryos	NZ[g]	FRI
1997	Test-tube grown wood fibres	NZ[h]	FRI, D. Smith.
1998	Transgenic plants	NZ[i]	FRI
2002	Agrobacteria – mediated gene transfer	NZ/Chile	
2004	Marker-aided selection explored	Aus./NZj	CSRIO
2005	Transgenic insect resistance	NZ[k]	FRI
2005	300 index of growth	NZ[l]	FRI

Note: Aus. = Australia; CSIRO = Commonwealth Scientific and Industrial Research Organisation (Australia); FRI = NZ Forest Research Institute; NZ = New Zealand; SA = South Africa; UK = United Kingdom of Great Britain and Northern Ireland.

Sources: a = Hinze and van Larr (1986); b = Kininmonth (1997); c = Miller and Clark (1935); d = Conway (1962); e = Will (1968); f = Drew and Flewelling (1977); g = Smith, Sing and Wilton (1985); h = Anon. (1997); i = Walter *et al.* (1998); j = Devey *et al.* (2004) for older trees; k = Grace *et al.* (2005);l = Kimberley *et al.*(2005)

BOX 1.1

Early recognition of radiata pine's commercial potential

As early as 1866, Baron Ferdinand Von Mueller (Director of the Melbourne Botanic Gardens) suggested that *Pinus radiata* be used as a commercial plantation species. However, it was not until 1876 that the species was first planted in South Australia for this purpose.

In New Zealand, the wide-scale planting of radiata pine began in the 1870s, especially in the Canterbury region. In an invited paper to the Agricultural Conference in 1898, Sir John Hall (who later served as a prime minister of New Zealand), after describing the failures and advantages of many tree species with which he had experimented, stated:

> "... the one tree which is conspicuous for rapidity of growth and abundance of foliage, and which by its strength and constitution is enabling it to resist frost and drought and to thrive in the poorest soil, is the *Pinus insignis** ... it is an abundant seeder, and is easily grown from seed ... it is difficult to believe that for such timber, many useful purposes will not be found".

* An early name for *Pinus radiata* – see main text.

timber or shelter. This was particularly true in Canterbury, New Zealand, where the first large-scale plantings appeared. Many native species in those recently colonized countries were thought unsuitable for plantations because of their slow growth or difficulties in their use as timber, and temperate Australia lacked fast-growing native softwoods. In New Zealand, a 1913 Royal Commission found that if fast-growing plantations were not established, there could be a wood shortage by the 1960s because of extensive clearing for agriculture and the slow growth of the native conifers. In Chile, radiata pine was used extensively to afforest degraded agricultural land and to replace wood coming from native forests (Contesse, 1987).

Perhaps another reason for the eventual acceptance of radiata pine was that leaders promoting it were not always trained forestry people; quite often they were farmers and enthusiasts (Box 1.1), people who were willing to experiment and to believe their eyes, not what they had been taught. For instance, T.W. Adams planted 240 species on his farm in mid Canterbury, but in the 1913 Royal Commission on forestry he backed radiata pine. Before that Royal Commission, the New Zealand government was mostly still planting traditional European trees, even though other growers had already shifted to radiata pine. Important research into wood properties and experience in end-use during the acceptance phase was also integral to the species' ultimate acceptance in the market place.

During the acceptance phase there were a number of early silvicultural studies (Table 1.1). In Australasia, studies were conducted on radiata pine in its natural habitat[2]; growth, and factors affecting growth[3]; establishment[4]; spacing, thinning and pruning[5]; and nutrition.[6] The South Australians led the way in general forest management in

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[2] Habitat studies of Lindsay (1932) and Fielding (1953).

[3] Growth aspects (Gray, 1931, 1943, 1944; Poole, 1933; Syme, 1933; Moorhouse, 1935; Jacobs, 1937; MacDougal, 1938; Adams, 1940; Fielding, 1940; Fielding and Millett, 1941; Millett, 1944a,b; Stoate, 1945).

[4] Establishment studies of Carter (1933), Field (1934) and Jacobs (1939) – the latter two on cuttings.

[5] Thinning and spacing (O'Conner, 1935; Craib, 1939, 1947; Lane Poole, 1943; 1944; Jolly, 1950); pruning (Hall, 1937; Roche and Hocking, 1937; Jacobs, 1938).

[6] Tree nutrition (Cockayne, 1914; Kessell, 1927; Walker, 1931; Stephens, 1933; Kessell and Staote, 1936; 1938; Askew, 1937; Ludbrook, 1937; 1942a,b; Smith and Bayliss, 1942; Smith, 1943; Adams, 1946; Stoate, 1950).

this period, but some important ideas were also developed in South Africa. O'Connor (1935) introduced the idea of free-growing and suppression zones and then, shortly afterwards, I.J. Craib suggested some (what were then) very radical ideas on thinning (Craib, 1939, 1947). After the Second World War, John Ure in New Zealand proposed a schedule for naturally regenerated stands that included the idea of thinning to waste, as well as two pruning lifts to 6.1 m (Ure, 1949). During this period there were also early genetic (Sherry, 1947) and nutritional (Laughton, 1937) studies in South Africa. The biological control of the sirex wood wasp was tried in New Zealand in the 1930s (Miller and Clark, 1935).

From the early 1950s, the acceptance phase was followed by a "development" phase – a period of intense activity that came with the realization that radiata pine was a "winner" (Figure 1.4). A concerted effort was made to develop all aspects of silviculture, use and marketing (Table 1.1), and there was a second wave of planting around the world.

New Zealand and Australia led this development phase. A smaller research programme was undertaken in South Africa, and from the 1980s research expanded rapidly in Chile, although some studies were also undertaken there from the 1960s (J.A. Prado, personal communication, 2012). In Spain, most research on radiata pine has been recent. In New Zealand the effort was concentrated largely in the Forest Research Institute at Rotorua. In Australia it was spread between CSIRO and state government research groups, with cooperation facilitated by the Australian Forestry Council and its associated research working groups. In all countries, however, some individual field foresters and academics made important contributions.

The New Zealand experience is particularly instructive. After the Second World War a deliberate effort was made to expand forestry research, and new scientists were recruited. The focus was largely on radiata pine and the efforts were led by visionaries (Sutton, 1984; Kininmonth, 1997). Most aspects of silviculture and wood science came under scrutiny. By the 1960s there were teams of researchers in tree breeding, nurseries, establishment, the economics of silviculture, mensuration, soils and tree nutrition, pathology and entomology, and tree physiology. The researchers came from diverse backgrounds but significantly included a number who had their initial training and experience as foresters. Major advances were made in most fields, some of which were complemented by research going on elsewhere. The vision at this time was to develop a new silviculture that would lead to greater productivity and profitability. All the signals were that this was important to the industry, the government and society.

In essence what happened during the development phase, especially in New Zealand and Australia, was that radiata pine began to become domesticated. Before this, silviculture was based around seed from wild sources (i.e. unimproved) and the degree of management was largely limited to getting the trees to grow. Often, management objectives were poorly defined. But the development phase saw:

- intensive breeding programmes commenced;
- nursery techniques substantially improved;
- intensive field establishment methods developed and accepted;
- fertilizers introduced to correct serious deficiencies and also to improve growth in apparently healthy stands;
- disease control systems introduced;
- thinning and pruning schedules physically and economically evaluated and developed.

Other activities that affect silviculture were also undergoing improvement. These included mensuration and management models, hydrological aspects, harvesting systems and improvements in wood technology.

In the last decade we have passed beyond this development phase. There is now a major focus on ensuring the sustainability of pine radiata plantations – biologically, economically and socially. Research is ongoing into radiata pine silviculture, management and harvesting and end-uses, sometimes based on new technologies, in an effort to increase productivity and competitiveness (Table 1.1). At the same time, the planting surge that occurred in the latter part of the twentieth century has abated and it is unclear if there will be any further significant expansion of the radiata pine estate. The current period could be described as a “consolidation” phase.

If the new areas of research lead to a major change in the quality and growth rate of radiata pine, coupled with refined management and perhaps increased planting, radiata pine could be described as having a fully domesticated status. This has occurred with many food crops but has yet to be seen in forestry.

This book is largely based around these great leaps – the discovery, acceptance, development and consolidation phases – that have helped to revolutionize plantation forestry throughout the world.

DISTRIBUTION OF RADIATA PINE PLANTATIONS

Today there are over four million ha of planted pine radiata worldwide (Table 1.2, which also shows the main uses, by country), with the largest plantations in Chile and New Zealand (about 1.5 million ha each) and Australia (0.77 million ha). Between them, these three Southern Hemisphere countries account for over 90 percent of the world’s radiata pine plantations. The species is also planted on a moderate scale in Spain (0.29 million ha) and South Africa (57 000 ha), and at a small scale in several other countries. The expansion of radiata pine forests has been rapid in the last half-century, there being only about 650 000 ha worldwide in the mid 1950s (based on Scott, 1960). In recent years, the area of radiata pine worldwide has remained static (Table 1.2), driven largely by poor returns (Manley and Maclaren, 2009).

New Zealand

Over 90 percent of plantations in New Zealand are privately owned, although growers generally do not own the land. The majority of radiata pine plantations are in the Central North Island wood-supply region, which accounts for 31 percent of total

TABLE 1.2

Estimated radiata pine plantation areas and the average annual change in area over the last five years, together with major uses by country

Country	Estimated area ('000 ha)	New area or loss ('000 ha/yr)	Main uses
Australia	773* (2010)	1.5*	Sawlogs, pulplogs, reconstituted, posts and poles, energy, shelter
Chile	1 478* (2009)	11.5*	Pulplogs, sawlogs, veneer, energy, erosion control
Ecuador	20* (1990)	ND	Erosion control, sawlogs, fungi; agroforestry
New Zealand	1 545* (2011)	-11*	log export, sawlogs, pulplogs, reconstituted, posts and poles, energy, shelter, erosion control
Italy	6** (2005)	0*	
Spain	287*** (2006)	ND	Sawlogs, mixed plantations, agroforestry
South Africa	57* (2008)	-2*	Sawlogs, veneer logs, posts and poles
Argentina	5.5* (2011)	0	
Other	35		
Total	4207	-1	

* Uses in-country data up to 2011; ** FAO (2006); *** MMAMRM (2006); estimate includes 61 000 ha of mixed species.

Note: The year of estimate is given in brackets. ND = no data

TABLE 1.3
Percentage of stands for radiata pine by tending schedules and age class for the whole of New Zealand and for the Central North Island Region (CNI) in 2011

Tending schedule	1–5 yrs	11–15 yrs	21–25 yrs	Central North Island Region, 1–5 yrs
Minimum*, no production thinning	61	38	27	51
Intensive**, no production thinning	31	47	54	29
Minimum* + production thinning	3	3	2	7
Intensive** + production thinning	5	12	17	12
% production thinned	8	15	19	19
% intensively tended**	36	59	71	41

* Minimum tending schedules will not be high pruned but may be thinned.

** Intensive tending schedules will be pruned to ≥4m and thinned.

Note: Percentages may not add up to 100 due to rounding.

Source: MAF, 2011

plantings, compared with 25 percent in the entire South Island (MAF, 2011). Most of this Central North Island resource is in the hands of ten large growers, who manage 80 percent of the plantation area. The total volume of radiata pine harvested in New Zealand doubled in the last 20 years, to 25 million m^3 in 2011. A large proportion (approximately 48 percent) of this harvest is exported in log or chip form or as processed products, primarily to Asia. About 45 percent of radiata pine products are used within New Zealand. In 2010, the forest industry produced 3.6 million m^3 of sawn timber, 1.5 million m^3 of panel products (43 percent as fibreboard) and 1.5 million tonnes of dry pulp. In recent years, older sawmills have struggled to remain profitable, and there has been a downturn in the pulp and paper industry. The Central North Island region processes about half of all logs in the country. Radiata pine is also used for posts and poles, energy, shelter and erosion control. Most of the industries are not fully vertically integrated – that is, they do not own the land and the forests that supply their industrial plants.

Four generalized radiata pine management practices are applied in New Zealand (Table 1.3). Minimum tending schedules, without high pruning, are often used on steeper country or low-quality sites, while intensive schedules are employed on easier and more fertile sites. Both the minimum and intensive tending schedules include thinning, but production thinning is relatively unusual. Table 1.3 provides data by selected age classes based on what has occurred or is planned in the case of stands in the 1–5 year age class. It is apparent that managers are moving away from intensive high pruning schedules and overall there will be less production thinning. In the Central North Island region, the area of plantation subject to production thinning has halved in the last 15 years (MAF, 2011).

Chile

In Chile, radiata pine forests are located largely between Valparaíso (Region V) and Puerto Montt (Region X), with the greatest concentrations in regions VII, VIII, IX and XIV. Region VIII (Bíobío) has 44 percent of the total radiata pine plantation estate and is the centre of the main pulp and paper industries. High rates of radiata pine planting in Chile began in the mid 1970s, but in recent years Region XIV (Los Rios) near Valdivia has been the focus of new planting and now contains about 10 percent of the resource. Most is owned by large, vertically integrated companies. In 2009, the total harvested volume was 35 million m^3, of which 56 percent was used as sawlogs, 35 percent was used for pulp and 8 percent was used for panel products (INFOR, 2010).

Unlike in New Zealand, less than 2 percent of the harvest, by volume, was exported unprocessed as logs or chips. A large part of Chilean manufactured production, however, is exported.

Most of the resource is managed for maximum volume production and includes production thinnings (Mead, 2010a). High pruning is often used to obtain clear veneer logs. Some stands are grown with less intensive management for pulp logs.

Australia

Radiata pine plantations in the states of New South Wales, Victoria, South Australia, Tasmania and Western Australia are concentrated around a number of wood-supply regions (Gavran and Parsons, 2011). The area of new plantings expanded rapidly between the 1960s and the 1990s, often led by state governments, after which the rate of expansion slowed (Table 1.2). Almost half the total area of radiata pine plantations is in the Murray Basin and Green Triangle wood-supply regions of Victoria and South Australia. The wood-supply regions of the Central Tablelands of New South Wales, Central Gippsland of Victoria, Western Australia and Tasmania each has between 7 and 11 percent of the resource area, for a total of 36 percent of the Australian resource. In recent years, the state governments of Victoria and Tasmania have sold their plantations and large parts of their estates are now owned or managed by companies.

Australia's total annual softwood log supply is 10.3 million m^3, most of which is radiata pine. The cut is expected to remain fairly stable in the medium term. The Green Triangle region (mainly in eastern South Australia) and the Murray Basin area each supply about 20 percent of these logs, while Western Australia, the Central Tablelands of New South Wales and Tasmania supply 7 percent each. The logs are used primarily to make structural lumber and pulp, with lesser quantities going to panel and treated roundwood. The industry is generally not vertically integrated, although there are exceptions.

Radiata pine stands are commonly grown with multiple production thinnings but are seldom pruned (see Chapter 9).

Spain

Of Spain's 287 000 ha of radiata pine, most is in the Basque region. Of this, 226 000 ha are in pure stands (MMAMRM, 2006). The annual production deriving from these trees is 1.5 million m^3 of sawlogs, amounting to 20 percent of the Spanish conifer cut.

RADIATA PINE IN THE GLOBAL CONTEXT

According to Evans (2009a), there are 271 million ha of planted forests worldwide, of which 141 million ha can be described as plantations. Almost 80 percent of plantations are grown primarily for wood production. One-quarter of planted forests employ introduced species, although in South America and Oceania the percentage is much higher (97 and 77 percent, respectively) (FAO, 2006).

While the 4.2 million ha of radiata pine plantations worldwide is a relatively small part of the total planted forest estate, radiata pine is the most productive and widely planted introduced conifer (Table 1.4; note, however, that some countries have considerably larger areas of native conifer plantations). Not shown in Table 1.4 are very large areas of various introduced broadleaf and palm species, such as a range of eucalypt species in South and Southeast Asia (4.0 million ha) and Brazil and Chile (3.7 million ha), rubber (10 million ha), coconut (11 million ha) and oil palm (6 million ha). In Brazil, hybrid eucalypts can have extremely fast growth rates of up to 70 m^3 per ha per year.

Table 1.4 shows that radiata pine mean annual increments (MAIs) range from 12 to 34 m^3 per ha per year for merchantable volume, but these country averages do not indicate upper limits to the growth rates of the species. In the New Zealand permanent sample plot data set, the single greatest MAI for total net volume was 52 m^3 per ha per year at age 24 (Shula, 1989). This was considered similar to the Australian experience. In a mapping study of radiata pine growth rates in New Zealand for trees planted after 1975 using the 300 index (total stem volume MAI for trees pruned to 6 m and having a final crop stocking of 300 stems per ha at age 30), the MAI ranged from 7 to 47 m^3 per ha per year with a mean, weighted by area, of 27 m^3 per ha per year (Palmer *et al.*, 2010). In this same study, site index (height at age 20) ranged from 13.5 m to 46.3 m, with a weighted mean of 30 m. On a fertile farm site in New Zealand, the periodic mean annual increment (PMAI) for radiata pine (between the ages of 11 and 21) was 54 m^3 per ha per year (Maclaren and Knowles, 1999) while Beets *et al.* (2011) reported a maximum PMAI (between the ages of 9 and 13 years) of 73 m^3 per ha per year, although the average was 47 m^3 per ha per year. Thus, the upper limit of MAI for radiata pine is about 50 m^3 per ha per year, although current annual increments and PMAIs can be higher.

Radiata pine also provides a very small proportion of the total industrial wood harvested worldwide. The estimated 60 million m^3 of logs harvested annually is only 3.3

TABLE 1.4

Growth rates, typical rotation lengths and areas of selected species used in large-scale plantations in selected countries

Species	Mean annual increment* (m^3/ha/yr)	Rotation (yrs)	Countries included	Total area (million ha)
*Pinus radiata***	14–34	18–28	Chile	4.2**
	16–21	25–30	Australia	
	17–20	25–32	New Zealand	
	12–16	28–35	South Africa	
	12–16	20–40	Italy	
	14–22	18–35	Spain**	
P. elliottii	12–18	25–35	Argentina/South Africa	3.1
	7–8	20–30	USA	
P. patula	12–18	35–35	South Africa	0.4
P. pinaster	5–14	40–70	France/Australia	1.0
P. sylvestris	2–5	63–87	Europe	9.0
P. taeda	14–17	21–29	Argentina/South Africa	11.3
	9–10	20–30	USA	
Acacia mangium	20–32	6–12	Southeast Asia	2.1
Cryptomeria japonica	8	40	Japan	5.0
Cunninghamia lanceolata	3–14	15–30	China	15.4
Eucalyptus globulus	16–25	10–27	Australia	0.4
E. grandis	21–27	21–22	Argentina/Australia/ South Africa	0.5
E. nitens	15–24	12–40	Australia	0.3
	22–28	7–9	South Africa	
Larix decidua	4–13	90–129	Europe	2.0
Picea abies	3–8	66–86	Europe	5.5
Picea sitchensis	2–8	43–67	Europe	0.8
Pseudotsuga menzesii	9–13	49–81	Europe/New Zealand/Chile	0.6
Tectona grandis	5–11	34–58	South and Southeast Asia/Sudan/Brazil	5.9

* Typical minimum and maximum values – extremes outside these ranges do occur.

** Area based on Table 1.2. Radiata pine growth rates taken from FAO, 2006, and for Spain from Fernández and Sarmiento, 2004, and Rodríguez *et al.*, 2002a. The upper growth rate for New Zealand is conservative (see text).

Source: adapted from FAO, 2006, although note that not all countries are in that report percent of the total world production from natural and plantation forests. However, for the countries that have large areas of radiata pine, it is a very important wood resource and the basis of significant industries.

As a plantation species, radiata pine has numerous economic and social benefits, although it is restricted to a definite ecological niche and has end-use limitations. As the following chapters will show, it is a valuable and versatile timber species, which is managed with a high degree of sophistication.

2 Site requirements

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

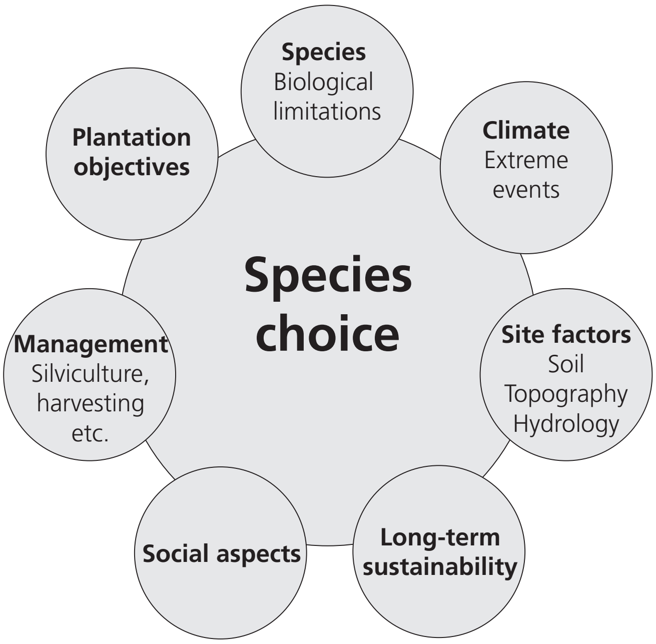
Radiata pine has proved to be a very adaptable species in its main adopted countries. It is often planted on a wide range of sites with seemingly little regard to its ecological niche. However, its history of successes and failures shows that there are places where it should not be planted and other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

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

MATCHING SPECIES TO SITE

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

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



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

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

CLIMATIC LIMITATIONS

Natural habitat

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

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

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

Exotic plantation experience

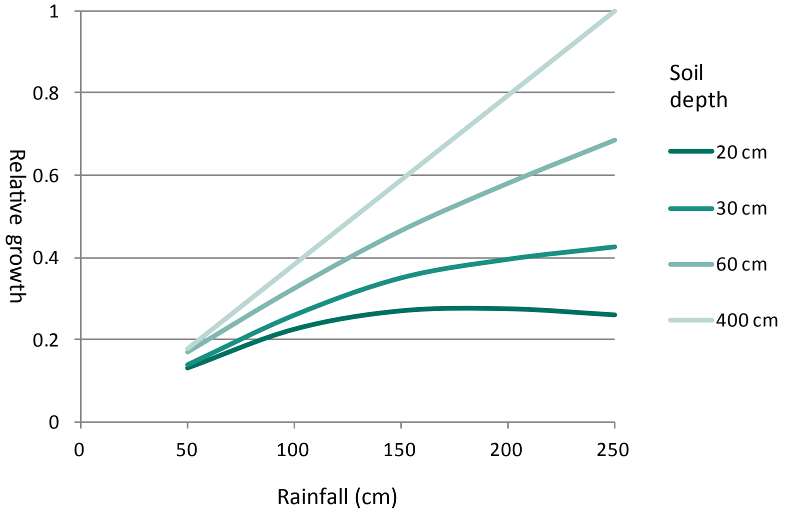
Radiata pine plantations have been established in a wide variety of climatic types but have only been successful in temperate areas where the summers are relatively dry. Most Australian, Chilean and some Spanish plantations occur in a Mediterranean climate. The northern New South Wales plantations tend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

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

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

FIGURE 2.2

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



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

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

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

FIGURE 2.3

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

FIGURE 2.4

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

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

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

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

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

TABLE 2.1

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

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

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

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

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

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

Other abiotic factors

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

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

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

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

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

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

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

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

FIGURE 2.5

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

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

FIGURE 2.7
Sun-scald on radiata pine, Western Australia

PHOTO: RAY FREMLIN

FIGURE 2.8
Fire damage to young stand of radiata pine

Fire

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

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

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

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

Latitude and altitude

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

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

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

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

Aspect

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

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

Potential impacts of climate change

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

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

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

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

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

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

EDAPHIC LIMITATIONS

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

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

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

Physical properties of soil

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

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

Nutrient stresses

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

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

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

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

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

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

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

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

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

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

FIGURE 2.9
Boron deficiency can cause repeated dieback

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

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

Diagnosing nutrient deficiencies

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

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

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

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

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

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

TABLE 2.2

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

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

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

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

Soil microbiological factors

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

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

OTHER SITE CONSIDERATIONS

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

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

Catchment hydrology

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

BOX 2.1

Radiata pine plantations reduce landslides

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

Source: Marden and Rowan, 1993

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

PHOTO: PETER SCOTT

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

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

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

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

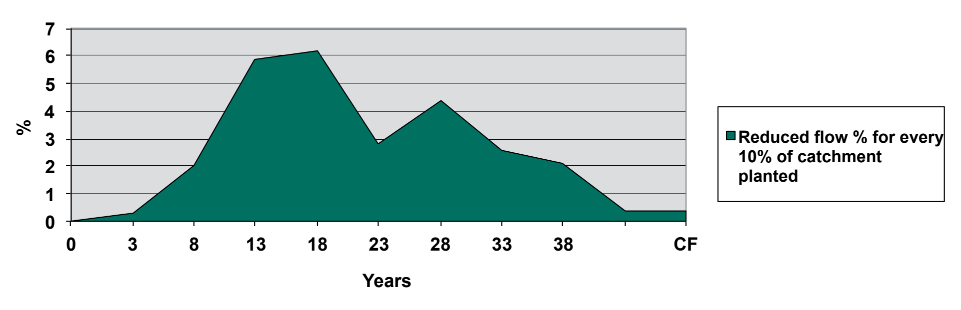
The biggest conflicts about water use associated with plantations have largely been in areas of low rainfall and where there is an existing demand for water by other users (O'Loughlin, 2005; Scott, 2005). O'Loughlin (2005) lists approaches to managing the impacts of plantations on water availability.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

BOX 2.2

Longer-term effects of radiata pine plantations on stream flow

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

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



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

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

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

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

Source: Scott and Prinsloo, 2008

RADIATA PINE’S ECOLOGICAL NICHE

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

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

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

3 Social, economic and environmental considerations

In the last 100 years there have been rapid changes in how society views forests. Perley (1997) suggested that these changes have been driven by evolving human values. Human values and our world view arguably dictate which management regime is "right" at any given time. Initially, radiata pine plantations were seen as a means for meeting wood requirements. Over time, economic return became the priority. Today, a higher value is placed on ecological values, social services and sustainability. The nature of societies is also evolving rapidly. This chapter reflects these changes in human values.

SOCIO-ECONOMIC SETTING

The establishment of radiata pine plantations began in the first half of the twentieth century and expanded rapidly in the second half. Only in the last decade has planting on new land decelerated and in some cases even contracted. This pattern of development has occurred because of changing societal needs and values. Although the contexts and societies are diverse, in all cases the impetus for planting radiata pine plantations derived from the demand for timber, at least in part. The social setting and the drivers for radiata pine plantations is explored below in the contexts of Australia, Chile, New Zealand, South Africa and Spain.

Australia

Australia is a developed industrialized country (Table 3.1) with some 147 million ha of native forest stretching over 19 percent of its total land area (ABARES, 2011b). Almost all the native forests are hardwoods and 78 percent are eucalypt forests. Closed native forests, however, with over 80 percent crown closure, cover only 4.3 million ha. About 26 percent of native forests are privately owned, with another 44 percent leased from government. In 2010, native forests accounted for about 26 percent of total wood production in Australia, but this had decreased by 44 percent in the previous ten years.

In Australia, plantation forests cover 2 million ha, of which half are softwood plantations. Radiata pine plantations cover 773 000 ha; it is the main softwood species, accounting for three-quarters of the softwood plantation estate (Table 1.2).

Radiata pine forestry began in Australia in the late nineteenth century and, by 1956, some 122 000 ha of plantations had been established (Scott, 1960). Until 1960, almost all radiata pine planting was done by state governments as part of the "softwood import replacement policy" (Gerrand, *et al.*, 2003; FAO, 2004). This was followed by a rapid expansion of radiata pine plantations from the 1960s with the implementation

TABLE 3.1
Characteristics of the main countries with radiata pine plantations

Country	Area ('000 km²)	Population (millions of people)	Average income ($US)	Human Development Index (rank)	Main official languages
Australia	7 741	22	34 300	2	English
Chile	775*	17	13 300	44	Spanish
New Zealand	268	4	23 700	5	English; Maori
South Africa	1 220	50	9 500	123	11**
Spain	505	46	26 500	23	Spanish

* Excludes Antarctica.

** Of the 11 official languages, the main ones are English, Afrikaans, IsiXhosa and IsuZulu.

Source: UNDP, 2011

of a softwood self-sufficiency policy. This successful policy was supported by low-interest loans from the federal government to state governments, which have the primary responsibility for forest management on public lands (FAO, 2004). The state governments of New South Wales and Victoria also provided low-interest loans to farmers, and Landcare programmes were implemented throughout Australia, but these had a relatively small impact on radiata pine planting rates. During this period, private industrial-scale planting of radiata pine forests also occurred, largely without subsidies.

From the 1990s, an expansion of short-rotation eucalypt plantations occurred because of private investment, while the expansion of softwoods declined (FAO, 2004; ABARES, 2011b). During this period there were also tax changes and the removal of other impediments to assist forestry. The 1997 strategic policy "Plantations for Australia: The 2020 Vision" aimed to increase forest plantations to 3.3 million ha, although it is doubtful if this target will be achieved (FAO, 2004). Many state-owned plantation forests were transferred to the private sector from the late 1990s through privatization or corporatization (Gerrand *et al.*, 2003; FAO, 2004). Currently, the biggest role of government in plantation forestry is to provide indirect incentives, such as an enabling environment for commercial plantation investments and their associated industries, and support for research and development. Climate change is likely to limit the area in which radiata pine is suitable for planting (see Chapter 2). Moreover, associated greenhouse gas control measures, including carbon price mechanisms, may eventually have an impact on Australian forest plantations.

In summary, the Australian government's policies have consistently supported forest plantation investment for over 100 years. This stability has given investors confidence that the government is unlikely to change the ground rules. This social setting has been critical for radiata pine plantation development in Australia.

Chile

Chile is a rapidly emerging Pacific economy with forestry accounting for 7.4 percent of its gross domestic product (Table 3.1). Native forests cover about 18 percent of the land area (13.5 million ha), of which 6 million ha is classified as production forest (Morales, 2005). Most of the native forests are in the temperate areas south of 38° latitude. However, native forests supply a mere 6 percent of the country's wood production. Plantation forests cover 2.3 million ha, of which 63 percent is radiata pine; most of the remainder is made up of eucalypts.

The realization that the clearance of native forests was a problem for wood supply led to the passing of a law in 1931 to promote plantation forestry by providing tax incentives as well as greater protection for native forests (Morales, 2005; Armesto, *et al.*, 2010). There was also recognition that these forests could be planted on degraded agricultural land. This increased radiata pine annual planting rates, mostly by private owners, which reached a peak of 49 000 ha in 1949, after which rates declined because of concerns over political instability and land reform. By 1956 there were 200 000 ha of radiata pine plantations in Chile (Scott, 1960). Between 1970 and 1985 the state became involved in planting forests, building an estate of 377 000 ha (Morales, 2005). Towards the end of this period, planting also became a measure to provide employment. The recession of 1983–1985 held up privatization, but the state sold off its plantations in the years that followed.

In 1974, a key Chilean law (DL701) was passed that gave certainty of ownership and provided subsidies for planting forests (Morales, 2005). This law declared "preferred forestry aptitude" areas and provided a 75 percent subsidy for establishment, exemption from land taxes, a 50 percent reduction in income tax and other management subsidies. These benefits were conditional on replanting, and the conversion of native forest to forest plantations was not permitted. There was, however, substantial plantation establishment on degraded secondary forest (Armesto *et al.*, 2010). In the late 1990s the DL 701 law was altered to focus on small growers, erosion-prone areas and other aspects. In 1977, another law was passed to promote foreign investment, which brought in companies and further promoted forest plantations (Morales, 2005). A law promoting the management of second-growth native forest was promulgated in 2007.

In summary, the development of forest plantations in Chile was driven by a need to stimulate economic development and the use of degraded agricultural land. The expansion of the estate was underpinned by free enterprise, free trade and large government incentives. This led to three strong vertically integrated industries based on radiata pine plantations, with much of the manufactured produce exported. Log and chip exports of radiata pine remain minimal.

New Zealand

New Zealand is the smallest of the industrialized countries that grow substantial areas of radiata pine (Table 3.1). Native vegetation covers almost 44 percent of the land area. Improved pastures, native forests and exotic plantation forests cover 33, 24 and 7 percent of the land area, respectively. The plantations are largely on lower-quality land (Adams and Turner, 2012) and 90 percent are radiata pine (Table 1.2). Nearly all the native forests are legally protected, while the plantations are in private ownership and grown for commercial purposes.

Before human arrival some 800 years ago, about 85 percent of New Zealand was forested. By the time of European settlement in the mid 1800s this had decreased to 53 percent, and over half of what remained was subsequently removed for agriculture (FAO, 2004). There was already interest in plantation forests in the late nineteenth century, but large-scale planting only began during the Great Depression of the 1930s and was partly assisted by government schemes for the unemployed. This impetus arose from the 1913 Royal Commission of Forestry, the development of government policies to address issues of wood supply, and the formation of the State Forest Service in 1919. By 1936, almost 300 000 ha of plantations (60 percent radiata pine) had been established, of which the private sector planted about half. In this period, the State Forest Service provided direct and indirect incentives, including research into the management and use of introduced forest trees. Some of this planting was on degraded land or land considered unsuitable for agriculture because of nutrient deficiencies.

The first planting boom was followed by a period (1936–1958) in which the New Zealand government promoted and led the development of large-scale harvesting and use of trees planted during the Great Depression (Roche, 1990; FAO, 2004). These were largely indirect incentives, but the industry and interest in further planting were hampered by price controls on wood.

From the 1960s the government initiated a second wave of forest planting aimed at providing wood and fibre for export, so that by the mid 1980s there were over 1 million ha of plantations. This was assisted by direct incentives to the private sector and tax changes. By 1984, incentives had been used to support one-third of private plantation planting (FAO, 2004). Indirect incentives by way of research and education were also instrumental in developing the industry. Some of this afforestation effort was also aimed at erosion control and providing employment.

From 1984 there was large-scale deregulation of New Zealand's economy, which included the privatization of the vast majority of the state's plantation forests (FAO, 2004). The New Zealand Forest Service was dissolved and subsidies, including indirect subsidies for research and education, were largely removed. One of the objectives of privatization was to spur large-scale industry investment, but, since this did not occur, log exports increased markedly as harvesting increased.

A third wave of private-sector planting markedly expanded the plantation forest area in New Zealand from the 1990s, partly propelled by tax changes and small investor interest, but this dwindled in the first decade of the twenty-first century

(FAO, 2004). In recent years the area of radiata pine plantations has actually decreased (Table 1.2). This decrease, which will be discussed later, has been caused by the reduced profitability of plantation forestry compared with other land-uses, particularly dairy farming. Deregulation in New Zealand also led to large changes in agriculture, including its intensification, which led in turn to concerns about environmental impacts and long-term sustainability (PCP, 2004; MacLeod and Moller, 2006). Finally, there is a possibility that a recently introduced greenhouse gas emissions trading scheme will see renewed interest in planting forests, although as of 2013 this had not eventuated.

One major result of the privatization of the state's plantations was that much of the land on which planting took place was subsequently transferred to Maori tribes as part of the Treaty of Waitangi settlements (MAF, 2009). The trees themselves are often owned by others, such as institutional investors or foreign-based forestry companies, and management arrangements vary. Relatively small areas are managed by Maori tribes, while a significant area is owned by farmers and small investors.

In brief, the New Zealand radiata pine plantations were promoted initially to provide timber for domestic use and subsequently for export revenue. Some planting was also for erosion control in addition to providing timber. The expansion of the plantation estate was supported up to the mid 1980s by government policies, indirect incentives and limited direct incentives. Today, New Zealand has an open economy and relatively little government involvement in promoting forestry. Moreover, there is no comprehensive national forest policy (MAF, 2009). Despite its open economy, plantation forestry is still not on a level playing field with respect to agriculture, as ecosystem degradation by agriculture is not usually accounted for in land-use decisions.

South Africa

Despite its large area (Table 3.1), South Africa has always been lightly forested. Today, there are only 0.5 million ha of closed native forests and 23 million ha of open woodlands, which together cover less than 20 percent of the country (Dlomo and Pitcher, 2005). These forests produce minimal timber, although woodland (bushveld) is an important source of firewood and is rich in biodiversity. The closed forests have high conservation value.

Experimental plantations of introduced trees for wood supply were set up by the state in the latter part of the nineteenth century. However, large-scale afforestation did not occur until after the Second World War, when there was a rapid expansion of private planting. By 1972, the total plantation area had reached about one million ha, of which three-quarters had been planted by private industry (Dlomo and Pitcher, 2005). Private planting was promoted by incentives and a guaranteed price. Larger companies tended to focus on pulpwood, although there was also significant investment in plantations to produce sawlogs.

In 2003, plantation forests covered 1.5 million ha, which is 1.2 percent of the country's land area (Dlomo and Pitcher, 2005). The South African plantation forest resource is almost evenly split between hardwoods (eucalypts and acacias) and pines. The area of radiata pine plantations (57 000 ha) is small compared with plantings of other pines such as *P. patula* and *P. elliottii* (Donald, 1993), and the area has decreased slightly in recent years (Table 1.2). About half of the pine plantations were privately planted, although the state owned 63 percent of the radiate pine resource (Donald, 1993). Most private radiata pine plantations were small in size and less well-managed than state plantations.

In 1996, in post-apartheid South Africa, the government moved towards the privatization of the state's plantations. Details of this complex process are described by Dlomo and Pitcher (2005). The government has pledged to transfer 30 percent of white-owned land to black owners by 2015; an estimated 40 percent of privately owned plantations and 70 percent of state-owned plantations are subject to land claims. In addition, new controls on plantation forestry have been introduced to control and tax water use.

Spain

There are 18 million ha of forest in Spain, of which 30 percent is publicly owned (MMAMRM, 2006). Spain had been deforested over a 4 500 year period and reforestation only began in the twentieth century (Valbuena-Carabaña, *et al.*, 2010). However, in the northwest, where radiata pine is planted, forest cover is higher than most of Spain. Ownership patterns vary within this region. In the Basque country, for example, where radiata pine plantations cover 21 percent of the land (and constitute 39 percent of the forest area), about 85 percent of plantations are under private ownership (Michel, 2006). In Galacia, in contrast, the National Forest Service manages 55 000 ha of communal forests, while small private stands cover 27 000 ha (Rodríguez *et al.* 2002a). Much planting of radiata pine has taken place on abandoned agricultural land.

Between 1940 and 1975, under the dictatorship of General Franco, radiata pine planting was supported by the Spanish National Forest Service. From 1976 to 1982 this role was transferred to regional administrations and, beginning in1983, planting was undertaken by landowners receiving subsidies under the European Union's Common Agricultural Policy (Valbuena-Carabaña *et al.*, 2010). Spain has a national forest policy.

In short, the development of large areas of radiata pine plantations in northwest Spain was largely a response to long-term deforestation, which in later years enjoyed benefits from the European Union's agricultural policies. These policies have served – to varying degrees – to reduce land degradation and erosion, but above all they have been crucial in securing a wood supply.

Synthesis

After achieving self sufficiency in wood supply, both Chile and New Zealand have planted radiata pine for export markets. Chile has developed strong vertically integrated industries around radiata pine, but this is less evident in other countries. New Zealand has a different ownership pattern in that it has often separated ownership of the tree crop from ownership of the land on which it grows. Despite some consolidation, Spain still has a very high proportion of small growers. In South Africa the radiata pine resource is small compared with other forest plantations, while in New Zealand the reverse is true, with radiata pine accounting for 90 percent of the entire forest plantation estate. Australia, Chile and Spain have developed more diverse plantation forest resources. The establishment of new radiata pine plantations has slowed in recent years.

The large-scale development of radiata pine plantation forestry and associated industries in the five countries outlined above share the following common aspects:

- Most major countries where radiata pine is grown boast a high Human Development Index (Table 3.1).
- There was a perceived need to supply timber that was not readily available in natural forests.
- Central government policies were established to promote afforestation. Subsidies were usually available, although in different forms in different countries, with variations over time.
- The governments themselves usually took a direct role in planting forests. Subsequently, many of the state forests were privatized and governments concentrated on removing barriers to the forest industry and supporting research, education and training.
- Plantation forestry has also been used to reduce land degradation or restore landscapes, and there is growing awareness of its role in providing other ecosystem services (see discussion below).

ECONOMICS OF RADIATA PINE PLANTATIONS

Economic evaluations have been used for both evaluating radiata pine plantation projects and deciding management options. Discounted cash flow analysis (DCF) is almost always used, although the assumptions and difficulties with this process are seldom considered by managers (Horgan, 2005). For example, the choice of a discount rate has major implications on evaluations because of the long-term nature of forest crops and the inherent exponential nature built into calculations. Discounting treats future events with decreasing significance until they become of little consequence; this is the antithesis of sustainability. Another complication with DCF is deciding on what to include in an analysis. For example:

- Are calculations to be made pre-tax or post-tax?
- Are land values to be included?
- Does the evaluation include harvesting or manufacturing?
- Should a single or an infinite number of rotations be used?
- Are social benefits to be evaluated?
- Is risk – including market and biotic and abiotic risks – a factor?
- How should sustainability, including intergenerational equity, be addressed?
- Is inflation a consideration?
- Is future uncertainty a factor?

Moreover, social benefits are often ignored, despite their vital contribution to people's lives and livelihoods. For example, plantation forestry has received criticism for ignoring impacts on local communities, even though the forests are generally profitable for owners (Menne and Carrere, 2007; Du Monceau, 2008). Other social benefits, some of which are often difficult to quantify, are discussed below.

Hepburn and Koundouri (2007) have reviewed new discounting theories and argued that decisions should be made based on a "social discount rate" that decreases over time (Box 3.1). Social discount rates are not the same as market interest rates but are a shadow price on capital. Uncertainty and intergenerational equity are taken into account by using decreasing discount rates for longer-term investments. Thus, using decreasing discount rates would be appropriate when evaluating long-term social benefits such as carbon storage, biodiversity and landscape values. Another approach is to use two different discount rates, as was done in a recent Western Australian study (Townsend *et al.*, 2012), when a lower social discount rate was applied to social benefits compared with those derived from growing trees for timber. Similarly, Manley (2012a) pointed out that the cash flow accruing from plantation management for wood production may be quite different from that accruing from carbon accretion and therefore need to be evaluated separately.

A common approach in industrial radiata pine plantation forestry is to use a discount rate selected by the owner or manager, perhaps based on the cost of borrowing (Horgan, 2005). Often, projects are assessed on whether they achieve the selected rate, and the choice of project to pursue is based on net present worth (NPW). Sometimes land costs are included, or land expectation value (LEV) is compared with actual land values. The internal rate of return (IRR) may also be calculated and used to compare alternatives. Another use of DCF is to determine a break-even stumpage (i.e. the minimum price at which wood should be sold to cover compounded costs at a selected discount rate). Sensitivity analysis is also frequently employed to explore uncertainty. These approaches, however, do not consider the recommendations given in Box 3.1 to account for social values.

The practice of increasing the discount rate to allow for risk is not recommended because it is too simplistic (Manley, 2012a). A better option is to change the cash flow, as Rodríguez *et al.* (2002a) did to account for fire risk in radiata pine plantations in Spain.

Typical discount rates and plantation forest profitability

In 1923, a discount rate of 4.5 percent was employed for the evaluation of plantation forestry prior to undertaking large-scale planting in New Zealand (Roche, 1990). This was the usual rate used at that time by the State Forest Service for loans. Similar discount rates have been used more recently in Spain (Rodríguez *et al.*, 2002a). These discount rates are lower than the 7–10 percent currently used in Australasia and Chile to evaluate radiata pine plantation management options.

Discount rates used by plantation forest valuers in New Zealand average 8.7 percent (with a range of 8–12 percent) when applied to pre-tax cash flows (Manley, 2012b); valuers include land costs in these calculations. Similarly, estimated pre-tax discount rates that are implicit in the transaction prices of forests sold in Australasia in 2009–2011 averaged 9.3 percent (with a range of 7.8–10.6 percent). These implicit discount rates have not varied greatly since 1997. Post-tax discount rates are lower than pre-tax discount rates.

Table 3.2 shows the variation in LEV and IRR (at 8 percent and without land costs) by species and country. Many of the growth rates for species other than radiata pine are considerably higher than those given in Table 1.4. Profitability depends on growth rate, cost and revenue, and rotation length. On average, radiata pine is not as profitable as some other species, such as *Eucalyptus grandis* grown on short rotations and where IRRs often exceed 20 percent but, even so, there is an overlap in IRRs between the two species (Table 3.2). For radiata pine, the best returns are in Chile: at an 8 percent discount rate an investor could pay up to US$2 780 for new land, whereas in New

BOX 3.1

The new concept of using declining discount rates in forestry evaluations

In their paper on the implications of recent advances in discounting for forest economics, Hepburn and Koundouri (2007) found that:

> "There are several clear conclusions from our analysis. First, moving to declining discount rates based on uncertainty is theoretically justified. Second, this has important impacts for long-term investments. Third, it has little impact on short-term investments (where a constant discount rate may serve as a legitimate approximation to the correct declining scheme). Fourth, the particular shape of the decline matters a great deal ...
>
> "Given these conclusions, it would appear sensible for forestry managers to employ declining discount rates in their economic analysis, which would both increase inter-temporal efficiency, and contribute to intergenerational equity and sustainability. Hence our basic recommendation is to build declining discount rates into proprietary software used for forestry financial analysis. Moreover, forest managers will no doubt realize that the implementation of a declining discount rate scheme is not only important for the economic value of future timber products. It is also crucial in determining the net present value of forestry benefits that people derive from forest services, such as extraction of genetic material, tourism, protection of watersheds, support of other ecosystems, carbon storage, etc. Some of these benefits, especially those derived from genetic material and carbon storage, provide very long run benefits, and hence are highly sensitive to the choice of the discount rate schedule used in their economic evaluation."

Source: Hepburn and Koundouri (2007)

TABLE 3.2

Economic comparison of forest plantations of various species in selected countries

Species	Country	Details	Rotation (yr)	MAI (m^3/ha/yr)	LEV (US$/ha)	IRR (%)
P. radiata	Chile	Sawlogs	22	30	2782	15.6
		Pulpwood	16	20	894	13.1
	New Zealand	Sawlogs	28	17	-230	7.6
		Sawlogs[a]	25	29	1215	9.5
	Spain	Sawlogs[b]	30	21	NA	9.0
		Sawlogs[b]	38	14	NA	5.8
P. taeda	Argentina	Sawlogs	18	30	3202	20.0
	Brazil	Sawlogs	15	30	5242	20.8
	Paraguay		20	32	1658	12.8
	Uruguay		24	20	1048	12.8
	USA	South	30	15	171	8.5
		North Carolina	23	12.5	-324	6.9
P. patula	Columbia		19	19	1592	11.2
	South Africa	Sawlog	30	14	1862	11.1
E. grandis	Argentina		15	35	3178	18.2
	Brazil	Sawlog	15	40	8311	25.5
	Paraguay		12	38	4233	21.4
	South Africa		16	32	2872	12.4
	Uruguay		16	30	1389	13.9
	Paraguay		12	38	4233	21.4
	South Africa		16	32	2872	12.4
	Uruguay		16	30	1389	13.9

Note: Land costs are not included and LEV is calculated at an 8 percent discount rate; NA = not available; a = based on an average New Zealand site (Maclaren *et al.*, 2008); b = based on good and poor sites in Spain (Rodríguez *et al.*, 2002b).

Source: Cubbage *et al.*, 2010 (except where noted)

Zealand the LEV has even been negative. The major reasons for the difference in profitability between New Zealand and Chile are the latter's lower growing costs and shorter rotations (Cubbage *et al.*, 2010).

Cubbage *et al.* (2010) argued that their analysis partly explained why the radiata pine-based industries in New Zealand and Chile are so different, with Chile being vertically integrated and New Zealand much less so. In the case of Chile, the break-even cost for growing sawlogs was about US$11 per m^3, while the stumpage price was US$34 per m^3 (not shown in Table 3.2). Cubbage *et al.* (2010) argued that this favoured vertically integrated industries that own the land and can transfer wood cheaply within their industry. In New Zealand (and incidentally also in the United States with other species), the break-even growing cost is similar or higher than stumpage prices, so it makes financial sense for companies to pass the risk of owning land to others and not to be vertically integrated. However, as noted above, other social reasons have also had an effect on the situation in New Zealand.

While overall rates of return are important when deciding where to invest capital, decision-makers also need to take into account infrastructure, technology and industrial development, labour, interest rates and biological, political and economic risks (FAO 2004; Cubbage *et al.*, 2010). These can vary widely between countries. Land costs and availability, which are not included in the analyses in Table 3.1, are also critical factors for investors to consider.

Discount cash flow analysis can be used to compare the profitability of different land uses. One such analysis in New Zealand (Evison, 2008), which included capital on-farm investments, found that dairy, viticulture and arable farming provided the best returns (IRRs of 5–8 percent). Radiata pine plantation forestry and sheep and beef farming gave intermediate returns (IRRs of about 2 percent), while kiwifruit orchards gave negative returns on investment (an IRR of -1 percent). The study took into account the type of land being used. Dairy farms, for example, are primarily on high-quality land, while forestry and sheep and beef farming are generally on lower-quality land (Adams and Turner, 2012). The results are also dependent on the date at which the analysis was undertaken. Moreover, the relative returns on investment could easily alter with changing market conditions, subsidies and other assumptions. In Chile, for example, small treegrowers can obtain subsidies for plantations that can increase IRRs by up to 40 percent (Sotomayor, Helmke and García, 2002).

SOCIAL AND ECOSYTEM SERVICES

This section focuses on the services provided by radiata pine plantations beyond wood production. Ecosystem services can be classified using the Millennium Ecosystem Assessment framework (MEA, 2003) as either provisioning, regulating or cultural (Table 3.3). Underlying these services are soils, nutrient and water cycles, biota production and ecological processes. Forests have major effects on stream water quantity and quality and on erosion (Hock *et al.*, 2009) which were reviewed in Chapter 2.

Forest managers often need to optimize and combine commercial and social benefits.

TABLE 3.3

Ecosystem services provided by radiata pine plantation forests and associated agroforestry systems

Product provision	Fibre and farm products (renewable)
	Fresh water
	Energy (renewable bioenergy)
	Carbon sequestration (long term)
	Biodiversity (habitat and protection)
	Shelter on farms (microclimate)
Regulating	Air quality
	Climate and microclimate
	Water quantity and quality
	Erosion
	Biotic and abiotic hazards
	Landscape quality
Cultural	Social relationships, communities
	Wealth and employment
	Cultural diversity, heritage
	Spiritual, inspiration, lifestyle
	Knowledge, education
	Aesthetics
	Recreation, tourism

The difficulties with the economic evaluation of social and ecosystem services are discussed above and some approaches suggested. An alternative approach is premised on the need for stakeholders to be involved in appraising forest values, which do not necessarily need to be quantified in monetary terms (Rivas Palma, 2005). The results of such appraisals should be taken into account by managers and planners and can be part of decision-support systems (Höck *et al.*, 2001). The evaluation is often undertaken by surveys of various forms. In New Zealand, a study in two contrasting areas found that plantation forests were viewed by stakeholders as having high ecological value for water regulation and erosion control but as having lesser value for biodiversity, climate regulation and nutrient cycling (Rivas Palma, 2005). Of the social services that directly affect people, employment was considered the most important, followed by living standards and recreation.

There can also be tradeoffs in the services associated with plantation forestry. A study by Dymond *et al.* (2012) on radiata pine plantation forestry showed that in some locations the value of carbon sequestration and reduced erosion can be offset by reduced water flows.

Employment

Employment opportunities are often cited as one of the benefits accruing from establishing plantations and their associated industries. In 2009 in New Zealand (where 90 percent of production forests are radiata pine plantations), 3.5 and 9.6 people per 1 000 ha of plantation were directly employed in radiata pine growing and harvesting and in growing through to the first stage of processing, respectively (FOA, 2011). This number fell by one-third between 2002 and 2009, largely due to difficult trading conditions, the downturn in planting, and greater automation. About one-quarter of the people employed were Māori. The number of people employed in New Zealand in wood-using industries after the first stage of processing is of the same order as the number employed to the first stage of processing.

Australian softwood plantations may support more workers (although direct comparison is difficult). Paul *et al.* (2013) found that 6.1–12 people were employed per 1 000 ha of softwood plantation in forest management and harvesting and 1.2–13 people were employed per 1000 ha in sawmilling, preservation and log or chip export. The flow-on effect to support industries in Australia has been estimated at 0.65 people for each person employed in the forest plantation sector (Schirmer *et al.*, 2005). On the basis of these estimates, about 30 people are employed for each 1 000 ha of plantation forest.

According to Paul *et al.* (2013), there would be little change in total employment if forest plantations replaced pastureland. In New Zealand, however, plantation forestry and associated industries employ more people than do agriculture on comparable land (Fairweather, Mayell and Swaffield, 2000). Furthermore, as plantation estates mature and industries grow, employment per unit of forest area increases.

Changes in forest ownership, rates of new planting, silviculture and wood-using industries, together with the drive for increased productivity, can all influence the number of people employed (McClintock and Taylor, 1999). The afforestation of farmland may redistribute jobs from farms or small towns to larger places and regional centres with processing facilities or ports. These changes can alter the nature of communities and can create resentment against plantation forestry.

Biodiversity

There has been considerable debate over how forest plantations, including those using radiata pine, influence biodiversity (Bremer and Farley, 2010; Brockerhoff *et al.*, 2008). A common myth is that forest plantations are biological deserts and should be avoided. Research on radiata pine and other forest plantations does not support this myth, although such forests do alter what is present. For example, radiata pine plantations favour insect-feeding birds rather than nectar feeders or obligate cavity nesters, while some vertebrates may be absent or less common (Lindenmayer, Hobbs and Salt, 2003). Bird species associated with open habitats are reduced by afforestation, while species preferring forest are at an advantage (Lindenmayer, *et al.*, 2008). In some cases, endangered species may inhabit radiata pine forests. In New Zealand, for example, endangered animal species that have been found in radiata pine plantations include the brown kiwi (*Apteryx mantelli*), the New Zealand falcon (*Falco novaeseelandiae*) (Figure 3.1), the long-tailed bat (*Chalinolobus tuberculatus*), the ground beetle *(Holcaspis brevicula)*, land snails (*Powelliphanta spp*.) and the native frog (Maunder, Shaw and Pierce, 2005; Brockerhoff *et al.*, 2008), although the role of such plantations in the conservation of these species is unclear. Native plants are also common in radiata pine plantations (Figure 3.2; Ogden *et al.*, 1997; Ramírez *et al.*, 1984).

Generally, larger numbers of birds, both native and introduced, are found in older stands and on stand edges (Seaton, Minot and Holland, 2010). Biodiversity is usually higher in mature radiata pine plantations and in pruned and thinned stands than in young, unpruned or unthinned stands because they have increased spatial and vertical heterogeneity, more ambient light, well-developed soil organic layers, increased dead wood on the forest floor and a wider range of understorey species (Estades and Temple, 1999; Brionesa and Jereza, 2007; Brockerhoff *et al.*, 2008). Understorey vegetation changes as stands age, with adventive exotic species often dominating initially, followed by native species that are frequently introduced by birds (Ogden *et al.*, 1997; Brockerhoff *et al.*, 2008).

It is generally agreed that natural forest and other native ecosystems have richer biodiversity than forest plantations. Plantations are most likely to contribute to biodiversity when established on degraded lands or on agricultural land rather than replacing these natural ecosystems (Bremer and Farley, 2010; Brockerhoff *et al.*, 2008; Hock *et al.*, 2009). Conversely, the conversion of forest plantations to pasture may reduce biodiversity. Establishing plantations can also alleviate pressure on native forests by reducing the demand for wood. However, excluding native forests from wood production is not always possible, and multiple objectives that include both

FIGURE 3.1

The New Zealand falcon *(Falco novaeseelandiae)* in a radiata pine plantation forest in Canterbury, New Zealand

FIGURE 3.2
Copihue, the Chilean national flower, growing in a radiata pine plantation forest in the BioBio region

wood production and conservation may be preferred. Where the restoration of native forests is an important objective, forest plantations are usually a better starting point than agriculture (Brockerhoff *et al.*, 2008). In Spain, radiata pine plantations play a crucial role in promoting the regeneration of original oak forests (Onaindia and Mitxelena, 2009).

Even small patches of remnant native vegetation embedded in forest plantations are important for maintaining the biodiversity of vertebrates (Figure 3.3). In this vein, the importance of promoting heterogeneous landscapes is crucial (Lindenmayer *et al.*, 2008; Estades and Temple, 1999; Hock *et al.*, 2009). In Western Australia, it has been found that indigenous logs left in radiata pine plantations are important habitats for bryophytes (Pharo and Lindenmayer, 2009). Riparian areas can be important as wildlife corridors and for the protection of streams, even when narrow (e.g. 10 m in width), although wider strips are often advised (Langer, Steward and Kimberley, 2008). Over a radiata pine rotation cycle, riparian strips can become botanically similar to the natural forest provided there is a seed source, and they can survive careful plantation harvesting and re-establishment.

There is good evidence that streams in radiata pine plantations and native forests have similar fish assemblages and that these are different to streams in pasture areas (Hicks, Glova and Duncan, 2004). In New Zealand, whitebait (*Galaxias* species), for example, are very much lower in streams surrounded by pasture than those in forests (Rowe, 2000). In a Chilean study, the abundance of native fish was lower (mean 1.1, range 0.23 per 10 m^2) in nine catchments with more than 50 percent native forest compared with two catchments where there was a preponderance of radiata pine plantations (3 per 10 m^2) (Lara *et al.*, 2009). However, this result may partly be due to higher trout numbers in native forest areas; the authors considered the presence of trout to be a positive social benefit. The main danger to waterway ecosystems arises from reduced water quality and sediments associated with harvesting operations.

Low-cost nesting boxes placed in radiata pine plantations in Chile have been found to be successful in attracting birds (Muñoz-Pedreros, Gantz and Saavedra, 1996) and have been recommended in New Zealand (Clout, 1984) but have not yet been widely used.

Management practices that can benefit biodiversity in radiata pine plantations include:

- protecting remnant indigenous ecosystems (Figure 3.3);
- using riparian strips, preferably with native species, greater than 10 m wide;

- limiting herbicide sprays during the establishment phase, especially blanket applications on indigenous plants;
- leaving woody debris, particularly indigenous logs, on site;
- manipulating stand density – where stand density is high, the understorey gets shaded out quickly, but if it is too low, light-demanding adventive weed species may persist longer;
- using longer rotations;
- minimizing disturbance during logging – this, together with careful roading and leaving riparian margins undisturbed, is also important for stream health;
- developing special management plans for some threatened species – these may be required to limit the impact of forestry operations or to control predators;
- planning at the landscape level to ensure the retention of wildlife corridors and maintain a diversity in stand ages – for large-scale afforestation or farm forestry projects, an even more heterogeneous landscape can be planned, perhaps at the catchment level (Box 11.1);
- the additional planting of species favoured by native wildlife;
- monitoring biodiversity over time using indicator species suitable to the region.

Plantation certification has increased the number of plantation biodiversity surveys, as well as improved their management and the management of embedded remnants of natural vegetation (Hock and Hay, 2003). It has also improved general awareness among radiata pine plantation managers of biodiversity issues. Australia has produced a scoring method for plantations to assess their biodiversity potential, but this has yet to be employed by plantation managers (Cawsey and Freudenberger, 2008).

FIGURE 3.3

A native forest remnant in radiata pine plantation forest in New Zealand

Note that the farmland is on the more fertile flatland.

Landscape

Radiata pine plantations or smaller on-farm plantings such as shelterbelts have an impact on how people perceive a landscape. Large-scale plantation forests can reshape landscapes and affect community values (Gerrand *et al.*, 2003). Surveys of public perceptions show that many people prefer "pure natural" landscapes, but others are happy with modified "cultural" landscapes (Fairweather and Swaffield, 2003). The "cultural" view sees landscapes as a resource for human enjoyment and is not so concerned if it is modified. However, even these people often find planted pines at the lower end of acceptability. Generally speaking, more mature plantations are preferred over young plantation forests and recently logged sites, and a mixed landscape is preferred over blanket plantation forests (Figure 3.3). Similar conclusions were reached in a Chilean study, which found that large-scale radiata pine plantations rated very poorly on visual grounds and had resulted in a large decline in landscape values (Muñoz-Pedreros and Larraín, 2002). Clearcut and burnt sites were particularly disliked, but mixed-species exotic plantings were often perceived as acceptable.

Landscape values and public concerns should be considered in forest plantation planning and management (Hock, 2005). The degree of planning depends on location and scenic quality and the number of people affected. The two basic approaches used are to screen operations and to reduce plantation visual impacts. Screening operations from view is sometimes an option. Reducing visual impacts can be achieved by altering the size, shape and pattern of operations and by avoiding excessive tracking and disturbance on visible slopes. Closer integration with farming can create a more complex landscape with increased biodiversity and better public acceptance (Gerrand *et al.*, 2003). A guide on how to incorporate plantation forestry into the landscape has been produced for New Zealand (Anstey, Thompson and Nichols, 1982). A Tasmanian manual for forest landscape management, primarily written for native forests, also provides detailed relevant advice on principles and practices (FPA, 2006).

Recreation in radiata pine plantations

Radiata pine plantation forestry is occasionally managed to encourage recreation or tourism (Figure 3.4). This primarily occurs in those forests close to urban populations,

FIGURE 3.4
Recreation in mature radiata pine plantation forest near Auckland, New Zealand

but more remote plantations may also be used for hunting and fishing. In New Zealand, for example, several forest plantations near cities are used intensively for activities such as picnicking, walking, running, horse-riding and mountain biking. A study in a commonly used part of a forest of 288 ha near Rotorua, New Zealand, found that most recreational users tended to be locals (Turner *et al.*, 2011). While some users expressed their preference for more stand complexity, others did not have strong opinions. The surrogate market value of these recreational services estimated by travel costs for this small part of the forest was estimated at US$12 million annually. A similar study in a radiata pine plantation close to Adelaide, South Australia, found that recreational benefits were worth 30 percent of annual timber sales (Smailes and Smith, 2001). In neither of these two examples were the values captured directly by the owners. Potential conflicts between users (e.g. between hikers and logging operations) need to be managed, such as by separating them in space.

Carbon storage

Carbon storage by afforestation is considered one way of mitigating climate change through a one-off capture of CO_2 (see Chapter 2). Planted forests are included in national carbon inventories, and new post-1990 planted forests may provide additional carbon storage under the Kyoto Protocol. However, the area of radiata pine plantations worldwide has remained static in recent years (Table 1.2). New Zealand has implemented an emissions trading scheme and this has the potential to increase tree planting (Manley and Maclaren, 2009; Adams and Turner, 2012). Australia has opted for a carbon tax in the short term, and this may become an emissions trading scheme in 2015 (Australian Government, 2011). Neither of these schemes has led yet to increased rates of new planting because of uncertainty and the changing value of carbon credits. The additional storage of carbon in wood products also has a modest positive effect (Manley and Maclaren, 2010).

Afforestation with species such as radiata pine can change landscape albedo, resulting in the greater absorption of light energy (Whitehead, 2011), and this needs to be considered when evaluating the impacts of afforestation on climate change. It is also necessary to account for changes in the storage of soil carbon, which can be either positive or negative (see chapters 3 and 10).

Other aspects need to be considered when discussing carbon storage and balance. The use of bioenergy from forest plantations can reduce the use of fossil fuels, as the energy balance is positive (Hall, 2009). Greenhouse gas emissions can be reduced by 75–94 percent, depending on the bioenergy technology employed. However, the economics of forest biofuel options in New Zealand have not changed much for 30 years, suggesting that widespread uptake is likely to be slow unless other factors drive their use (Horgan, 2009). In Chile, there is an incentive for greater uptake of biofuels because electricity companies are required by law to increase their use of non-conventional renewable sources (Acuña *et al.*, 2010), and unused forest residues from radiata pine plantations are currently the largest potential source of these. Substantial energy and CO_2 emission savings can also be achieved by building in wood rather than concrete, steel, aluminium or plastics.

Wilding spread

There has been increased regeneration of radiata pine in its native habitat following grazing and other disturbance, although it has not expanded its natural range without planting (Richardson and Higgins, 1988). However, wilding spread from wind-blown seed, usually within 500 m, has been recorded in all the major grower countries (Richardson and Higgins, 1998; Simberloff *et al.*, 2010) and, in Australia, cockatoos are also known to spread the seed. Radiata pine tends to invade open vegetation, sometimes after fire, rather than dense forest. In South Africa, there has been widespread invasion of radiata pine into fynbos vegetation over an area of about 340 km^2, although *Pinus pinaster* has spread over a greater area than radiata pine. In Australia, radiata pine has invaded heathlands, grasslands and dry open eucalypt forests while, in New Zealand, the species most commonly invades grasslands, tussock land and shrubland where farmland has been abandoned and grazing animals removed (Ledgard, 1988). In New Zealand, the species is not considered to be as invasive as other pines, particularly *Pinus contorta*. In South America, radiata pine has invaded burnt, grazed sites in Argentina and fragmented secondary forests in Chile. Wildings have also been recorded in burnt areas, along roadsides and on abandoned fields in Spain.

Radiata pine is reasonably palatable, so it can be controlled by grazing animals. Physical removal, sometimes aided by weedicides, has also been used. Avoiding planting pines on "take-off sites" such as ridges is another strategy to reduce wilding spread.

Working with communities

Building good relations with local communities and other stakeholders is an important part of forest management. This takes time and dedication and needs to be an objective of forest management planning (Barnard, Fitzgerald and Langer, 2005). One objective of community engagement is to identify local concerns and devise mutually agreed ways to resolve them. Typically, the process first develops insights into community concerns or controversies, often through scoping surveys. This is followed by wider community engagement – usually using social learning processes – to develop agreed strategies to address concerns and build ongoing relationships.

ENVIRONMENTAL STANDARDS

A range of approaches have been developed to reduce the environmental impact of forest plantations. These include voluntary forest management guidelines, local laws, the systems certification approach of ISO 14001 (taken up in the mid 1990s), the "sustainable forest management approach" that arose out of the 1992 United Nations Conference on Environment and Development (also known as the Rio Earth Summit) and the subsequent Montreal Process, international conventions such as the Convention on Biological Diversity and, increasingly, the use of third-party certification schemes. Chile, for example, has a range of forest and environmental laws that cover environmental damage, protect native biota and require forest management plans. The Government of Chile is a party to the Convention on Biological Diversity and has developed the CertforChile Standard for plantation forests, and plantations in the country have been third-party certified (Morales, 2005; Paredes, 2005).

The increasing emphasis by plantation managers on environmental management has been driven in part by forest certification, which demands adherence to prescribed standards, and in part by changes in societal values, which increasingly feature a demand for sound environmental performance by land managers. The Forest Stewardship Council (FSC) standards are applied in more than half of the radiata pine plantations in New Zealand (FOA, 2011). In Australia and Chile, locally developed standards, allied to the Programme for the Endorsement of Forest Certification (PEFC), prevail (Paredes, 2005; Crawford, 2009). Certification has been slower to be applied in Spain because of the preponderance there of small growers (Michel, 2000). New Zealand is developing a national environmental standard for forest plantation as a component of the Resource Management Act and aims to standardize regulations throughout the country.

Paredes (2005) has argued that the FSC and PEFC schemes were taken up rapidly by many large radiata pine growers because their structure allowed for easy implementation and they encouraged sound forest management. Companies also took up the schemes to ensure access to markets. Although large parts of the resource are still not well-managed from an environmental standpoint and remain uncertified, certification has improved environmental management in many enterprises and there is also increasing engagement between such enterprises and local communities (Dare, Schirmer and Vanclay, 2011). Small growers have had more difficulty in achieving certification because of the cost, but group schemes have sometimes helped to overcome this problem. Markets are yet to respond strongly by way of providing a price premium for certified wood (Hock, *et al.*, 2009).

TRENDS

Historically, radiata pine plantation forestry has focused on commercial objectives and supplying wood products. However, the increasing recognition of their multiple benefits and potential negative impacts is changing the attitude of government and forest managers (Hock *et al.*, 2009). This has included recognition of indigenous people's perceptions and rights (Du Monceau, 2008; Rotarangi and Thorp, 2009). There is also growing recognition that participatory decision-making needs to be embraced with an emphasis on equity, representation and transparency. Such societal interaction ties in with adaptive forest management (see Chapter 10) and is an important element of certification schemes and sustainable forest management.

There is also considerable research into how to quantify, value and increase consideration of ecosystem services (see for example, Hock *et al.*, 2009). This can include modelling systems, visual tools and using remote-sensing or allied tools. For example, an assessment was made of a range of regulating ecosystem services provided by planting radiata pine on an eroding, 585 000 ha pasture catchment in New Zealand (Ausseil and Dymond, 2010). Using a range of models, the assessment estimated that the plantation would increase carbon sequestration by 13.4 million tonnes of CO_2 per year and "natural" habitat by 155 percent. It also estimated that it would reduce:

- agricultural greenhouse gas emissions by 1.94 million tonnes of CO_2 per year;
- sediment yield by 3.8 million tonnes per year;
- stream water supply by 31 percent;
- stream nitrogen losses by 2 334 tonnes per year;
- stream phosphorus losses by 302 tonnes per year;
- stream faecal coliform by 51×10^{15} organisms per year.

Moreover, if only 5 percent of the catchment was planted to radiata pine, there would still be useful improvements in carbon balance, erosion control and nutrient retention (Ausseil and Dymond, 2010).

The use of direct government subsidies to promote the planting of radiata pine has largely halted, but indirect support is often present. However, governments have and will continue to influence the decisions of land managers through efforts to mitigate climate change and perhaps to increase the use of non-fossil energy sources. Society and governments are also concerned with reducing erosion and the loss of biodiversity while maintaining landscape values; a range of interventions is possible to achieve these goals. Certification schemes and other instruments have had an important role in promoting a better balance between production and ecosystem and social services, but the provision of wood products, wealth and employment that stem from forest plantations will continue to be a major goal.

4 Pests and diseases

Radiata pine plantations are not currently affected by pests and diseases that cannot be controlled or tolerated, provided they are not planted "off-site" – that is, on a site where they are stressed by factors such as damp heat (see Chapter 2). However, some radiata pine pests and diseases can be troublesome and require modified forest management, and foresters need always to be vigilant regarding forest health. From an economic viewpoint, pests and diseases can result in significant damage to the plantation resource, end-use and value. What is considered "significant" will be related to management objectives. Organisms that are benign or helpful to the forest ecosystem, such as mycorrhizal fungi and most birds, are not considered pests. The management objective, however, should be to focus on growing a healthy forest in which pests and diseases are perceived as a symptom of an unhealthy forest rather than as the problem (FAO, 2001).

This chapter covers insects, fungi and animals of commercial significance; it also covers the issue of plantation forest vulnerability and risk management compared with natural forest. Weeds, which can also be pests, are covered under "establishment" (Chapter 8) because it is at that stage that they have the largest impact on management. Abiotic limitations are considered in Chapter 2, and the topic of radiata pine as an alien invasive species is addressed in Chapter 3.

MAJOR INSECT PESTS

Sirex wood wasp

Sirex noctilio, commonly known as the sirex wood wasp or simply sirex, is endemic to Europe, parts of Asia, Turkey and North Africa. Its preferred host trees are *Pinus* trees, but it rarely kills native pines in its native range. Sirex is only found on trees that have been stressed due to overcrowding exacerbated by drought. The female actively seeks out trees with low sap pressure and during its attack infects the tree with a symbiotic associate, the fungus *Amylostereum areolatum*. This fungus reduces the moisture content of green wood to levels more favourable for egg hatching, supplies essential nutrients to larvae, and causes dry white rot of the wood, thereby assisting the tunnelling activity of larvae.

The first sirex population in New Zealand established itself in the Wairarapa in 1900, most probably introduced on imported wood from Europe (Bain, Sopow and Bulman, 2012; Hurley, Slippers and Wingfield, 2007). Sirex attracted little attention in New Zealand until the late 1920s, when deaths attributed to the wasp became evident in young radiata pine plantations at high planting densities. Between 1946 and 1951, a large outbreak wiped out 30 percent of individuals in unthinned, intermediate-age radiata pine stands in an area of 120 000 ha in the central North Island. Within these plantations, stress from overcrowding was aggravated by a series of unusually dry summers. What at the time was a major biological catastrophe is now considered to have had a beneficial impact because the infestation performed what in effect was a broad-area thinning during a period in which neither markets nor labour for the thinnings were available. Following the collapse of sirex populations in New Zealand in 1951, there have been no further outbreaks. The adoption of silviculture using low stand stockings since the 1960s has furthermore mitigated sirex outbreaks.

In Australia, sirex is still considered the most serious insect problem in radiata pine plantations (Collett and Elms, 2009). In the late 1940s, based on what occurred in New

Zealand, forest authorities in Australia increased quarantine vigilance, but in 1952 the first discovery of sirex in Australia was made in Tasmania. Ten years later, the first mainland infestation was found near Melbourne in Victoria. These two infestations are believed to have originated from separate accidental introductions through imported timber. Sirex spread through Victoria into South Australia, New South Wales and the Australian Capital Territory, advancing at an average rate of 30–40 km per year. Sirex has not been found in Western Australia.

Sirex populations built up in Tasmania despite early search-and-destroy operations and the release of two species of wasp parasitoids. In one 1 100 ha plantation, sirex had killed 40 percent of all trees by 1959. In southern Victoria, the first substantial radiata pine mortalities from sirex occurred in the 1960s in shelterbelts on farmland and in private plantations in central Gippsland. In the Green Triangle region near Mount Gambier, an infestation in the late 1980s resulted in the death of 4.8 million trees, partly because of problems with control operations (Hurley, Slippers and Wingfield, 2007). In New South Wales, there have been occasional localized outbreaks in unthinned stands.

Sirex was discovered in radiata pine plantations in Argentina in 1985 and had spread to the radiata pine resource in Chile by 2000 (Hurley, Slippers and Wingfield, 2007), but it has not yet caused widespread mortality there. It was found in South Africa in 1994, where it now generally occurs at low levels. Sirex and related species are found at low incidence levels in radiata pine stands in Europe, but are not considered a major problem (Hall, 1968).

The prevention of sirex epidemics is largely a silvicultural issue. Populations usually only build up to high levels when conditions are adverse, as healthy radiata pine trees are very resistant to attack. The insect is drawn to stressed or recently killed trees, although green logs and large-diameter logging slash are also attractive. Young trees are seldom attacked because they are too small. The following silvicultural practices have been advocated to maintain tree vigour, minimize water stress and reduce the build-up of sirex:

- avoid planting in drought-prone areas or on sites that are difficult to thin;
- reduce initial stocking and/or carry out timely thinnings to remove suppressed trees;
- restrict high-pruning and waste-thinning operations in susceptible areas to periods outside the insect’s flight season;
- minimize injury to trees and quickly salvage trees damaged by natural causes.

In New Zealand, biological control programmes date back to the late 1920s (Hurley, Slippers and Wingfield, 2007). The initial focus in Australasia was on the introduction, mass-breeding and release within infected plantations of sirex-specific parasite wasps of the *Ibalia*, *Megarhyssa* and *Rhyssa* genera. In South America, sirex already had paristoids when first introduced, but new introductions have been made in both South America and South Africa. Up to 70 percent parasitism has been recorded but it is generally about half this level. Thus, while they are an important control measure, parasitoids are not sufficient by themselves.

A European parasitic nematode, *Deladenus siricidicola*, was found to be present in New Zealand in 1962; this led to the wider use of the nematode and the selection of virulent strains (Collett and Elms, 2009; Hurley, Slippers and Wingfield, 2007). These strains can result in over 90 percent parasitism. However, a loss of virulence can occur when they are bred artificially for a long period, as was discovered during the outbreak of sirex in the late 1980s in Australia’s Green Triangle region.

Both Tasmania and South Africa attempted to eradicate sirex when it was discovered; while unsuccessful, these efforts may have slowed the build-up of populations. Quarantine measures have been successful in keeping sirex out of Western Australia. Finally, there is some evidence that the island provenances of radiata pine are less susceptible to sirex than are mainland provenances.

The Siricid wood wasp, *Urocerus gigas gigas,* was found in radiata pine in Chile in the 1970s, but since it only attacks logs and severely weakened trees it is not considered a problem (FAO, 2008).

Bark beetles

Radiata pine is susceptible to numerous bark beetles, of which *Ips grandicollis* causes most concern in the Southern Hemisphere. Fortunately, the majority of bark beetles are not economically significant in radiata pine plantations, although a few are troublesome vectors for bluestain and decay fungi. In Spain, 15 species of bark beetle have been found in radiata pine, of which two, *Tomicus piniperda* and *Ips sexdentatus,* are of greatest concern (Goldazarena, Romón and López, 2012).

Dendroctonus valens, the red turpentine beetle, and three species of *Ips* (*I. paraconfusus*, *I. mexicanus* and *I. plastographus*) occur in native radiata pine stands in California (McDonald and Laacke, 1990). They have the ability to kill trees and are particularly destructive in drought-stressed stands. There are also other bark beetles of lesser importance. Bark beetles are one of the vectors of the introduced pitch canker, described below.

I. grandicollis, the five-spined bark beetle from the eastern United States, was introduced accidently to South Australia in 1943 and Western Australia in 1952 (Morgan, 1989) and has spread to all the radiata zones in mainland Australia. It is not found in other major grower countries but has been frequently intercepted at quarantine stations in New Zealand and South Africa. The insect is commonly found in logging slash and in the wake of fire. If numbers build up, the beetle will attack living trees, particularly if the trees are stressed. Deaths are usually confined to small areas. In New South Wales, however, droughts have triggered more extensive attacks on living trees up to 30 years of age. The beetles carry bluestain fungi (*Ceratocystis ips*), which causes problems with stockpiled logs, and therefore logs should be removed promptly from forests in which the beetles occur.

In Australia, *Ips* control measures and pest management strategies have included regional quarantine, rapid log extraction, insecticide spraying of logs, slash management, biological control through parasitoids, and pheromone trapping.

Hylastes ater, the black pine beetle, and *Hylurgus ligniperda*, the golden-haired bark beetle, both from Europe, are found in radiata pine plantations in all major grower countries. They are generally found feeding on the cambium of recently felled logs and fresh stumps. *Hylastes ater* can subsequently attack the root collar of planted seedlings and natural regeneration, causing some deaths but many more sublethal infestations (Reay *et al.*, 2002). The species can also infect seedlings with sapstain fungi. Seedlings planted in autumn-felled stands are at greater risk. *Hylurgus ligniperda* does not attack seedlings in New Zealand but does so in Chile (FAO, 2008). From an economic viewpoint, a major problem with these species is that infested logs cannot be exported unless fumigated immediately before shipping, while green sawnwood may have to be fumigated or kiln-sterilized if the insect is present.

The Mediterranean pine engraver, *Orthotomicus erosus*, is another bark beetle that has been introduced accidently to Chile, South Africa and California and is known to attack weakened pine trees (Haack, 2004).

There is considerable potential for further species of bark beetle to become pests within the radiata pine plantations of the Southern Hemisphere as a result of accidental introductions. These include *Ips sexdentatus* and *Tomicus piniperda*, which have been known to kill weakened radiata pine trees in France and Spain (Brockerhoff *et al.*, 2006).

FIGURE 4.1

The effects of the pine shoot moth, *Rhyaciona buoliana*

Pine shoot moth

Rhyacionia buoliana, the European pine shoot moth, is the most significant insect problem in radiata pine stands in Chile, having first been detected in 1985 (Ramos and Lanfranco, 2010). It is thought to have come from Argentina, where it was first seen in 1939 and where it attacked pines, including radiata pine. After its detection near the southern limit of radiata pine in Chile, it spread north at the rate of about 50 km per year. The species is also found in radiata pine plantations in Turkey, where its effects have been pronounced, and in Galicia, Spain (Allen, 1973).

The moth does not kill the tree; rather, the larvae invade the shoots (Figure 4.1). In Chile there is usually only one generation per year. The larvae weaken the shoots, in which they are present for ten months, leading to breakage, malformation and reduced height growth. Up to five larvae have been observed in one terminal shoot. Damage to the main leader is worse in stands up to 6–7 years of age; in older stands there may be less leader damage but branch tips are still attacked. In young stands, 50 percent of leaders can be damaged, although all trees will be attacked.

In 1989, the specific parasite *Orgilus obscurator* was introduced to Chile, and other native Chilean insect species also opportunistically attacked the pine shoot moth (Ramos and Lanfranco, 2010), greatly reducing the damage caused by the moth. In southern areas the insect is under control, but control is only modest further north in drier areas and on poorer sites (Alfaro *et al.*, 2010). Other insects are attacking the introduced parasite and the longer-term balance is unknown (Box 4.1). The impact of climate change, which may lead to greater moisture stress in the north, could also have implications for the effectiveness of *O. obscurator.* Insecticides have produced mixed results and are not used.

Aphids and adelgids

The Monterey pine aphid, *Essigella californica*, quickly became a major concern after it was detected in Australia in 1998 and caused extensive defoliation in mid-rotation stands (Eyles *et al.*, 2011). Typically, the defoliation shows as very thin mid-to-upper crowns, the yellowing of needles and premature needle shedding. This insect has also

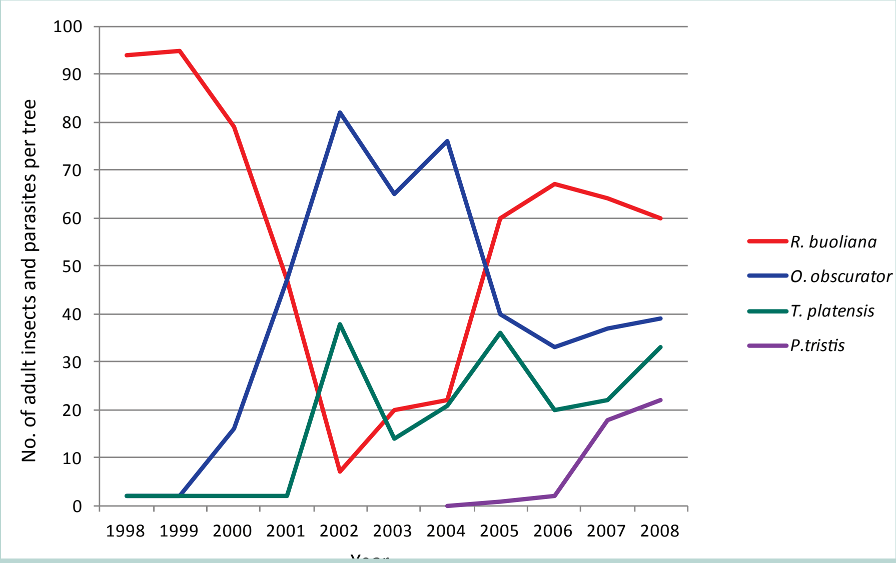
BOX 4.1

The impact of parasites and hyperparasites on the control of the pine shoot moth, *Rhyacionia buoliana*

The introduction of the specific parasite *Orgilus obscurator* in 1989 to Chile was initially slow, so a large-scale release programme was introduced in the Bio Bio region. As shown by the red line in the figure below, this quickly led to a large reduction in the number of pine shoot moth per tree as the number of parasites (blue line) increased. Later, several native species of insect also attacked the pine shoot moth. One, *Temelucha platensis* (green line), a competitor with *O. obscurator*, increased in number in parallel with *O. obscurator*. Other insects, such as the non-native *Perilampus tristis* (purple line) acted as hyperparasites by parasitizing *O. obscurator*, and appear to be reducing the parasite's impact. As the figure shows, the number of pine shoot moths per tree increased from 10 to 20 in 2002–03 to about 60 per tree in 2005–08. Overall, this resulted in a 40 percent reduction in pine shoot moth infestation in the Bio Bio region since the pine shoot moth epidemic first occurred. Control is currently higher elsewhere in Chile.

It is clear that the situation is dynamic in Chile and the future direction of biological control is not easy to predict. Control efforts will require continuous management.

Population dynamics of pine shoot moth and various parasites, 1998–2008, Bio Bio region, Chile



Source: Redrawn from Ramos and Lanfranco (2010), with permission

been present in New Zealand since 1998; it is not considered a problem there at present but could become more prevalent with climate change (Watson *et al.*, 2008).

The Monterey pine aphid is a greater problem where trees are under moisture stress. Studies have shown that infestations will reduce growth rates, although interpretation is complicated by the effects of moisture stress. Some radiata pine genotypes are more susceptible to attack (heritability 0.4) than others, and since 2005 aphid-resistant breeds have been available in New South Wales (Sasse, Elms and Kube, 2009). Thinning and balanced fertilizer treatments have been suggested as appropriate silvicultural treatments for some sites. Biological control with a wasp, *Diaeretus essigellae*, is also being pursued.

The pine woolly aphid, *Pineus pini* (syn. *P. laevis* and *P. boerneri*), which is present in all major radiata pine-growing regions, has been a problem in South Africa since the early 1980s (Zondag, 2009; FAO, 2007). Both the severity and impact of infestation of pine trees by this sap-sucking insect are influenced by tree health and vigour. Stands on drier sites and at high stockings are most susceptible, particularly after a dry summer. Within heavily infected radiata pine stands, however, there is always a contrasting mosaic of uninfected and infected trees. A heavy infestation can reduce stand productivity.

Biological control of the pine woolly aphid occurred naturally in New Zealand and has had variable results elsewhere. Resistance varies among radiata pine genotypes. Currently, the main management approach to reducing the impact of this pest is site selection and silviculture, but it is considered to have little economic impact in Australia, Chile and New Zealand.

In Chile, the aphids *Cinara maritimae* and *Eulachnus rileyi* have been recorded but are currently of low significance (FAO, 2008).

Other localized insect problems

A number of other localized insect problems in radiata pine stands have been identified:

- There have been isolated defoliations by native insects in Australia, Chile and New Zealand, but these are not considered a major cause for concern.
- In Spain, the native pine processionary moth (*Thaumetopoea pityocampa*) is considered a significant defoliator. It limits the use of radiata pine in other parts of Europe and is a possible threat if introduced elsewhere (Brockerhoff *et al.*, 2006).
- In South Africa, the pine emperor moth (*Imbrasia cytherea*), a native insect, has occasionally been a problem, although populations usually collapse due to a viral disease (Allen, 1973; FAO, 2007).
- The deodar weevil, *Pissodes nemorensis*, first detected in South Africa in 1942, attacks stressed radiata pine trees and can cause dieback. It can act as a vector for pine-pitch canker (FABI, undated).

MAJOR DISEASES

Dothistroma needle blight

Dothistroma needle blight, *Dothistroma pini* and *D. septosporum* (teleomorph *Mycosphaerella pini*), is a fungal disease resulting in premature defoliation. It has become established in all radiata pine regions (Bradshaw, 2004; Bulman, Ganley and Dick, 2008). The disease has devastated radiata pine in some high-rainfall subtropical and tropical environments and led to the abandonment of radiata pine plantations in East Africa (Nsoloma and Venn, 1994), Zimbabwe (Barnes, 1970) and India (Bakshi and Singh, 1968). It is not a problem where rainfall is less than 1 000–1 200 mm per year in the latitudes where radiata pine is normally planted. In drier regions there may be localized infections, often associated with young unthinned stands, where the topography encourages mist. The disease is suspected to have entered New Zealand in the late 1950s or early 1960s and was positively identified in 1964. It was first found in Australia in 1975 and confirmed in Chile in 1965, although it was likely present there in the late 1950s. The economic cost of the disease in lost productivity and for control measures is about US$15 million per year in New Zealand (Watt, Bulman and Palmer, 2011). In New Zealand there is only one strain, and the introduction of a new strain of the fungus is considered a significant additional threat (Hirst *et al.*, 1999).

Usually, but not always, infection begins at the base of the crown and progresses upwards, with a clear division between infected and uninfected parts of the crown (Figure 4.2). Trees are very rarely killed, but repeated defoliation reduces diameter growth and, under very severe conditions, height growth. Some studies suggest that the impact at the end of the rotation may be small, as the worst-affected trees are likely to be thinned out (van der Pas, Bulmand and Horgan, 1984). However, other studies

FIGURE 4.2

The effects of *Dothistroma* in radiata pine is usually most noticeable in the lower crown

have found that growth reduction is proportional to the level of infection (Whyte, 1976; Bulman, Ganley and Dick, 2008). Stand growth is reduced if the level of infection reaches 25 percent; stand growth stagnates at an infection level of 75 percent.

In South Africa and New Zealand, radiata pine is considered resistant to dothistroma at about age 12–16 years (sometimes 20), although older radiata pine has occasionally been found to be infected in Australia. In New Zealand, peak infection is at 2–8 years, and high disease levels appear to occur in two of every five years; in infection years, about 20 percent of the stands in the susceptible age classes require control measures.

The chemical control of dothistroma needle blight by the aerial application of copper fungicide is generally effective and is widely practised in New Zealand and occasionally in Australia if infection levels reach 25 percent (Bulman, Ganley and Dick, 2008). A study in southern stands of radiata pine in Chile, however, showed that it was not cost-effective there (Alzamora, Hauer and Peredo, 2004). In the Southern Hemisphere, infected stands are sprayed with cuprous oxide from the air in October/November (Bulman *et al.*, 2004). This kills most of the inoculum at a time when it is multiplying and also protects the foliage from new infections for up to three months (Bulman, L.S. unpublished data). Three to five sprays per rotation are usually adequate. Other fungicides can also be used (Bradshaw, 2004). Ground and aerial surveys are used to identify stands needing treatment, and recently the use of spectral imaging has been studied. Detailed advice on spraying is given by Bulman *et al.* (2004).

Pruning branches bearing infected foliage lowers the rate of increase of the disease. Experience in New Zealand indicates that pruning a stand with 25–40 percent crown infection generally postpones the need for a fungicidal application for several seasons. Thinning also assists in controlling infection. Tree-breeding for disease resistance has had some success (see Chapter 6). Breeding may reduce infection by 15 percent and chemical spraying by 56 percent (Carson, Dick and West, 1991). Sulphur deficiency also increases dothistroma infection (Turner and Lambert, 1986). Dothistoma produces a toxin, dothistomin, which was considered initially to be a health concern, but further research found that it does not pose a significant problem (Bulman *et al.*, 2004; Bradshaw, 2004).

Sphaeropsis sapinea

A variety of diseases of *Pinus radiata* are attributed to the opportunistic fungal pathogen *Sphaeropsis sapinea* (syn. *Diplodia pinea*). It is considered one of the most serious forest diseases in South Africa (Swart, Knox-Davies and Wingfield, 1985), but is found in all the world's radiata pine areas.

The following symptoms are associated with *S. sapinea*:

- leader dieback
- wood cankers
- crown wilt
- root rots
- blue stain in timber
- damping-off in nurseries.

Leader dieback is probably the most common symptom (Figure 4.3; Swart, Knox-Davies and Wingfield, 1985). The first indications of shoot blight are resin droplets on growing shoots and a few stunted needles. Later, needles turn brown and the shoot tips become crooked or curled. After about three weeks, black pycnidia appear on the surface of dead needles. When terminal shoots are infected they exude large amounts of resin. The result is dieback of the leader. Warm temperatures (20–25 °C) and high humidity favour its development, particularly when coinciding with new shoot growth. Infection of lateral shoots is generally less likely to retard growth and cause malformation of the tree than infection of the terminal shoots. Although unwounded drought-stressed trees can be infected, generally the disease is worst where there has been wounding by hail, insects or other agents. Crown wilt is a result of wood canker infection lower down on the bole or branch; the needles first turn chlorotic and then reddish-brown.

FIGURE 4.3

Sphaeropsis sapinea **(syn.** ***Diplodia pinea*****) often results in leader dieback**

Pruning wounds are a common source of entry for *S. sapinea*. Studies in New Zealand have shown that heavily pruned trees are more susceptible to infection than lighter-pruned trees and infection tends to increase with increasing branch diameter (Ridley and Dick, 2001). Sunscald following pruning will also allow infection.

S. sapinea is another disease that has prevented the use of radiata pine in more humid tropical countries (Swart, Knox-Davies and Wingfield, 1985). In the major radiata pine areas, careful selection of forest plantation sites will reduce the incidence of the disease. Sanitation, practices to reduce stress and injury to trees, and tree-breeding are also avenues of control. Spraying fungicides is practical only in nurseries.

Pine pitch canker

Pine pitch canker (*Fusarium circinatum*) was first seen in the natural stands and planted trees of radiata pine in California in 1986 and is now considered a major threat to plantations (Box 4.2; Ganley *et al.*, 2009; Wingfield *et al.*, 2008). In California, the canker is spread by insects – including bark beetles (*Ips* spp.), twig beetles (*Pityophthorus* spp.), cone beetle (*Conopthorus radiatae*) and *Ernobius* spp. – that wound the trees and cause localized cankers and branch dieback. It is not yet a major problem in radiata pine stands outside California but has been recorded in radiata pine stands in Italy, Spain and South Africa and in nurseries in Spain, South Africa and Chile. Pine pitch canker, which is found on a wide range of pine species and Douglas

BOX 4.2

Pine pitch canker: a growing threat?

Pitch canker (*Fusarium circinatum*) was first recorded in radiata pine in coastal California in 1986. It appeared in nurseries in South Africa (1990), Chile (2002) and Spain (2003) and later in plantations in Spain (2004) and South Africa (2007). Many consider this disease to be a major threat to radiata pine.

The disease infects all parts and ages of radiata pine and at any time of the year. Branch dieback and cankers are typically resinous. However, the fungus does not spread far from the site of initial infection. Trees can become malformed and their growth rates can be affected by a reduction in foliage. The fungus can attack cones and seeds and in nurseries cause damping-off and seedling root-rot and mortality.

The fungal spores are easily dispersed, but fungal infection in trees is facilitated by insect vectors that damage the trees. Insects associated with the spread include weevils, twig beetles, bark beetles and the pine shoot moth. Fresh mechanical damage may also allow entry, although this is not considered important in Californian radiata pine stands. Warmer temperatures, high humidity and high fertility favour the spread of the fungus. Climate mapping studies suggest that the California coast and Chile should be only moderately susceptible to this disease, which may be the reason why insect vectors are so important in California. Parts of Spain, South Africa, Australia and New Zealand are possibly more favourable for the disease.

Quarantine measures are the first line of defence for countries without the disease, which involves keeping out insect vectors as well as infected material. For nurseries, high levels of hygiene and the control of insect vectors are important. In plantations, reducing environmental stress through stocking control and the careful use of fertilizers may reduce the impact of the disease. Given that there is wide variation in resistance to the disease in radiata pine, breeding is another control option. However, this may be complicated because the disease has a number of strains. Biological and chemical controls have not proved effective.

It has been reported that resistance to the disease in radiata pine trees in California increases with time (induced resistance) and may be leading to a remission of pitch canker. For further information see Wingfield *et al.* (2008) and Ganley *et al.* (2009).

fir, is considered an indigenous disease in the United States, where it has been affecting native southern pine stands since 1946. It occasionally causes epidemics there that result in malformation and a loss of growth and occasional tree death. Radiata pine shows less resistance to this disease than most other pines, but like other pine species there is a large genetic diversity from which to breed resistance (Wingfield *et al.*, 2008).

Other localized diseases

Diseases that, at least at present, are relatively restricted in radiata pine include the following:

- Western gall rust (*Peridermium harknessii* or *Endocronartium harknessii*) – commonly found in the Californian native stands, this disease has not yet spread to other countries. The rust, which does not require an alternate host, is considered a potential threat in other countries, partly because of its climatic niche (Ramsfield, Kriticos and Alcaraz, 2007).
- *Neonectria fuckeliana* – first documented in New Zealand in 2003 from a 1996 collection, this disease occurs in the South Island (below latitude 43°S) and was initially assumed to be *Sphaeropsis sapinea* because it caused stem fluting associated with pruning (Figure 4.4; Hopkins and Dick, 2009). Pruning small branches (<60 mm) in summer helps control the infection. Some genotypes of radiata pine are resistant. The disease has been detected in Chile (Morales, 2009).
- Cyclaneusma needle-cast (*Cyclaneusma minus*) – a widespread, locally destructive needle cast that appears in plantations 6–20 years of age, is most damaging in areas with mild and wet conditions in autumn and winter (Bulman and Gadgil, 2001). Studies have found that an infection level of 60 percent over six years would halve diameter growth. However, control with sprays is not cost-effective. Breeding resistant strains may be possible, as the narrow sense heritability is about 0.2–0.3.
- *Phytophthora* root rot (*Phytophthora* spp.) – an occasional problem for radiata pine on ex-pasture and waterlogged sites. This disease is also of concern in nurseries and can be controlled by applying phosphorous acid and other nursery practices (Reglinski *et al.*, 2010).

FIGURE 4.4

Stem fluting caused by infection of pruned branches by *Neonectria fuckeliana*

- *Phytophthora pinifolia* – appeared in Chile in 2003 and had spread to about 60 000 ha of radiata pine plantations by 2006. Unlike other *Phytophthora* species, which attack roots, this fungus infects foliage at the base of the crown and can also form cankers on trees less than six years old (Durán *et al.*, 2008). Whole stands can die after three years of defoliation, probably from secondary infection by *Sphaeropsis sapinea*. *Phytophthora pinifolia* has been most virulent in humid areas and wetter years. Studies indicate that it is a single clone, and recent reports suggest that the disease has collapsed (Frankel and Hansen, 2011). Planting non-susceptible species on disease-prone sites and changing weather conditions may have helped reduce its impact. It has been recently hypothesised in New Zealand that a *Phytophthora* species may be associated with red needle cast.
- *Armillaria* root diseases – these have been found to occasionally kill small groups of trees in New Zealand, Australia and South Africa. The *Armillaria* species are generally natives of the region. In parts of New Zealand in the 1990s, *Armillaria* was thought to be becoming a greater problem in second- and third-rotation forests, and stump removal was advocated (Self and MacKenzie, 1995). Biological control with *Trichoderma* has been investigated (Dyck, 2006) and a commercial product is now available for use. However, recent research has found that the impact of *Armillaria* was overestimated in New Zealand (Hood and Kimberley, 2009).
- *Rhizina undulate* – a root rot found in South Africa, this disease attacks seedlings, particularly following burning of slash. It is also spread by *Hylastes* spp. (FAO, 2007).
- Endophytic fungi that infect radiata pine – these are gaining interest among researchers (Bulman, Ganley and Dick, 2008; Burdon, 2011). They are non-pathogenic but may have ecological effects; for example, endophytic fungi may have been responsible for ameliorating episodic dieback in radiata pine caused by pathogens such as *Sphaeropsis sapinea*.

ANIMAL AND OTHER PESTS

Animals have generally had a relatively minor impact on radiata pine plantations (Lewis and Ferguson, 1993; Maclaren, 1993). Apart from human encroachment, only goats on Guadalupe Island are considered a threat to the species in its native habitat. Elsewhere, young radiata pine trees are sometimes damaged by grazing stock in silvopastoral situations (see Chapter 11) or by wild rabbits, hares and wallabies. In Australasia, possums can climb trees and damage leaders, while in South Africa baboons have been observed stripping bark (McNally 1955; Bigalke and van Hensbergen, 1990). Birds and mice may also limit the use of natural regeneration as a means of re-establishing sites.

In silvopastoral systems, animal damage can be managed by careful stock control (see Chapter 11). Methods such as direct animal control, avoiding problem areas and using physical barriers and chemical repellents have all been used to reduce the problems caused by wild animals (Maclaren, 1993).

Nematodes have not been a significant pest in radiata pine plantations, although they have been found in dead and dying pines in Melbourne, Australia (Ridley, Bain and Dick, 2001). The pine wood nematode, *Bursaphelenchus xylophilus*, has caused significant losses of pine trees and other conifers in North America, Asia and Europe, but is not considered damaging to radiata pine.

PROSPECTS

Overall, there is a sense that the number of pests and diseases in radiata pine forest plantations worldwide is increasing. Occasionally an indigenous species may cross to radiata pine, but most commonly this increase is a result of introductions from outside the country. Some have argued that this is a major risk to growing forest plantations of non-indigenous species, while others say that there are distinct advantages in using non-indigenous species because they are released from their natural enemies. Gadgil and Bain (1999) studied these hypotheses in several species, including radiata pine, Douglas fir, *Pinus taeda* and *Eucalyptus nitens*, and concluded that there are usually fewer problems with non-indigenous forest plantations, provided they are in sites that suit the species and are remote from their natural origin. In addition, there are other advantages with forest plantations that make them less risky than managed natural stands.

Predicting the long-term impact of pests and pathogens is speculative for both forest plantations and natural forests. Today, the speed, breadth and volume of human travel and trade are unprecedented, and pests (both animals and insects) and pathogens are being spread widely. Radiata pine genotypes are also changing through tree-breeding, which may be reducing their resource allocation to defence mechanisms (Kay, 2008). Further, global climate change is likely to stress ecosystems and in some cases the lifecycle and virulence of pathogens and pests may change (Alfaro *et al.*, 2010). On the basis of climate models, Watt *et al.* (2011) suggested that the potential impact of climate change on dothistroma and pine pitch canker may reduce the suitability of radiata pine in some parts of the world. Alfaro *et al.* (2010) described the large-scale management efforts that may be required to mitigate the impacts of climate change on pests and diseases in forests.

Thus, in both natural forests and forest plantations, the prospect of novel ecosystems in a changing environment makes it more difficult to predict long-term outcomes. This complexity has been illustrated by the occurrence of pine shoot moth in radiata pine plantations in Chile (Box 4.1) and the effects of the recently introduced pitch pine canker in natural stands of radiata pine in California (Box 4.2). Similarly, the theory that planting radiata pine well outside its natural range is always advantageous because it releases the species from natural enemies does not always hold (Lombardero, Váquez-Mejuto and Ayres 2008). In addition, the use of mixed species in Spain did not prevent radiata pine from being attacked by the pine processionary moth (Brockerhoff *et al.*, 2006).

Nevertheless, experience with radiata pine plantations suggest that risks can be managed and that, because of the local importance and size of the resource in the major grower countries, prevention measures and research will be able to contain future problems. The main lessons from this experience are as follows:

- Radiata pine should not be planted "off-site" – climate and to a lesser extent soils should match natural stand conditions (see Chapter 2). Planting radiata pine in areas of damp heat should be avoided. Marginal sites often have more pest and disease problems because trees are more predisposed to attack due to stress.
- New pests and diseases have appeared regularly in the last 120 years and caused initial anxiety. In the longer term, however, most have been found to have only relatively minor impacts and can often be controlled easily.
- Most new pests and diseases in exotic forest plantations are introduced from outside the country. Only a few are indigenous.
- Good quarantine measures have been successful in intercepting potential threats, slowing their introduction or spread.
- The eradication of new insects that pose a major threat may be possible, particularly if they are detected early and spread slowly (Brockerhoff *et al.*, 2010).
- Keeping stands healthy and vigorous will often reduce pest and disease impacts and should be a management goal. Stocking and competition control and nutritional management are frequently used.
- Biological control using introduced or naturally occurring parasites has been successful against many insect pests, but has not always been fully effective.
- Research into the biological control of fungi is being actively pursued.

- Chemical control has been used infrequently, with the exception of nurseries and for containing dothistroma needle blight.
- The impacts of many insects and diseases can be reduced through tree-breeding. This strategy also requires keeping a wide genetic base (see Chapter 6).
- Transgenic insect-resistant radiata pine has been produced experimentally by implanting a gene from *Bacillus thuringiensis*. This technology is yet to be implemented by forest managers.
- Animal damage is generally a minor problem in radiata pine plantations, although it is sometimes a nuisance.
- Monitoring and reporting on forest health and vitality by forest managers and biosecurity authorities for insect, disease and animal pests is a critical part of risk and adaptive management.
- Prevention is the ideal approach, but early detection, preparedness and early response to outbreaks are essential to minimize social, environmental and economic impacts.

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.

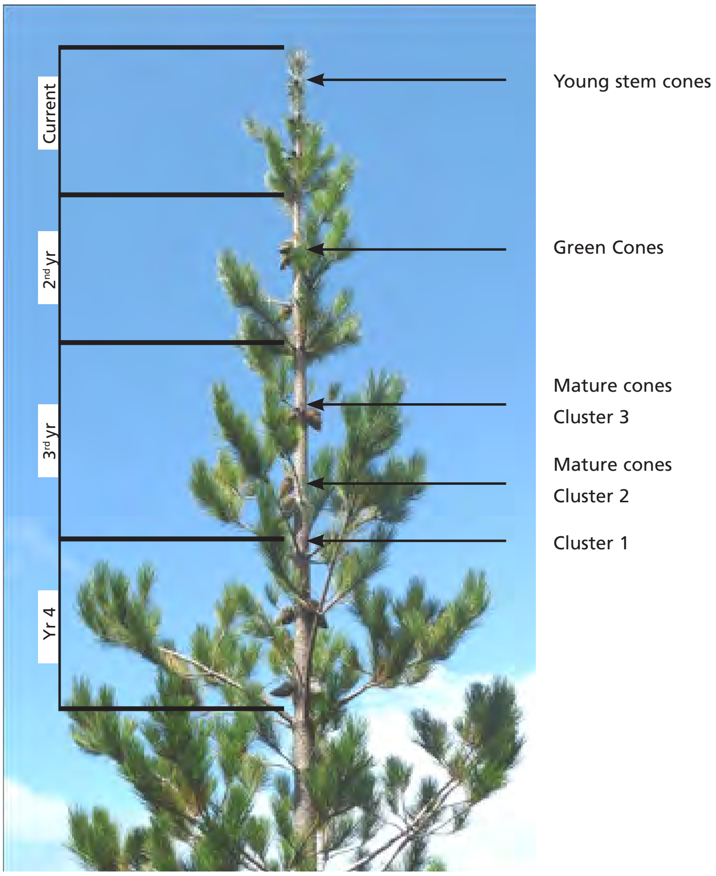
RADIATA PINE GROWTH

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.

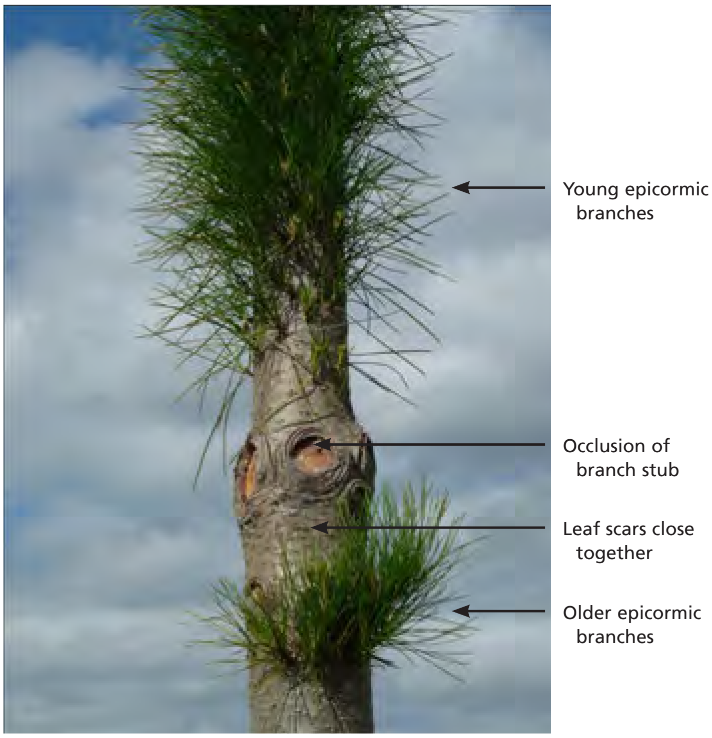
Shoot development

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.

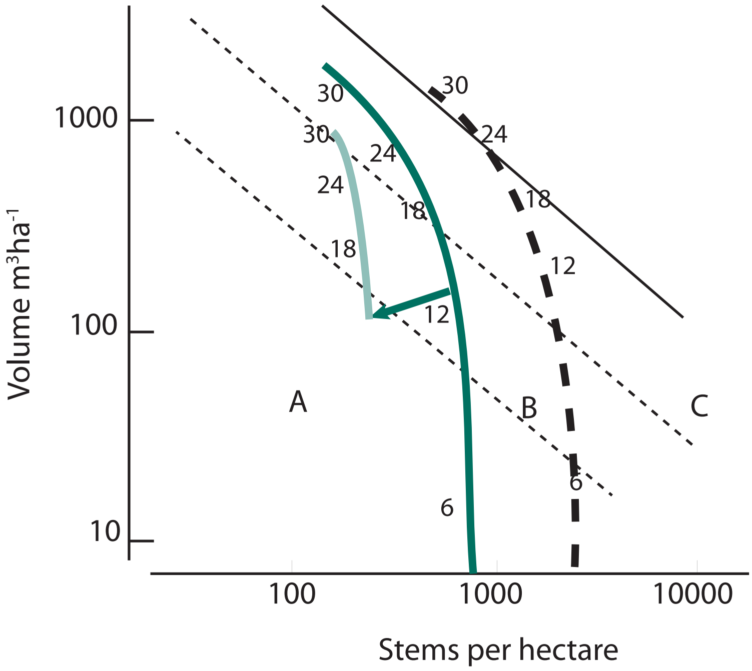
Stocking and stand density

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:

Crown width (m) = 0.75 + 0.2073 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.

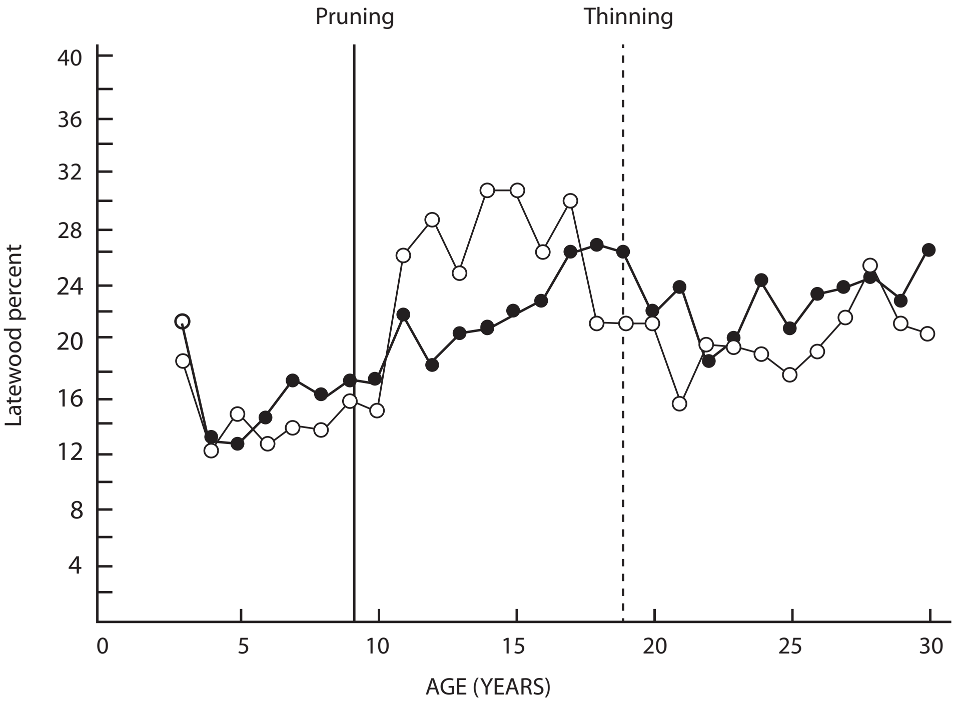
Basic density

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:

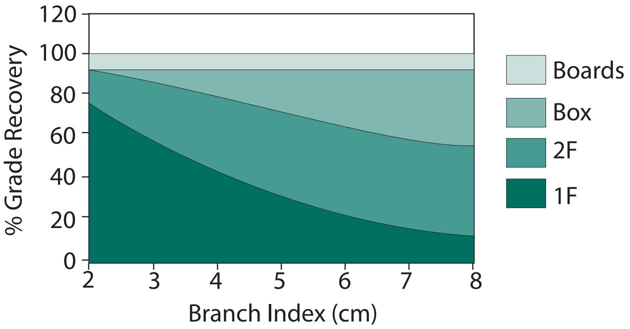
- Sound inter-grown knot: this forms when the branch is alive.
- Partially bark-encased knot: this is a variation of the sound inter-grown knot and results from a bark occlusion in the crotch (upper surface) of an acutely angled branch.
- Fully (bark) encased knot: this is formed where a dead branch 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.

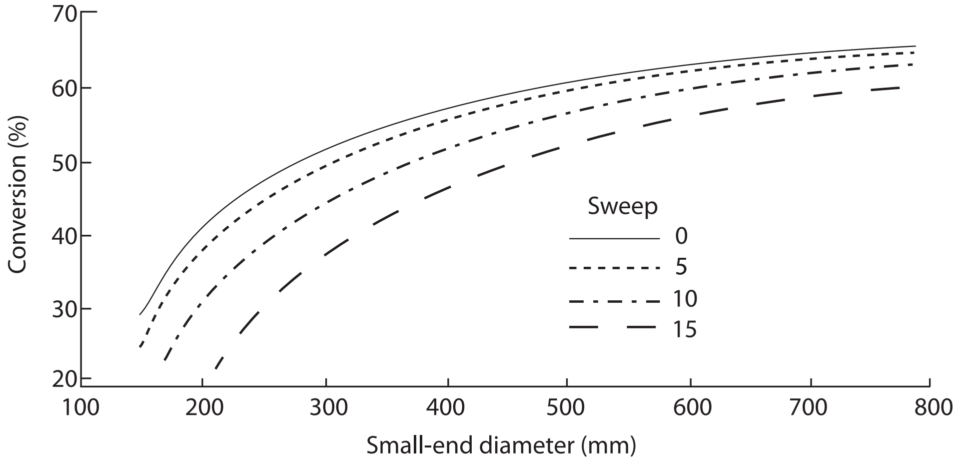
Other defects

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.

6 Radiata pine tree-breeding

Radiata pine has proved to be very adaptable to domestication. It is easy to propagate and grow using a wide range of silvicultural techniques on a variety of sites. This adaptability to domestication and the species' inherent genetic variability are two reasons for the rapid genetic improvement that has been achieved in radiata pine. The third ingredient for a successful breeding programme is also present in several countries: the commitment to a large planting programme coupled with an intensive research effort. This commitment has also been present in some countries for several other major plantation species, such as the southern pines, some eucalypt species – particularly hybrid eucalypts – and rubber, as well as for some minor plantation species, such as Douglas fir. However, advanced tree-breeding is not as rewarding for species grown in natural forests or for for very slow-growing species.

In New Zealand and Australia, tree improvement in radiata pine began in the 1950s, with the planting of the first seed orchards in 1957 (Shelbourne *et al.*, 1986; Wu *et al.*, 2007). The early efforts aimed to improve growth rates and tree form and, by the 1980s, seed orchards were producing most of the seed needed by growers. The South African radiata pine tree-breeding programme started in 1961. In Chile, tree-breeding began in the late 1970s and also focused on growth rates and tree form. There is a university–industry radiata pine breeding cooperative in Chile. A breeding programme was launched in Galicia, Spain, in 1992.

IMPROVEMENT OBJECTIVES

Establishing the goals of a tree-breeding programme needs careful thought. Not only must the biological potential of the species be considered, its long-term market requirements also need to be evaluated. For some characteristics, this may be difficult because industrial processes and market preferences are subject to continual change. Silviculturists also face this when making other decisions, such as whether to high prune. However, the problem is compounded for the tree-breeder because changes in the genetic make-up of a tree are slower and more expensive to obtain, are potentially permanent and may be difficult to retrieve if a mistake is made. The time factor also dominates tree-breeding decision-making, since the key tree-breeding objective is to obtain the maximum gain per unit of time (Zobel and Talbert, 1984). At the same time, it is necessary to be aware that the land base for radiata pine plantations may change, that the future plant growth environment is likely to be affected by climate change, and that other forms of silviculture can sometimes achieve similar ends.

Despite these difficulties, it is generally possible to decide on reasonable tree-breeding objectives. These do, however, tend to concern those traits that will generally be desirable no matter what the end use and to allow a flexible breeding strategy. Thus, for most purposes, fast growth, stem straightness, a lack of malformation, good wood properties and resistance to common diseases are important factors in tree-breeding programmes (Zobel and Talbert, 1984; Burdon, 2001). Current radiata pine breeding programmes emphasize these traits because the focus is on improving the species for wood production. There has been no interest in improving the species for amenity or soil conservation values, partly because growers can either use existing breeds or other species to fill these roles. However, there is interest in breeding for some nutrient-deficient sites.

Five factors need to be heeded when setting tree-breeding goals:

- There is usually a need to breed for several traits. These are unlikely to be of equal value and may be uncorrelated or positively or negatively correlated. Including more traits in the tree-breeding programme will reduce the rate of gain made in any one trait.
- Perceptions of the most important traits change over time. The increasing disease load has become one of the biggest problems facing growers of radiata pine (see Chapter 4), and breeding is considered a strategy against these threats. Similarly, wood properties were initially given low priority but are now considered important (Sorrenson, 2007).
- The tree-breeder also needs to grapple with specific requirements such as special sites or distinctive end uses. Until recently, breeders have usually aimed to develop genotypes that are satisfactory for a wide range of conditions, but there is growing interest in developing specific breeds for some site types and a mix of end-use product characteristics (Carson, 1996).
- Goal-setting is also related to propagation and possible breeding techniques. Recent developments in micropropagation and somatic embryogenesis methods and in seed orchard design are providing greater flexibility in future breeding objectives (Walter *et al.*, 1997). New biotechnology techniques may also offer opportunities. New Zealand scientists have already inserted genes that make radiata pine more resistant to some insect pests, although these genotypes are yet to be deployed commercially, and they are also researching the use of gene markers (Grace *et al.*, 2005; Burdon and Wilcox, 2011).
- The relationship with other silvicultural methods and other management options aimed at achieving the same ends must be considered. To improve wood flows, for example, the forest manager may resort to options such as buying wood, applying fertilizer, thinning to prevent losses from mortality, planting new areas, or tree-breeding. An advantage of tree-breeding is that it provides long-term gains without the need for further interventions. Note, however, that the time to achieve the objective differs between options, the longest time being for tree-breeding (Mead, 2005a). Also, there is often synergism between tree-breeding, intensive silviculture and wood quality. For example, improving bole straightness enables the use of lower initial stockings, makes for easier thinning, reduces extraction costs and gives higher sawmill yields.

In Australasia there is now a push to redefine tree-breeding goals in the wider context of site, silviculture and end use (Box 6.1). Ultimately, the aim is to match genetic ideotypes (distinct breeds) with site characteristics and end use, propelled in part by the continuing development of clonal forestry. This foreshadows the full domestication of radiata pine, which has occurred in other crops.

BIOLOGICAL BACKGROUND

Radiata pine usually does not begin to bear mature female cones until it is about eight years old, although the actual age is partly dependent on the individual genotype and planting site (see Chapter 5). The serotinous cones take about three years after initiation and about two years after pollination to reach full maturity. These factors influence breeding plans and the rate of improvement.

Successive female clone clusters, which are modified shoots, are associated with the polycyclic nature of the species, so that cones may become receptive to pollen over a period of five or more weeks in spring (Lill and Sweet, 1977; Sweet *et al.*, 1992; Madgwick, 1994). Generally, an individual cone is receptive for 2–13 days and the ovules (female cells that could develop into seeds) are pollinated by several pollen grains. However, only one of these embryos will develop into a seed; the others abort. Under natural conditions, the movement of pollen to the ovule micropyle is dependent on either a pollination droplet or rain. It is also possible to manually apply pollen in a liquid with the aim of achieving this rapid transfer, thus preventing most unwanted pollination from outside sources (Sweet *et al.*, 1992).

The male strobili, which in radiata pine are produced from around age five years, are modified short shoots (fascicles) and are most numerous on the lower crown branches. Pollen is wind-distributed in spring, but, if required, it is easily collected and dry pollen may be stored for several years at temperatures well below freezing point. This is important for control-pollinated seed orchards.

There is commonly a 50 percent loss of female cones in the first year after pollination, although it can be as high as 90 percent. These losses occur 4–6 weeks after receptivity and appear to be partly related to rapid shoot extension and a lack of pollination, although frost and other biotic factors are sometimes important. Intensive silvicultural practices such as irrigation or nutrient applications have not proved advantageous

BOX 6.1

The changing breeding goals for radiata pine: an example from Australasia

Early on, breeders of radiata pine concentrated on vigour and, above all, tree form. Selection focused on non-malformed, straight, fast-growing trees with small flat-angled branches (as found with polycyclic trees). Selection for wood properties, such as wood density and spiral grain, was largely ignored, even though it was recognized that they were highly heritable traits. Industry largely concurred with this decision. One of the genetic problems was that there was a negative correlation between growth rate and density. The consequence of these breeding goals was that wood density dropped in favour of higher growth rates. Seed from these orchards had gains in stem volume of about 20 percent and increased the percentage of acceptable stems from 45 to 70 percent.

Silviculture in Australia and New Zealand was undergoing a revolution at about the same time. Rotation lengths were reduced substantially in both countries – especially in New Zealand and Western Australia. Partly because of the greater number of acceptable trees, initial planting stockings were reduced and in many cases precommercial thinning and pruning were undertaken. Weed control improved and often former pastures were replanted, again increasing early growth rates. The outcome was that the amount of low-density corewood (juvenile wood) increased substantially and became a major problem for sawmills. By the late 1980s, New South Wales foresters had decided that corewood density should be incorporated as a breeding goal.

Research on wood properties has led to greater understanding of corewood properties and to the identification of alternative breeding traits such as microfibril angle and spiral grain, as well as wood density. Acoustics can now be used to measure wood stiffness. The size of the corewood zone can be reduced appreciably by breeding. Economic studies have confirmed that more emphasis should be given to improving wood quality. Disease resistance has also become a more important goal.

The development of techniques such as the mass multiplication of seedlings and micropropagation has allowed the multiplication of top genetic material. Cryopreservation and embryogenesis have enabled the development of clonal forestry, which makes it possible to capture non-additive variance and to breed specific varieties for different sites, end uses and silviculture. In essence, this means exploiting the genetics x site and genetics x silviculture interactions. Using clones can also speed up the breeding programme and allow tree-breeders to select genotypes that break adverse correlations such as growth rate and wood density. It also brings reduced variability when clones are deployed as mosaics, compared to seedlings, thus providing a more uniform product. The improvement goals are changing as a result of these new technologies.

in either preventing abortion or increasing seed production in radiata pine (Sweet and Hong, 1978; Madgwick, 1994). However, the selection of a seed orchard site is important, with the most productive places having hot, dry summers and low site quality in terms of vegetative growth. The application of gibberellins (a type of plant hormone) can increase flowering by two-thirds and has been used in most radiata pine control-pollinated seed orchards (Sweet, Bolton and Litchwark, 1990).

Some 13 months are required following pollination before the ovules are finally fertilized. With subsequent development, food reserves accumulate in the endosperm and the seed coat hardens; maturation leads to seed dehydration. As the cones dry they turn brown. However, this maturation time may be shortened by picking the cones 18–20 months after pollination and ripening under controlled conditions – that is, in early winter, almost one year prior to the autumn in which they are expected to first open naturally (Rimbawanto, Coolbear and Firth, 1988). This procedure has been used commercially, although in New Zealand there is a move towards allowing the cones to ripen on the tree.

Like most conifers, radiata pine has a very large genome and this inhibits complete genome sequencing and makes it difficult to find important genes or gene sequences that are markers of important traits. Despite this, some progress has been made in identifying genetic markers (Burdon and Wilcox, 2011).

THE QUANTITATIVE GENETIC APPROACH

Most traits that breeders wish to alter in trees are controlled by multiple genes, so the variation in such traits follows an approximately normal distribution. Tree-breeders therefore tend to base their approach on the quantitative study of variances (Zobel and Talbert, 1984).

Total phenotypic variance (Vp) for a trait (i.e. what is observed in the field) is made up of a genetic (Vg) and an environmental component (Ve) and their interaction (Vge):

$$Vp = Vg + Ve + Vge$$

The proportion of the genetic and environmental components varies widely between traits. Diameter, for example, has a large environmental component, whereas wood density is largely controlled by genetics. Thus, wood density has a relatively high heritability compared with diameter (Table 6.1).

The importance of the genotype–environment interaction in breeding programmes for radiata pine is still under debate. For example, Spanish researchers suggest that for most traits it is possible to select trees that show good combining ability and that therefore there is no need to exploit genotype x site interactions (Codesido and Fernández-López, 2009), although they suggest that exploiting genotype x site interaction would be worthwhile for frost resistance. With the development of clonal forestry it is becoming easier to target gains for specific sites and traits (Carson, 1996; Carson and Carson, 2011). However, with traditional breeding programmes based around seed production in seed orchards, the additional gains to be made by using genotype–environment interactions is often small in relation to the effort required (Carson, 1991). For genotypes to be matched to the environment, the environment must be well-defined and repeatable.

The genetic variance (Vg) may be broken into two main parts: additive and non-additive (Zobel and Talbert, 1984). When individual parents pass on traits in combination with any other parent, this is termed their general combining ability, and it reflects the additive genetic variance (Va). Narrow sense heritability (h^2) is the proportion of the additive to total variance, and is used to estimate breeding value. However, some individuals may show dominance and epistasis due to the non-additive component (Vna). The specific combining ability reflects this non-additive part and is determined by studying the performance of individual crosses. Broad-sense heritability (H^2) is the combined additive and non-additive components (i.e. Vg) as a proportion of

TABLE 6.1

Estimated heritabilities (h^2) for a range of radiata pine traits

Trait	Heritability	Coefficient of variation (%)
Height	0.2	12
Diameter	0.1–0.3	15
Stem straightness	0.1–0.4	
Branch clusters	0.35	20–30
Branch size	0.27	
Branch angle	0.2	
Root regeneration (seedlings)	0.3	
Wood density	0.6–0.8	5–10
Acoustic velocity	0.4	10
External resin bleeding	0.3–0.4	50
Longitudinal shrinkage	0.3	35–50
Spiral grain	0.55	
Tracheid length	0.54	
Stiffness	0.5	
Dothistroma defoliation	0.3	
Cyclaneusma needle-cast	0.1–0.35	
Fusarium	0.3–0.8	
Essigella defoliation	0.2–0.5	
Mg deficiency	0.7	
Drought resistance	0.1	
Frost resistance	<0.2	
Wind damage	0.05	

Sources: Madgwick, 1994; Burdon, 2001; Beets *et al.*, 2004; Kumar, Burdon and Stovold, 2008; Ivkovi- *et al.*, 2009; Wu *et al.*, 2008

total phenotypic variability. While most breeding in radiata pine has revolved around pursuing general combining ability, one potential advantage of using clones is that the non-additive genetic variances can be captured and this can lead to larger gains (Figure 6.1).

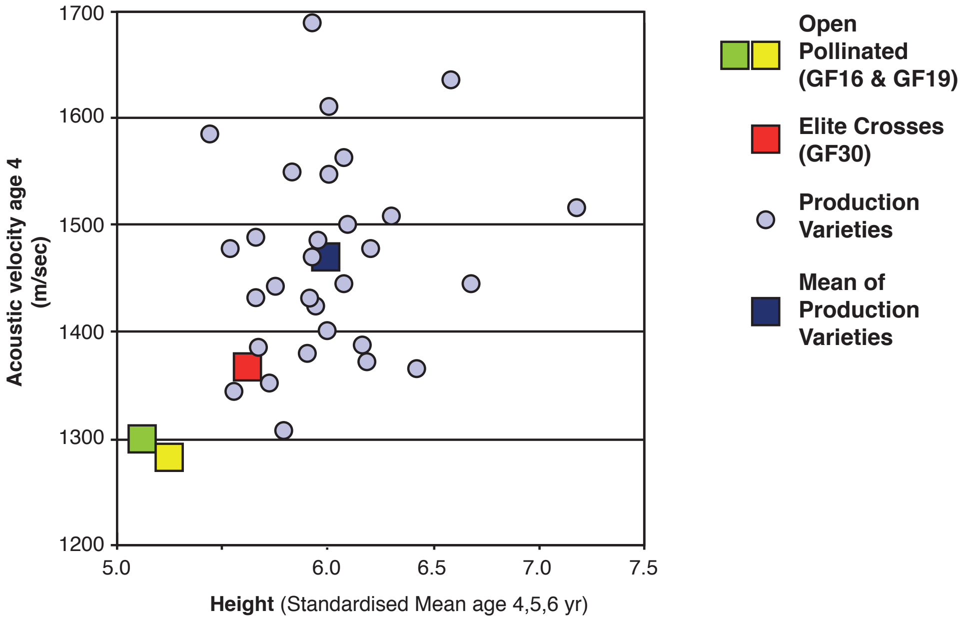
Breeders select above-average individuals for that trait and the difference between the mean of the selected group and the population average is the selection differential. Genetic gain (G) from seed orchards is the product of the selection differential and the narrow sense heritability and is usually expressed as the percentage gain. For clonal selection, G is the product of the selection differential and broad-sense heritability.

For most characters of interest in radiata pine it is appropriate to use reasonably high selection intensities. In the early years (1953–1958), the selection intensity in New Zealand was very high (selecting one tree per 100 ha or 1 in 25 000 from 30-year-old, land-race stands) and produced a relatively small number of plus-trees for potential use in clonal seed orchards (Burdon, Carson and Shelbourne, 2008). In light of selection theory, however, a second cycle of selections of many more plus-trees was made in New Zealand in 1968. These were from 12–18-year-old stands, with the selection intensity reduced to about one tree per 1.2 ha (1 in 400 trees). This was followed by comprehensive progeny testing and further selection.

Genetic gain depends on the availability of moderate to high heritabilities and a useful amount of genetic variation. The heritabilities (Table 6.1) of different traits vary widely for radiata pine. Some characters are highly heritable and large gains can be

FIGURE 6.1

The use of selected clonal varieties can simultaneously improve both acoustic velocity (i.e. wood stiffness) and growth rate



Note: The seed orchard trees from open-pollinated orchards (green and yellow) were inferior to control pollinated seed (red), while the selected clones were often better in both characteristics.
Source: M. Carson, personal communication, 2012 (see also www.forest-genetics.com/pine-trees/pine-trees-pages/tree-performance.aspx)

made through an initial plus-tree selection. Other traits have low heritabilities and it is necessary to test how their progeny perform relative to others to obtain acceptable gains. This is called "backward selection" (because the breeder looks backward to see which parental selections performed best), in contrast to the "forward" direction of a phenotypic selection. The phenotype is simply the sum of the features or traits observed in a tree.

Quantitative tree-breeding, the basics of which were introduced above, should take into account the following complicating and practical factors:

- Simultaneous selection for several traits results in less improvement in any one trait (multitrait selection methods are discussed later).
- The correlation between traits may be positive, negative or nil. For example, it is difficult to select for both long-internode trees and high growth rate in radiata pine or for both high growth rate and wood density (Carson, 1986; Sorrenson, 2007). However, large gains might be made by finding exceptional trees that do not conform to these adverse correlations. Another approach is to develop distinct breeds (or ideotypes) in which particular combinations of traits are emphasized (Carson, 1996).
- In determining heritabilities and gains the assumption is made that the population of trees for which these genetic parameters are estimated produces its seed through random interpollination, and that it has not yet undergone selection. However, this is often not so and may influence the extent of improvement that can be made.
- Site factors can influence the selection process. For example, radiata pine tends to be more malformed on fertile sites, so that selection for low malformation or sweep is easier on such sites. In contrast, the frequency of branch clusters, which is under reasonable genetic control, is less influenced by nutrition but is strongly influenced by the length of the growing season.
- The high cost involved in large-scale testing of the selected material, together with the technical expertise and support to undertake this, may cause the strategies

FIGURE 6.2
Provenance differences: the bark on Monterey trees is thicker and more fissured than that on trees from Guadalupe Island

Monterey provenance

Guadalupe Island provenance

employed to be modified.

- The rate of improvement made in a breeding programme is dependent on the propagation method and the time taken to obtain improved seed. The breeding methods described in the next section illustrate this.

IMPROVEMENT OPTIONS

Provenance selection

Exploitation of provenance variation in radiata pine has been slow, although provenance studies have been made in several countries. There can be large phenotypic differences between provenances (Table 6.2 and Figure 6.2). In Australia and New Zealand, most of the improvement has been by selection and breeding within existing land-race plantations derived from Año Nuevo and Monterey sources (Burdon, 2001). In Spain, Año Nuevo was the main source of genetic material (Aragonés *et al.*, 1997). Tree-breeders have concentrated on improving existing land-race stands because:

- There was a great deal of variability to be exploited in these stands.
- There had already been selection and adaptation towards local conditions called land races (distinctive genotypes adapted to the new habitat).
- Existing stands were thought to be derived from the better provenances.

It was fortunate that the early introductions came from the better provenances and that this gamble paid off. Furthermore, allozyme analysis has indicated that most of the variation within the two native populations (i.e. Año Nuevo and Monterey) is captured in the tree-breeding programmes. Nevertheless, it has been found that Año Nuevo provenances do better in the south of New Zealand, while Monterey is more suited to the north and on phosphorus-deficient soils (Burdon, Carson and Shelbourne, 2008).

However, provenances outside these two main areas may contain valuable traits

TABLE 6.2
Selected provenance differences in radiata pine

Feature	Provenance				
	Año Nuevo	Monterey	Cambria	Guadalupe	Cedros
Needles per fascicle	3	3	3	2	2
Bark thickness	Thin	Thick	Medium	Very thin	Very thin
Inner corewood density (kg per m^3)	325	330	320	360	360
Growth rate*	2	2	2	4	5
Frost tolerance*	1	2	4	3?	5
B deficiency tolerance*	2	2	2	4	5
P deficiency tolerance*	4	1	1	4?	5
Soil salinity tolerance*	3	2	1	5	4
*Dothistroma septospora**	1	1	5	3	5
*Cylaneusma minus**	2	1	5	4	4?
*Sphaeropsis sapinea**	1	1	5	5	4
*Phytopthora cinnamomi**	5	2	1		
*Peridermium harknessii**	3	5	5	1	2

*1–5 scale, with 1 = best, 3 = average and 5 = worst.
Source: Burdon, 2001

that could be incorporated into the gene mix, or certain provenances could be advantageous on some sites (Burdon, 2001; Table 6.2). For example, the Guadalupe Island provenance has a 10 percent higher corewood density and superior straightness compared with other provenances. Although slower-growing and prone to some disease and nutritional disorders, the F1 hybrids show promise. This provenance is now being incorporated into some breeding programmes. In New Zealand, a small amount of seed is produced by control pollination, with selected mainland pollen sources applied to grafted Guadalupe plants. The importance of infusing the Cambria provenance has also been advocated (Gapare *et al.*, 2011). Cambria shows tolerance to phosphate deficiency, *Phytophthora* root rot and soil salinity, and has good stem form. However, it is more susceptible to some other diseases.

There is also interest in crossing radiata pine with *Pinus attenuata* to produce plants suitable for colder climatic conditions.

Mass selection

Mass selection involves choosing trees based on their observable characteristics or phenotype. Some genetic improvement may be obtained by phenotypic selection of superior individuals from stands of radiata pine and the collection of their open-pollinated seed. This is a simple and inexpensive method and has the advantage that improvement is obtained rapidly for characters with high heritability. Note that under this method only one parent of the improved seed is known.

The mass selection method was used in New Zealand and Australia from the early 1960s prior to the availability of orchard-produced seed (Burdon, Carson and Shelbourne, 2008). In New Zealand, seed was generally collected from the best 25 trees per ha, either at felling (felling-select) or by climbing (climbing-select). Small but useful gains in multinodal branch habit, straightness and volume were made by this method (Table 6.3).

TABLE 6.3
Improvement ratings for growth and form for different seedlots, New Zealand

Category	Years	Growth and form rating	GF Plus rating	Percent gain in stem volume	Percentage of acceptable stems
Unselected NZ	To 1962	1		0	45
Climbing select	1968 on	7		5–10	50
Early OP orchards*	ca 1985	14		13–18	65
Later OP orchards**	1988	16		15–20	70
CP orchards	1988	22	20–22	17–30	80
CP orchards	1995	30	23–28	20–32	80

Note: OP = open-pollinated; CP = control-pollinated; * = selected 1950s; rogued; ** = selected 1968; rogued.
Sources: Burdon and Miller, 1992; Burdon, Carson and Shelbourne, 2007; M.J. Carson (personal communication 2012 (for GMplus data)

Advanced breeding strategies

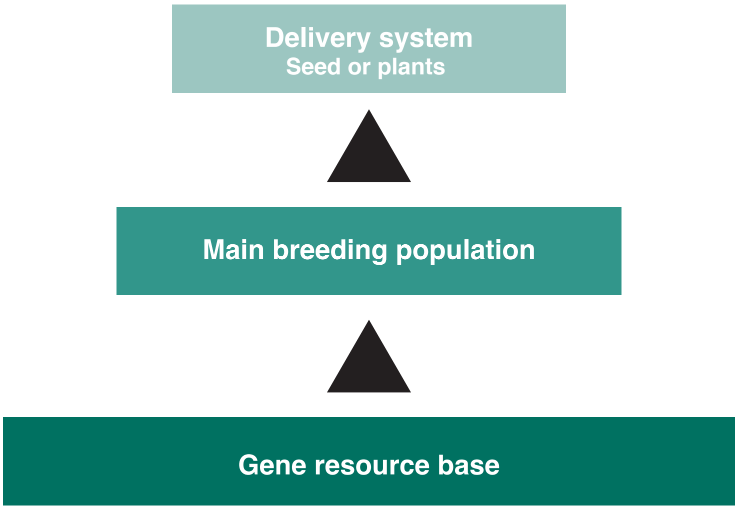
Tree-breeding strategies are devised to meet specific goals but, as discussed above, they can be difficult to define. Furthermore, goals and technology are changing (Box 6.1) and in turn influence the strategy used. Good strategies need to be flexible to allow for changes and should recognize that there is considerable uncertainty and risk. Economics must also be considered.

There are three main components to a strategy:

- organization of populations (the physical component);
- breeding methodology (non-physical design aspects);
- research component (a developmental programme feeding into both of the other two components).

A hierarchy of populations is often recognized (Libby, 1973; Figure 6.3). The base level is the gene resource, which should encompass most of the genetic variability within the species, and the gene conservation population should be managed and regenerated to ensure that a wide genetic base is maintained. For radiata pine, the gene conservation population includes provenances from California, land races and other slightly improved genotypes. The natural stands are an important part of this conservation effort, despite strict precautions on importing new material into most grower countries because of diseases such as pine pitch canker and western gall rust. Rogers (2002; 2004) studied the need for genetic conservation in California, while Gapare *et al.* (2012) reviewed and developed strategies for the *ex situ* conservation and use of these gene resources in Australasia. Fortunately, for major growers of radiata

FIGURE 6.3
The hierarchy of populations



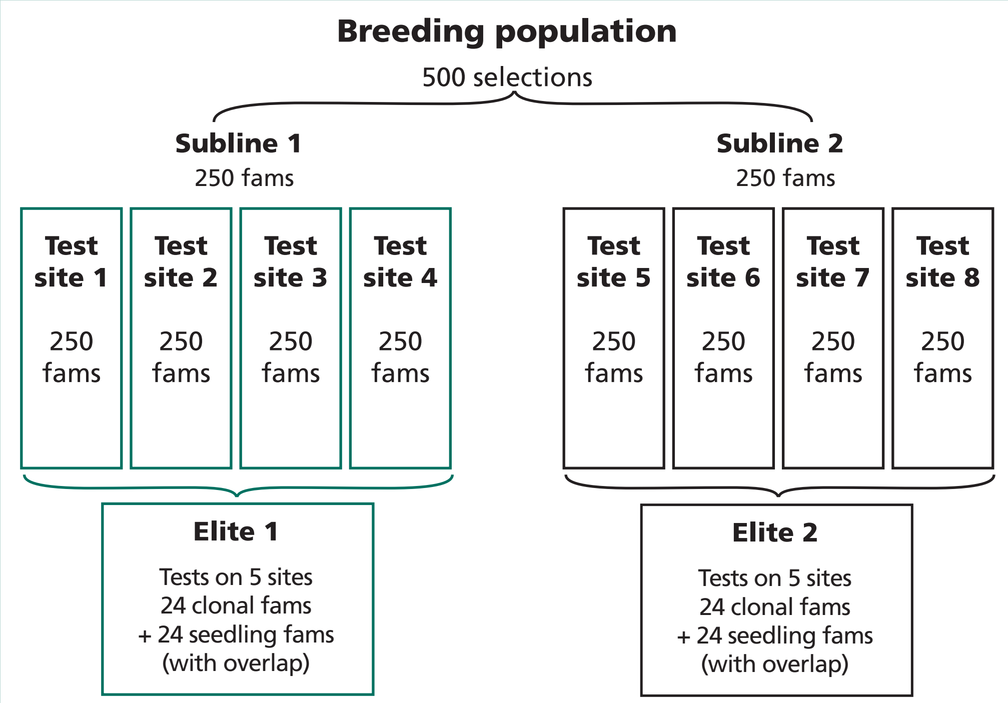
pine, a series of collections was made from the natural stands in California, with a major seed collection in 1978 that is known as the Eldridge collection (Burdon, Carson and Shelbourne, 2008; Gapare *et al.*, 2012). The seed from these stands has been planted at more than 100 sites, mainly in Australasia, including in specific gene resource plantings, and there are plans to ensure that more conservation plantings will be rolled out over time. Seed and pollen are also being kept in long-term storage. This base population can be drawn on to introduce further genetic variability into the breeding programme and perhaps to introduce new characters that are poorly represented in the current breeding population. It may also be viewed as part of the genetic defence against potential threats such as disease.

The breeding population, drawn from the base population, usually has 300–500 parents at any one time. Current plans, for example, suggest there will be 500 parents in the breeding populations of the joint "New Zealand plus New South Wales" breeding programme (Dungey *et al.*, 2009) (see Box 6.2). The Southern Tree Breeding

BOX 6.2

Structure of the joint New Zealand plus New South Wales radiata pine breeding programme

The most recent breeding strategy for radiata pine in New Zealand and New South Wales, Australia, is based on 500 selections which will include the infusion of ten selections from less-represented provenances. This breeding population is subdivided into two independent sublines, each with 250 families (fams). The progeny of these selections will each be tested on four sites, for a total of eight test sites.



On the basis of these progeny tests, an elite group will be selected for each subline. Each elite group will have 24 control-pollinated clonal and 24 seedling families that may overlap and will be tested on five sites. If needed, the sublines or elite groups could be crossed to overcome any inbreeding. Source: Dungey *et al.*, 2009.

Association, based in South Australia, has 340 parents. In the small radiata breeding programme in Galicia, Spain, over 50 trees were selected and have been used in a seed orchard and in progeny tests (Codesido and Fernández-López, 2009).

The breeding population can be divided into sublines representing replicate breeding populations that can, if needed, be crossed to ensure completely outbred offspring (i.e. offspring that are unrelated). This concept has been incorporated into the joint New Zealand plus New South Wales breeding programme, as well as the plans of the Southern Tree Breeding Association (Box 6.2). The Southern Tree Breeding Association is moving from discrete generations of breeding towards a dynamic rolling front, since this will lead to increased gains and efficiencies (Wu *et al.*, 2007). The joint New Zealand plus New South Wales programme keeps discrete generations at the subline level and has a rolling front approach for the elite population (Dungey *et al.*, 2009).

There may be several smaller trait-based subpopulations within each subline to produce specific breeds. In recent years, the New Zealand programme has produced three distinct breeds: a growth and form breed, a long-internode breed for clear-cuttings, and a breed for structural timber (Burdon, Carson and Shelbourne, 2008). At one stage there was a dothistroma-resistant breed, but this is now part of the general breeding programme, along with breeding for resistance to *Cyclaneusma* needle cast. The recent strategy for the joint New Zealand plus New South Wales breeding programme calls for a general elite population within each subline that will test the performance of both control-pollinated clones and seedlings, on a rolling front approach (Dungey *et al.*, 2009; Box 6.2). The Southern Tree Breeding Association has three breeds: multi-purpose, density and growth, and *Phytophthora* resistance (Wu *et al.*, 2007).

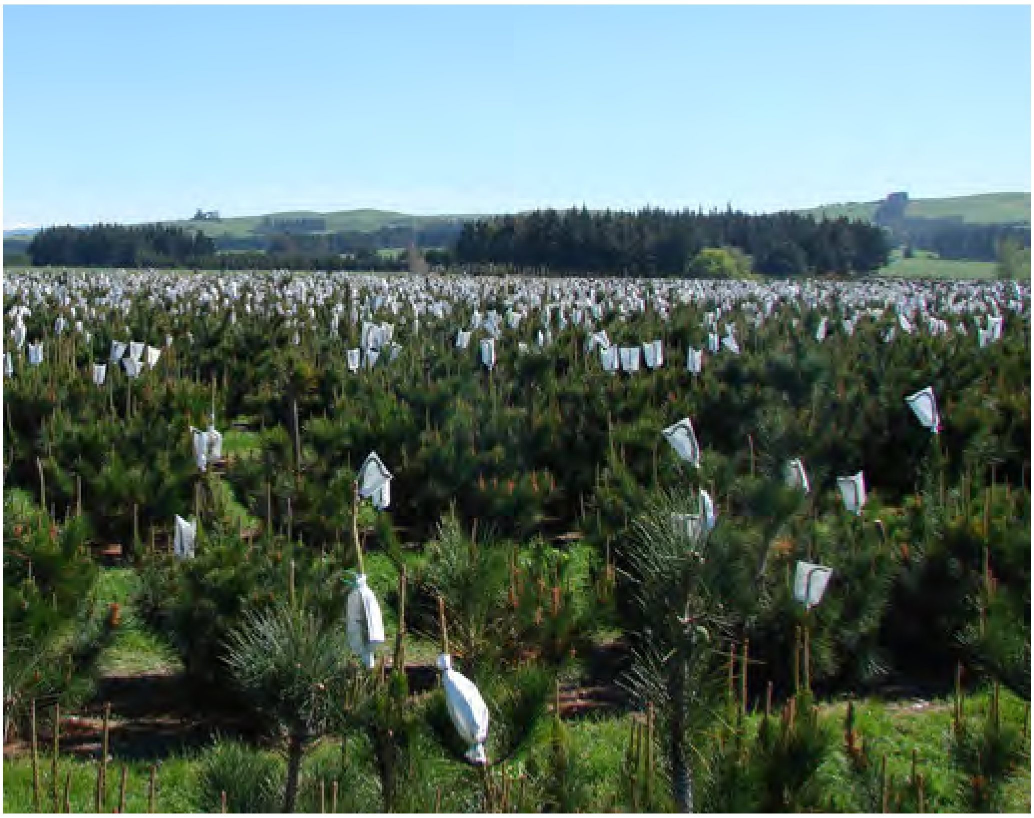
At the top of this hierarchy is the seed-producing or plant-producing population (Figure 6.3). Parents in this population have been selected from the breeding population to form the basis of the seed orchard, or for using other techniques to produce improved planting stock.

The early tree-breeding programmes employed open-pollinated seed orchards using grafts of selected parents (Burdon, Carson and Shelbourne, 2008). Later, on the basis of progeny tests, the worst parents were removed, or new orchards were established on the basis of proven general combining ability. Grafting incompatibility, site limitations and external pollen contamination were often problems with these orchards. These "classical" seed orchards provided large quantities of modestly improved seed (Table 6.3). Open-pollinated seed orchards currently provide about half of the radiata pine seed used in New Zealand, although today the grafted trees are hedged to make it easier to collect cones. The new hedged open-pollinated seed orchards are spaced at 4 m x 2 m and are expected to have a life span of up to 20 years (S. van Ballekom, personal communication, 2012).

The control-pollinated orchard concept was developed in the 1990s. It adopted closer spacing and grafted trees that were maintained in hedged form, enabling operators to carry out controlled pollination at near ground level (Carson, 1986; Burdon, Carson and Shelbourne, 2008). At the Amberley seed orchard in New Zealand, the current practice is to establish twin rows at 1 m x 1.5 m spacing along the rows and a 4 m-wide strip between the twin rows (Figure 6.4; S. van Ballekom, personal communication, 2012). This enables easy access to the grafted plants and assists with orchard maintenance. Flowering is stimulated using gibberellin injections, and dry pollen is applied to the bagged female strobili when they become receptive. In New Zealand, the best seed orchards are close to the sea in areas of high sunshine and low rainfall. Control-pollinated orchards almost double the genetic gain in the progeny compared to open-pollinated orchards but triple the cost of producing seed. Large breeding archives have been established in New Zealand and the application

FIGURE 6.4

Control-pollinated seed orchards at Amberley, New Zealand.



S. van Ballekom

Note: twin rows of trees

of similar procedures to these archive trees is enabling shorter turnover of breeding generations, leading to the prospect of faster genetic gains.

The parallel development of mass production by nursery cuttings, micropropagation and, more recently, somatic embryogenesis (see Chapter 7) has provided new avenues for obtaining planting stock from this greatly improved seed. It is now possible to deploy selected clones to achieve even larger gains and to customize seedlots, clonal mixes and single clonal varieties commercially for specific growers and sites (Carson and Carson, 2011). Current commercial varieties of radiata pine available in New Zealand and Australia show increases of about 25 percent in volume and dry matter production and 30–60 kg per m^3 in basic wood density compared with open-pollinated and control-pollinated seed orchard stock. They also have improved wood stiffness (Figure 6.1).

Other options for deployment have also been suggested (Dungey *et al.*, 2009), such as converting advanced progeny tests into seedling seed orchards after removing less-desirable individuals.

Incorporation of desired traits

The importance of selecting breeding goals, and thus the traits for improvement, has already been stressed. In practice, conflicts may arise over which traits are more important, and methods are also needed to incorporate and evaluate the use of multiple traits.

Selecting traits in tandem (i.e. sequentially, one at a time) has not proved applicable to radiata pine because of the long breeding cycle. However, it can have advantages where traits vary widely in either cost of assessment, optimal age of assessment, or where there are adverse genetic correlations between traits. The use of independent culling levels has also not found general favour, although it has been used to remove breeding parents that are particularly susceptible to a given disease. Tree-breeders have largely used selection indices.

The selection index combines the weights and scores for traits according to economic and genetic data for a candidate tree as well as its family. This method is used by all the main radiata pine growers. The main problems have been:

- determining economic weights, which could change with time or industrial end user;
- variability in the age at which traits can be evaluated (for some, such as growth rates, the older the tree the better);
- adverse genetic correlations, such as, for example, between growth rate and wood density.

Although there have been substantial developments in recent years, the task of incorporating desired traits remains challenging (Burdon, 2008; Burdon, Carson and Shelbourne, 2008; Wu *et al.*, 2007).

Other recent developments

Other developments being actively pursued in radiata pine breeding include the following:

- Techniques have been developed to screen for stiffness and shrinkage in the corewood of radiata pine in trees less than two years of age (Apiolaza, Chauhan and Walker, 2011). This may provide an additional strategy for reducing the problems of poor-quality corewood in radiata pine (see chapters 5 and 9).
- Information management systems are being improved to enable access to data on over 500 000 trees in Australasian radiata pine breeding programmes. New data are continually being generated.
- New statistical tools are enabling improved estimates of breeding values.
- The use of gene markers for identifying quantitative traits is a promising approach to characterizing trees that may allow better selection using fewer progeny trials. They may also help to minimize inbreeding.
- The development of designer trees is a possibility and could lead to greater domestication of radiata pine and enhanced profitability (Carson, 1996; Carson and Carson, 2011).

DOMESTICATION PROGRESS

The native radiata pine stands have evolved in different directions as they adapted to specific sites after becoming isolated from one another. Similarly, the species has adapted rapidly to local conditions when planted in other countries, leading to the creation of local landraces over a period of about 50 years. The finding of induced resistance for pitch pine canker is intriguing and illustrates how radiata pine trees can perhaps adapt to new stresses without going through a sexual phase (see Box 4.2).

Tree-breeders and forest managers have altered the slow natural selection process in order to meet industrial needs. Over the last 60 years, tree-breeders have increased stand productivity and the stem straightness of trees developed from seed provided to growers (Table 6.3). The data presented in Table 6.3 hide the fact that trial results show that average growth rates differ with site and are greater on high-quality sites, and that percentage gains can decrease slightly during the crop rotation (Burdon, Carson and Shelbourne, 2008). Further, as Figure 6.1 and Box 6.1 illustrate, there are considerable additional gains to be made using clones. However, there have been some unintended changes with these breeding programmes, including reductions in wood density and perhaps increased susceptibility to magnesium and insect stresses (Beets *et al.*, 2004; Sorrenson, 2007; Kay, 2008). Burdon (2008) argued that the species is still in the early stages of domestication compared with agricultural crops. He suggested that the use of new vegetative propagation systems, integrating breeding with molecular biology and genetic engineering, to design trees that produce a greater amount of high-quality wood could lead to the further domestication of the species.

Improved silvicultural practices also affect the growth of stands, with the magnitude of gains depending on the limiting factors that are being overcome (Mead, 2005a; see Chapter 10). For example, very large responses are possible from the application of fertilizers to infertile soils, by improving soil rooting depth and through woody-weed control. For particular sites, all these can increase productivity as much as or more than has been achieved by tree-breeding. However, tree-breeding promises further gains with additional research efforts. Overall, doubling the productivity of wild Californian stands is possible in radiata pine plantations (see Chapter 10). This and more has already been achieved in some eucalypt plantations (Mead, 2005a). The domestication of rubber (*Hevea brasiliensis*) increased latex production by 8–10 times, of which 70–80 percent resulted from breeding and the selection of clones and the remainder from husbandry (Webster and Baulkwill, 1989). The success of rubber was also based on a large genetic x husbandry component – to get very high yields, both good clones and good husbandry are required. The integration of tree-breeding with other silviculture practices will also be critical for the full domestication of radiata pine.

7 Producing planting stock

Raising radiata pine plants in nurseries is a vital component of the plantation cycle because direct sowing and natural regeneration are now seldom employed. A range of techniques has been used to raise radiata pine planting stock (Table 7.1). In Australia, New Zealand and Chile, bare-rooted plant production predominates, but container-grown stock is more common in South Africa and Spain. South Africa experimented with bare-rooted stock in the 1970s but has since moved to container stock (Donald *et al.*, 1994); this has also occurred in Western Australia. Micropropagation techniques are gradually becoming more common but currently provide only relatively small numbers of planting stock. Some methods, such as grafting, have been employed for specialist uses such as seed orchards.

Today's nurseries can produce radiata pine plants that will both survive and quickly begin rapid growth. The techniques are firmly based on seedling physiology, including nutrition, a century of practical experience, and more recent technical innovations in sowing, plant conditioning, container design and micropropagation. Further, a systems approach allows nursery and forest managers to integrate silviculture, beginning at the seed source through nurseries to the establishment phase and beyond. It is important that the key people running the nursery have a close association with the plant users and appropriate research scientists who can advise on plant physiology, soils, diseases and other potential problems. The nursery gate should be an administrative boundary, not a silvicultural one.

In this chapter, the terms plants and planting stock are used generically, while the terms seedlings, cuttings and plantlets are used to describe particular types of plants raised in nursery facilities.

THE SYSTEMS APPROACH AND SETTING OBJECTIVES

The integration of the nursery with other parts of the establishment phase and with management in general implies that the nursery is part of a larger structure, making a

TABLE 7.1
Plant types and their key characteristics available for planting ***Pinus radiata***

Type	Characteristics
Direct from seed	
Bare-rooted seedlings	1+0[a] (1.5+0); large scale
(Transplants)	(1+1 – 1+3); infrequent
Container seedlings	Often <1 year; medium to large scale
Vegetative methods	
Grafts	~2 years; special uses only (e.g. seed orchards)
Juvenile cuttings	C1+0[b] year; common; collect from field or nursery stools; often bare-rooted; small to large scale
(Cuttings – old trees)	Special uses only
(Fascicle plantlets)	Started in greenhouse; occasional
Tissue culture / embryogenesis	Laboratory + nursery; often bare-rooted; ~1 year; moderate scale; being developed

Note: a = number of years as a seedling, plus the number of years as a transplant; b = the "C" prefix indicates rooted cuttings; those types in brackets are rarely used on a routine basis.

systems approach vital (Trewin and Cullen, 1985; Toro, 2004). The nursery phase of this larger system should be designed to produce the types and quantities of plants required at the times required. The value of such an approach was demonstrated by South *et al.* (1993), who showed that nursery practices that resulted in greater seedling diameter were less costly than later silvicultural practices, such as weed control, used to obtain the same growth after several years.

A key to the nursery phase is to define the type of plant required. Generally, the main objective is to produce plants that will survive the rigours of being transferred from the nursery to the field as well as the particular site conditions and will grow rapidly after planting. These objectives should be quantative – for example, demanding a minimum one-year survival rate of 90 percent. Such performance objectives then need to be reinterpreted into practical objectives and criteria for raising the plants in a nursery.

Optimum planting stock

For radiata pine, research has established that a number of plant features as well as nursery practices can be used to describe those plants that are likely to have a high chance of survival and rapid initial growth in the field (Table 7.2). They identify the ideotype that should be aimed for and expected by the plantation manager or buyer.

Planting stock height, by itself, is a poor indicator of subsequent performance and there is no advantage associated with plants over 30 cm tall (Menzies *et al.*, 2005). However, for bare-rooted stock, a minimum size of 20 cm is needed to ease handling. Container seedlings are typically smaller than bare-rooted stock (15–25 cm). Tree collar diameter, sturdiness and oven dry weight are better indicators of planting stock quality (Balneaves and Fredric, 1973; Menzies, Holden and Klomp, 2001). While physical measures are useful indicators of underlying physiological conditions, they

TABLE 7.2

Specifications for bare-root radiata pine seedlings and cuttings*

Indicator	Specification	Measuring technique	Achieved by
Root growth potential[a]	4–5 on a 0–5 visual scale	Lift, grow, lift and assess new roots	Wide spacing; regular conditioning; hand-lifting
Fine roots and myorrhizae at lifting[b]	Abundant – some soil on roots (vertically trained, non-spiralling for container stock)	Inspection	Mycorrhizal inoculation; regular conditioning; hand-lifting
Root length	~10 cm	Inspection	Careful trimming
Seedling nutrients	See Table 2.1	Analysis of tops	Fertilizer application
Soil nutrients	See chapters 2 and 7	Soil analyses	Fertilizer application
Water potential[a]	<0.5 Mpa	Pressure bomb	Adequate water before and during lifting; wet and cool storage; careful handling
Height	20–40 cm (15–25 cm for container stock)	Root collar to top	Timing of sowing and undercutting or topping
Diameter[b]	>5 mm (3–5 mm for container stock)	At root collar	Wide spacing; regular conditioning
Sturdiness	40-60	Height/diameter	Wide spacing; regular conditioning
Frost tolerance[a]	-12 °C winter; -6 °C summer	Test using artificial frost rooms	Grow seedlings at high elevation or inland nurseries
Pests or diseases	Absent	Inspection	Control measures

Note: * Height, diameter and root specifications for container stock are also presented; a = used less commonly, although important; b = cuttings should have roots in two or more quadrants and a collar diameter of 8–10 mm.
Sources: Maclaren, 1993; Menzies, Holden and Klomp, 2001.

do not unveil the full story. For example, seedlings of the same diameter, grown at wide seed-bed spacing, outperform those grown close together, presumably because of better root growth potential (Figure 7.1). How plants are grown and handled in the nursery is as important as the physical attributes of seedlings.

Table 7.2 lists tests of whole seedlings, sometimes under controlled conditions, although such tests are not used readily on a day-to-day basis. However, they can be translated into schedules that may be followed in the nursery and that are likely to produce the required type of plant. For example, root growth potential is related to good survival and growth after planting, while the root system needs to be compact and able to be lifted easily. This has been translated into undercutting, wrenching, lifting, root trimming and subsequent handling systems for open-grown plants.

SEED HANDLING

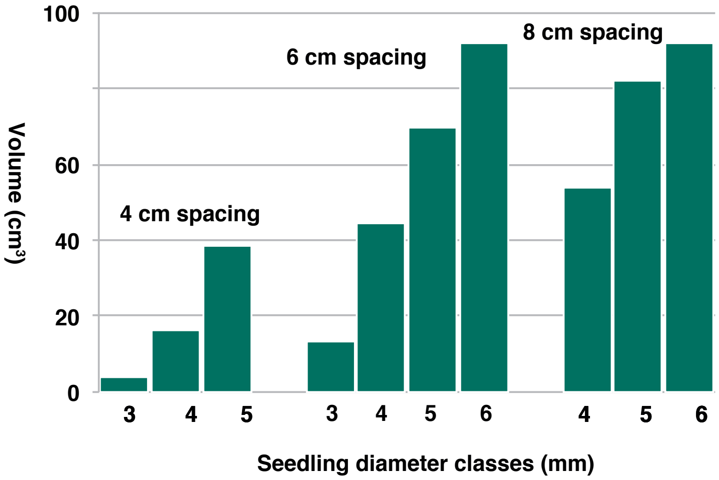
Seed handling in radiata pine is straightforward compared with many other species. The serotinous, prickly, persistent cones are hand-picked with gloves, often with the assistance of a simple tool. If necessary, the cones can be artificially ripened under mild drying conditions, such as in a well-ventilated shed, and can be stored in sacks prior to seed extraction (Rimbawanto, Coolbear and Firth, 1988), although some seed orchards are moving away from this practice. Green cones should not be kept in conditions of high humidity, however.

Cones are generally opened in well-ventilated kilns, solar kilns or glasshouses at 60–65 °C for six hours (Burdon and Miller, 1992). An actual cone temperature of 65 °C for four hours does not decrease viability. This heating breaks the resinous seal between scales and opens the scales enough to release the seeds. After opening, the cones are tumbled to extract the seeds, which, after de-winging, are usually cleaned by air flotation. If required, the seeds can be sorted by size.

The longer the seed has to be stored, the more exacting are the required conditions. The retention of viability is higher at lower temperatures and lower oxygen levels. Radiata pine seeds stored in airtight containers at ambient temperatures (23 °C maximum) will remain viable for several years, provided they do not have a high moisture content (Burdon and Miller, 1992). A seed moisture content of 9 percent is often recommended. Alternatively, keeping the seeds in a vacuum or replacing the oxygen with carbon dioxide or nitrogen will maintain germinating capacity and vigour for a long period. This latter technique has been used in Western Australia. Note that many other species need to be stored at lower temperatures than radiata pine (e.g. 2–3 °C).

FIGURE 7.1

The effects of spacing within the nursery bed and seedling diameters at lifting, on volume index (D^2H) at the end of the first growing season after planting



Source: Adapted from Balneaves and Fredric, 1983

For radiata pine, there are usually 25 000–40 000 seeds per kg, although numbers outside this range have been reported (Burdon and Miller, 1992). Viability is usually in excess of 75 percent; many growers use this figure as a basis for estimating seed requirements, but individual experiences with losses and culling practices should also be taken into account. In the absence of suitable information, it would be reasonable to assume about 15 000 saleable seedlings per kg of seed. About 20 percent of radiata seeds may be expected to show dormancy, meaning that such seeds do not geminate quickly if not stratified.

The traditional stratification procedure has been to soak the seed in water for 24–48 hours (removing the empty seeds, which float), drain and then seal in plastic bags at 2–4 °C for 30–40 days. This treatment breaks the dormancy by simulating what would happen naturally if the seed fell in autumn. Stratification ensures rapid, even and complete germination, although this can be vitiated if the soils dry out or are excessively wet at, or after, sowing. However, most radiata pine growers have found that the coolstore period is unnecessary and now soak the seeds in water for only 24 hours, particularly if they are fresh and have good germination energy (Burdon and Miller, 1992; Escobar, Sanchez and Pereira, 2002). Prior to sowing, seeds may be coated with fungicides or bird repellents.

BARE-ROOTED PLANTING STOCK PRODUCTION

Bare-rooted radiata pine is usually grown as 1+0[1] , sown in spring for planting the following winter, or occasionally as 1½+0 seedlings, sown in autumn (Figure 7.2; Menzies, van Dorsser and Balneaves, 1985; Escobar, Sanchez and Pereira, 2002). To obtain satisfactory seedlings, the nursery manager must pay particular attention to:

- choice of nursery site;
- seed bed preparation;
- seed sowing (both depth and spacing are critical);
- conditioning through root pruning and wrenching;
- soil and nutrient management;
- control of weeds and pests.

Considerable care is required in choosing the nursery site and its layout, as it can make a very large difference to the ease and cost of raising acceptable planting stock (Shepherd, 1986). Important attributes for the nursery site are:

- climate and microclimate – avoid very exposed or frosty sites and ensure there is adequate protection from erosive and desiccating winds. Rainfall and its seasonal pattern are important if irrigation is unavailable;
- topography – reasonably level, ideally with a slight slope (less than 5 degrees) to ensure good water and air drainage;
- the availability of ample water supplies;
- proximity to labour and servicing facilities and other infrastructure such as roads and electric power;
- soil, particularly its physical rather than fertility status – it needs to be capable of withstanding considerable mechanical usage and the weight of tractors in the winter. Well-drained, deep, stone-free, coarse-textured soils such as loamy sands or sandy loams with a silt and clay content of 10–25 percent have the most suitable trafficability, workability and root penetrability. Soils that are alkaline, saline, derived from ultrabasic rock or have other toxicity problems should be avoided. However, some unusual parent materials have proved to be acceptable, such as rhyolitic pumice and peat;
- low risk of erosion (wind and water) or flood;
- no known disease problems, such as *Phytophthora* root rot.

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[1] The two-number system (e.g. 1+0) denotes the number of years in the seedbed followed by the number of years as lined-out plants in the nursery.

FIGURE 7.2

Bare-rooted radiata plants are grown in long raised beds

Note the fallowed area in grass to the left.

The layout of the nursery requires careful planning. The main points to consider are access, the location of buildings, water storage and reticulation facilities, shelter requirements, the length of the beds (usually best at 200 m or more in length; Figure 7.2) and their relation to topography.

Seedbed preparation

Good nursery-bed preparation and forming is necessary to ensure accurate sowing of seed; good conditions for plant growth; the use of specialist machinery; and ease of harvesting. It involves preparing raised seedbeds of fine tilth, ensuring that soil fertility is correct, and controlling weeds or other pathogens.

New or fallowed land has to be ploughed prior to seed-bed preparation (Shepherd, 1986). This is usually carried out the previous autumn to allow the ploughed-in vegetation to break down. All areas will normally require further cultivation, several weeks prior to sowing, in order to produce a fine tilth. A base fertilizer dressing is evenly spread and worked into the top 10–15 cm at about the time of spring cultivation, although it may be delayed to the time of bed formation if slow-release fertilizers are being used.

The raised beds may be formed before sowing, although many nurseries use machinery which both raises the bed and sows the seed in one operation. Nursery beds are raised to about 10 cm to assist drainage and subsequent operations such as undercutting and wrenching. The formed beds are lightly rolled before the seed is sown. On some sites, where weeds are a problem it may pay to allow the seeds to germinate and to spray them before sowing. Soil fumigation before sowing is rarely undertaken and, unless essential, is best avoided as it can kill mycorrhizae.

Seed-sowing

In all the larger radiata pine nurseries, the seed is mechanically drill-sown. The old "Stanhay" drill-sower has been supplanted by vacuum precision drum-sowers developed in New Zealand, as these allow greater control of spacing within the drill row. The vacuum drum-sower produces over 90 percent singles, with an average placement error of less than 1 cm.

The critical factors to control are depth of placement, spacing between seeds, and the timing of sowing (Menzies, van Dorsser and Balneaves, 1985). Depth influences germination percent, bird predation and uniformity. Spacing has a major influence on the morphological characteristics of the seedlings and their subsequent performance in the field. It is important to provide the plants with space to intercept light and to minimize other competition effects. Well-spaced trees are also easier to lift and, because the roots are less intertwined, there is reduced damage to fine root systems and less loss of mycorrhizae. The timing of sowing influences final seedling size.

Sowing depth is usually 5–10 mm for radiata pine, although it may need to be a little deeper in soils where the surface is likely to dry out. Interdrill distances are usually 12–15 cm, and 5–6 cm along the rows (Menzies *et al.*, 2005; Escobar, Sanchez and Pereira, 2002). Autumn-sown seeds are often planted at wider spacing.

Spacing may also be controlled by thinning the nursery beds when the seedlings are 10–20 cm tall or even earlier (Menzies, van Dorsser and Balneaves, 1985). Such culling practices not only allow for higher-than-anticipated germination or where more than one seed has been sown, it also allows for the removal of less desirable seedlings. Some seedlings, perhaps as a result of bird or insect damage, are forked near the ground, and it is easier and cheaper to remove malforms and runts by in-bed culling than at lifting.

A seed covering is sometimes applied over the drill-sown beds to avoid soil cracking and to assist seedling emergence. Pine sawdust works well and is preferred to sand or fine gravel, which can promote damping-off or heat damage in summer (E. Appleton, personal communication, 2012).

Conditioning

The conditioning of bare-rooted plants is aimed at ensuring immediate prolific new root growth after planting, which in turn will help to ensure high survival and rapid initial growth (Menzies, van Dorsser and Balneaves, 1985). Conditioned planting stock is able to withstand the stresses of lifting, transportation, transplanting and mishandling. The development of conditioning techniques is based on understanding the growth habits of the species, including natural conditioning processes, and how various treatments influence conditioning.

In their first year, radiata pine seedlings make most of their height and diameter growth in the latter half of the growing season. Growth (more so height than diameter) slows during autumn and winter, but seedlings do not form a true dormant bud. These changes at the end of the growing season are a result of natural conditioning caused first by a shortening photoperiod, followed by a second stage of acclimatization to lower temperatures and particularly frost. This natural conditioning produces sturdier seedlings, influencing height more than diameter, and varies depending on the climate and latitude of the nursery. With radiata pine, natural conditioning needs to be augmented by the mechanical undercutting, wrenching and topping of seedlings. Some nurseries design their schedules to partly use natural conditioning.

In contrast to many slower-growing evergreen species (e.g. firs, spruces, Douglas fir and podocarps), it is necessary to induce radiata pine to produce fibrous root systems. Thus, mechanical conditioning with radiata pine has a twofold aim: to slow height growth and to produce a more fibrous root system. Before the development of the mechanical techniques described below, radiata pine seedlings were wrenched using spades (Matthews, 1905). Little wrenching is required for those species that produce fibrous root systems or store reserves in their stems and roots (e.g. deciduous trees), apart from undercutting to sever sinker roots.

Three types of operation are involved currently in the mechanical conditioning of radiata pine (Menzies, van Dorsser and Balneaves, 1985; Menzies *et al.*, 2005; Escobar, Sanchez and Pereira, 2002):

- Undercutting – the passing of a reciprocating, horizontal, flat, thin, very sharp blade beneath the seedbed to sever the taproots. Radiata pine is usually undercut at a depth of 5–8 cm when seedlings are about 20 cm tall. The operation is first undertaken prior to the first wrenching. Sometimes if the seedlings are not tall enough or the soil is too dry, the seedlings may first be undercut at a depth greater than 10 cm, and perhaps undercut at a shallower depth only in autumn. This later undercut will also remove any damaged taproots, allowing a new callus to form, which, provided that it is timed right, should allow rapid sinker-root development after planting. In Chile, radiata pine is usually undercut at a depth of 12–15 cm (Escobar, Sanchez and Pereira, 2002).
- Wrenching – the passing of a horizontal, thicker, tilted (at approximately 20 degrees), generally blunt blade beneath the seedbed. This severs any small roots growing below that point, aerates the root zone and encourages fibrous and mycorrhizal root development. Wrenching is repeated at intervals. To avoid bending the taproot, the blade is usually passed just below the undercutting depth and in opposite directions at successive wrenchings.
- Lateral root pruning – the passing of coulters (in preference to vertical knives) between rows of trees to sever lateral roots so as to restrict fibrous root development within a more limited volume of soil. This is often performed at six-week intervals. The concept of boxing involves lateral pruning across as well as along the rows but is not used in practice.

The physiological effects of these operations have been studied intensively and are summarized by Menzies, van Dorsser and Balneaves (1985). The effect of shallow undercutting is to impose a sudden shock, often causing wilting in dry weather. Some nurseries irrigate. Once the plants recover from this shock, the photosynthates are preferentially channelled to the root system, away from the shoot. The growth of both height and diameter slows, although the net effect is a tree with a lower height-to-diameter ratio. Root growth proliferates, particularly if temperatures are above 11–14 °C and if wrenching is also undertaken. Stomatal resistance in the needles is higher than in unwrenched seedlings. Undercutting and wrenching can cause yellowing, which can be corrected by applying nitrogen before and during the conditioning period. Very chlorotic seedlings may stagnate after planting. On planting out, conditioned seedlings are better able to maintain a favourable water balance and to readily absorb nutrients.

The timing of these operations is important. If undercutting or wrenching is done too early, seedlings may not reach a plantable size, as shoot growth slows considerably following the severing of the tap root. If the operations are delayed to autumn, seedlings are unlikely to become conditioned because they are not photosynthesizing rapidly enough and a smaller proportion of the photosynthates are translocated to the roots (e.g. 15 percent instead of 30 percent).

Thus, undercutting and wrenching are performed when the climate is favourable for growth and when there is vigorous height growth (Menzies, van Dorsser and Balneaves, 1985). Undercutting is often initiated to allow 2.5 months of active growing. Thus, the time of sowing needs to be prescribed so that the seedlings reach the desired size for undercutting and to obtain the required size of planting stock. In some circumstances, such as in locations where the growing season is short or larger planting stock is required, there can be advantages in sowing in autumn.

The frequency of wrenching has an influence on the type of planting stock produced (Menzies, van Dorsser and Balneaves, 1985). Wrenching at weekly to biweekly intervals produces stock with a high root/shoot ratio; wrenching less frequently at, say, monthly intervals does not produce as high a ratio but does increase carbohydrate reserves. Very frequent wrenching promotes fine roots at the expense of larger-diameter roots, which can be a disadvantage when planting on very fertile sites (A.R.D. Trewin, personal communication, 2012). Many nurseries wrench at about three-week intervals and some rely on topping seedlings as well. Seedlings can be held in a conditioned state for several months by continued wrenching, if required.

Topping is also practised to control height growth (Menzies, van Dorsser and Balneaves, 1985; Escobar, Sanchez and Pereira, 2002; A.R.D. Trewin, personal communication, 2012). If it has to be done more than once, it is best to top successively downward to final seedling height. Topping has the added benefit that the trees are not so readily browsed after planting.

Thus, the nursery operator is able to manipulate the type of plant stock being raised. Moreover, the type of plant produced and the way it is planted are related. Conditioning by wrenching can be reduced, but not eliminated, to encourage larger roots when trees are planted deeply using the positive pull-up technique (see Chapter 8; A.R.D. Trewin, personal communication, 2012). Together, they may result in greater tree stability.

Soil and nutrient management

Growing bare-rooted planting stock places considerable stress on the nursery site because nutrients, together with some soil adhering to the roots, are removed with each crop. Soil organic matter also decreases over time, and this, together with the use of machines, may degrade the soil structure and nutrient buffering capacity. Considerable care is therefore required to ensure that crops do not suffer from nutrient stress and that the soil structure does not deteriorate.

The basic principles of nutrient management, outlined in Chapter 10, also apply in nurseries. In nurseries, the role of nutrient cycling is minimal, except where cover crops or organic matter are deliberately used in a fallow phase. However, removed nutrients need to be replaced. Another major difference is that the annual nutrient demand is high (Table 7.3), although the uptake of added fertilizer is higher than that often observed in plantations. Studies in Victoria, Australia, found that, in nurseries, seedlings used 27–46, 4–8 and 32–41 percent of the fertilizer-applied nitrogen, phosphorus and potassium, respectively (Hopmans and Flinn, 1983). Knight (1978a) suggested that the total application of fertilizers needed to be 2–3 times the actual removal for nitrogen and potassium and about ten times for phosphorus.

Usually, nitrogen, phosphorus and potassium need to be applied to each crop, and on some sites magnesium and some micronutrients will be required as well. In New Zealand, for example, foliar-applied boron is sometimes used because it promotes root growth and is a common forest deficiency (E. Appleton, personal communication, 2012). Usually, the trees will receive enough calcium and sulphur from the soil or from the fertilizers used to supply other nutrients.

TABLE 7.3

Mean nutrient content in open-grown seedlings, at lifting

Age class	Height	Diameter	Dry weight	N	P	K	Mg	Ca
	cm	mm	kg per 1 000 seedlings	grams per 1 000 seedlings				
1/0	34	59	10	120	13	75	7	28
1½/0	49	86	24	278	32	151	17	81
			tonnes per ha	kg per ha				
1/0	34	59	4.3	52	6	33	3	14
1½/0	49	86	9.6	100	12	54	6	31

Note: Data are reported in two ways (per 1 000 plants and per ha). There was considerable variability between the nurseries sampled. See Knight (1978b) and Hopmans and Flinn (1983) for further details.

Generally, fertilizer applications are split into two distinct phases:

- Pre-sowing applications (so-called basal dressings) – this will often include those nutrients or forms of nutrients that are unlikely to be lost in leaching and that will be available over a significant proportion of the growing season; the objective is to top up the soil reserves. The use of soil tests is valuable in this phase. In New Zealand and Chile, a common procedure is to apply superphosphate (phosphorus and its secondary nutrients, sulphur and calcium), and perhaps other slower-acting and inexpensive fertilizers such as calcined magnesite (for magnesium) and lime (to correct pH), on the basis of soil tests (Knight, 1978a; Menzies *et al.*, 2005; Escobar, Sanchez and Pereira, 2002). Some nurseries in Australia have opted for the more costly alternative of applying specially formulated, slower-release, balanced fertilizers. In both cases, rates are fairly high and the fertilizer is mixed into the top 10–15 cm of the soil, allowing sufficient time (up to one month) prior to sowing to avoid injury to the germinating seedlings from high concentrations of dissolved fertilizer.
- Maintenance dressings – as the crop develops, the demand for nutrients increases so that additional nutrients are normally needed. Usually, the more soluble nutrients are required most frequently. To ensure the balanced nutrition of the growing crop and to counter the depletion of the soil nutrient capital, multi-nutrient, granulated fertilizers are often applied to the soil surface between rows (Knight, 1978a; Menzies *et al.*, 2005; Escobar, Sanchez and Pereira, 2002). Many nurseries apply 2–4 side dressings. Foliar applications of liquid fertilizers may also be used. Fertilizer rates are adjusted as the plants develop.

Foliar analysis is seldom used on a regular basis for prescribing maintenance dressings because of the delay in getting results, although they are used when a nutrient problem appears. Rather, maintenance dressings are prescribed on the basis of anticipated nutrient demand, the careful observation of the crop (colour, uniformity and rate of growth, etc.), the limitations of the application technique, and, for soluble and liquid fertilizers, the advisability of erring on the "sparing" rather than "generous" side. The symptoms of nutrient deficiencies in seedlings are described in detail by Will (1985); see also Table 2.1. The nutrient status of seedlings may affect their drought resistance and survival (Knight, 1978a).

Soil management also involves caring for organic matter and soil physical condition. The two are linked, because humic materials produced by the microbial breakdown of organic matter influence the stability of soil pores and soil structure. The workability of heavier soils, with higher clay content, is very dependent on their structure – a friable structure is important for good aeration, water movement and root development and penetration. Soil organic matter is also a store for nutrients and has, like many minerals, cation-exchange properties that prevent the leaching of cations while allowing them to be available for plant uptake. Sandy soils, which are often used in nurseries, are heavily dependent on this property of organic matter.

Continuous planting-stock production usually leads to the depletion of humus through increased organic matter oxidation brought about by tillage and the lack of return of crop resides. Thus, an essential part of good soil management involves maintaining adequate levels of organic matter. Although soils with very low organic matter status can be managed successfully through the careful use of chemical fertilizers and skilled cultivation, it is easier to maintain a high level of productivity in soils richer in organic matter. The risk of crop failure is reduced if a good level of organic matter is maintained.

The nursery manager therefore needs to accept that extended periods of cropping will lead to the deterioration of the soil's physical condition. Adding organic wastes may not be feasible for some nurseries and can pose other problems (Shepherd, 1986). The usual policy is to take all practical measures to conserve soil structure and rejuvenate areas at regular intervals using restorative crops (Figure 7.2).

Practical conservation measures include:

- reducing tillage – weedicides rather than cultivation may have a role;
- the use of surface mulches to prevent damage of aggregates by intense rains and to minimize erosion – mulches also have other advantages, such as reducing moisture loss, frost heave and crusting;
- avoiding unnecessary machinery traffic and resulting compaction;
- cultivating when soil conditions are optimal;
- keeping the exposure of soil to erosion and leaching to a minimum;
- using windbreaks to prevent wind erosion;
- controlling pH –decomposition may be too slow in very acid soils but too rapid in near-neutral conditions;
- maintaining nutrient levels that will promote root growth and consequently assist pore formation in the soil.

The soil structure may be rejuvenated by resting fallow areas for extended periods (2–3 years, at a minimum) under a perennial grassland such as a ryegrass–clover sward. Regular mowing is required to increase the litter cycle, promote fine root growth and sustain the associated legume. Fertilizers, particularly phosphate, may be required. While helpful, the use of annual green crops that are ploughed in, and the addition of off-site organic matter, are not always as good as pasture (Shepherd, 1986). However, New Zealand nurseries established on heavier soils have successfully rotary-hoed 5–8 cm of composted pine bark into seedbeds at the time of the application of the basal fertilizer over several decades (E. Appleton, personal communication, 2012). Deep ripping can also be used to improve drainage on heavy soils.

Mycorrhizae

Ectotropic mycorrhizae benefit radiata pine by aiding nutrient uptake, decreasing the effects of soil toxicity, deterring root pathogens, increasing drought resistance and improving soil structure (see Chapter 2; Shepherd, 1986; Madgwick, 1994; Duñabeitia *et al.*, 2004). The lack of mycorrhizae in a nursery can be seen soon after germination and is most common when a new nursery area is brought into production or after soil sterilization. The seedlings do not develop at the normal rate and often appear to be suffering from acute phosphate deficiency. At a later stage, when there may have been some fortuitous inoculation, nursery beds may show very uneven growth, with patches of healthy and unhealthy seedlings. An inspection of the root systems will quickly show if a lack of mycorrhizae is the problem.

There are four main methods for introducing mycorrhizae, but some are preferred over others:

- Soil or duff inoculation – with this traditional method, surface soil and raw humus are collected from established plantations and incorporated into the surface of the seed beds. In this method there is no control over the mycorrhizal species and there is a risk of introducing pathogens. Transport costs can be high.
- Planting mycorrhizal seedlings – planting infected seedlings at 1–2 m intervals a year or two prior to raising a crop has been found to be reliable. There is a lower risk of introducing disease, but there is unlikely to be good control over the strain of mycorrhizae introduced.
- Spores and fruiting bodies – common ectomycorrhizal fungi produce readily identifiable sporocarps (fruiting bodies) that can be collected from other nurseries or from plantations and their basidiospores extracted. This technique is a big improvement over the first two techniques because the species of fungus can be chosen, the spores are readily stored from one year to the next and the amount of material required is small. Seeds may be inoculated prior to sowing if no fungicide is used, or the beds may be inoculated shortly after seed germination.

- Pure cultures of vegetative mycelia – mycelia inoculation has the advantages of being free from contaminants and mycorrhizae are formed sooner and in greater numbers compared with the use of basidiospores. The mycelia can also be supplied in the desired species or strain. Despite these advantages, however, this technique has not been widely adopted for radiata pine because it requires specialized cultural and laboratory techniques. There are sometimes difficulties in obtaining pure cultures, or they may grow slowly in medium and there can be logistical problems associated with incorporating the considerable volume of moist-inert carrier, such as vermiculate, in the soil. Liquid application of cultures has proved to be as good as solid applications and better than spores, at least for some species of mycorrhizae (Chávez, Pereira and Machuca, 2009). To obtain the real advantages of this technique, species and strains need be selected for their efficiency and their ability to compete with other mycorrhizae and fungi.

Irrigation

Many nurseries have irrigation systems, particularly where rainfall is unreliable or where greater flexibility is required (Shepherd, 1986; Escobar, Sanchez and Pereira, 2002). Adequate soil moisture is important for sustained plant growth and stock uniformity. There are also a number of critical points in the nursery cycle at which it is very useful to have irrigation, such as during and immediately after germination when the seedlings are very susceptible to drought, and at wrenching, when the plants are susceptible to moisture stress. Nutrients and some pesticides may be applied through irrigation systems. Irrigation can also be used to control wind erosion.

Irrigation systems need to be able to apply the right amount of water at the right rate and uniformly across beds. At times, too much water can be just as harmful as too little, for example by promoting damping off or causing excessive nutrient leaching.

Control of nursery weeds, diseases and pests

Weed control is important for ensuring high, uniform growth rates. Weeds compete strongly for moisture, nutrients and light. Modern nursery practice relies largely on the use of chemical weedicides rather than on hand or mechanical weeding (South, 1995). However, where labour is cheap, hand-weeding is frequently used, and many nursery managers will hand-weed if the problem is minor or where there are difficult weeds. It is essential that weedicide-resistant weed species are hand-weeded before flowering and seeding. Failure to do this can cause a rapid build-up of the weed and make them difficult to control.

Weedicides used in radiata nurseries can be categorized into three broad groups depending on their use:

- those that assist in the breaking in of new or fallowed areas, for example where a major objective is to reduce the weed seed population;
- those used in pre-emergence weed control – applied after sowing and aimed at a broad spectrum of germinating weeds;
- those used in post-emergence weed control – these are more selective and can be applied over seedlings when weeds are small and easy to kill and before they have seeded or pose significant competition.

Weedicide schedules vary according to the weeds being controlled, soil type and climatic condition. South (1995), Escobar, Sanchez and Pereira (2002) and Menzies *et al.* (2005) list the common nursery weedicides used in radiata pine-growing countries. It is important to consider the potential contamination of groundwater by weedicides, as well as their mammalian toxicity. Glyphosate is frequently used as a knockdown weedicide applied prior to seed germination. Propazine and oxyfluorfen are pre-emergence sprays that prevent weeds from becoming established.

The following pest insects and diseases occur in some radiata pine nurseries: thrips, *Colletotrichum acutatum* (terminal crook disease), *Sphaeropsis sapinea* (diplodia), *Dothistroma pini* and various *Botrytis*, *Fusarium* and *Phytophthora* species. These are usually controlled by improved hygiene, applying chemicals and quarantining. Recent research using selected *Trichoderma* and *Bacillus* isolates as biological controls have demonstrated increased seedling growth in the presence of some nursery diseases (Hill *et al.*, 2007; Donoso, Lobos and Rojas, 2008; Regliński *et al.*, 2012). These new techniques have the potential to reduce the use of fungicides. In Spain, nurseries are required to obtain health certificates (Fernández and Sarmiento, 2004).

VEGETATIVE PROPAGATION TECHNIQUES

Vegetative propagules – created either by cuttings or micropropagation – have been used at a large scale since the late 1980s (Table 7.1). Vegetatively produced trees have some different characteristics to seedlings, with these differences increasing with physiological age (Table 7.4). Thus, differences are greatest with cuttings from field-grown trees over five years old compared with those from stool beds and from micropropagation.

TABLE 7.4
Characteristics of cuttings compared with seedlings of *Pinus radiata*

Aspect/factor	Characteristics
Morphology	• Appreciable maturation reflecting the length along the stem axis from the seedling collar, although many comparisons quote tree (ortet) age • An earlier shift to produce sealed buds • Thinner, smoother bark • Greater apical control • Straighter stems, including less butt sweep • Improved branch habit such as fewer, smaller branches (or smaller branch mean basal area) with flatter branch angles • Less malformation • Less stem taper • Larger root systems, although rooting ability decreases with ortet age
Growth	• Reduced height and diameter growth (although not necessarily underbark diameter) if cuttings are taken from older trees • Reduced volume growth under bark with ramets older than 4 years (19 percent for ramets aged 5 years), and becoming more marked with ramets from older trees • Improved stand uniformity
Silvicultural aspects	• Differences in disease incidence has been reported, including less dothistroma and more *Armillaria* root rot • Sometimes increased susceptibility to browsing • Increased ability to withstand droughts, cold and wind • faster pruning
Use	• Changes in intrinsic wood properties – lower wood density and increased spiral grain and tracheid length from older ortets • Smaller knots • Stem cones form lower on the bole, but seedlings have more places to produce cones once this begins to occur • Increased log value has been reported based on sawing studies

Note: Most characteristics are more pronounced with older ortets and are reduced where the physiological age differences are small

Cuttings have been grown widely as bare-rooted plants, although they can also be grown in containers (Menzies *et al.*, 2005; Escobar, Sanchez and Pereira, 2002). In New Zealand, Chile and Australia, over half the production of radiata plants is obtained using cuttings, and some nurseries no longer grow many seedlings. Cuttings are not widely used in Western Australia, South Africa or Spain. Micropropagated plantlets may also be on-grown as open grown stock.

For large-scale production, cuttings are restricted to trees under four years of age (Escobar, Sanchez and Pereira, 2002; Menzies *et al.*, 2005). Shoot-tip cuttings may be taken from healthy, lateral branches of trees in the field or from stool beds in the nursery. The latter are seedlings grown at wide spacings (approximately 50 cm between plants) using the very best seeds – indeed, a major objective has been to multiply scarce, high-value seed or plantlets resulting from somatic embryogenesis. The mother stool plants are topped in midsummer just above the top side shoot (about 15 cm) and the first cuttings are taken in winter (May through July in the Southern Hemisphere). Subsequently, the stool plants are topped from October to November to form bushy plants. Nutrient, weedicide and pest-control practices are followed as for normal seedlings. These stools may be used for up to five years; as they become bushy, the number of cuttings per stool increases to typically about 40 per plant from a three-year-old stool. The hedging of stool plants slows their maturity, so that cutting material from four-year-old plants is similar to 1.5–2.5 year-old field material.

The size of cuttings varies. Typically those taken from field trees are 10–15 cm long, with a basal diameter of 6 mm or greater (Menzies *et al.*, 2005). Stool cuttings are usually 7–10 cm long, with a basal diameter of 3 mm or more. According to Escobar, Sanchez and Pereira (2002), the ideal cutting for growing as bare-rooted nursery stock is 12 cm long and 4 mm in diameter. Cuttings are planted directly into normal nursery beds in winter without hormone treatment. Setting spacing is wider than that used for seedlings. Beds need to be irrigated and should not be allowed to dry out; shade or shelter cloth is often used (Figure 7.3). After setting, cuttings often show signs of

FIGURE 7.3

Cuttings of radiata pine from stool beds set directly into beds and protected by plastic covers

wilting; rooting and top growth begin in the spring. In New Zealand, magnesium–ammonium–phosphate fertilizer, applied prior to setting, has proved to be preferable to normal fertilizers; other fertilizers are also applied during the growing season. After the trees are about 20 cm in height they are conditioned in the same way as seedlings, although this conditioning process has been modified in Chile (Escobar, Sanchez and Pereira, 2002). This generally results in satisfactory large-diameter planting stock with good root systems (Figure 7.4). The cost to produce cuttings is higher than it is for seedlings but when they are used to multiply control-pollinated seed there are large savings (Menzies, Holden and Klomp, 2001).

Short fascicle cuttings (5–15 mm long with a basal diameter of >2 mm) may also be rooted, but because of their size it is usual to root them under mist in a greenhouse. It has been possible to root short-fascicle cuttings throughout the year, although greater success has been achieved with those rooted in summer. After rooting, fascicle cuttings may be lined out in beds and grown as bare-rooted stock or in containers. The multiplication rate for fascicle cuttings is higher than for cuttings from stool beds but the cost is also higher. Fascicle cuttings are not used on a routine basis.

In tissue culture, undifferentiated embryonic tissue is multiplied in sterile culture in laboratory conditions (Gleed, 1993; Hargreaves and Menzies, 2007). Subsequently, the unrooted plantlets are transferred out of the sterile conditions into misted greenhouses for three months, where they develop roots and adjust to non-sterile conditions. Finally, the plants may be transferred to the nursery for the production of bare-rooted or container stock. They are often used as stools for cuttings.

With somatic embryogenesis (Figure 7.5), the selected genetic material is held at very cold temperatures (-140 °C to -196 °C) for long periods to overcome the inevitable physiological aging that continues to occur with tissue culture. Holding the material this way gives time for the specific crosses to be field-tested before multiplication (Figure 7.6). Details on radiata pine somatic embryogenesis can be found in Klimaszewska *et al.* (2007) and Hargreaves and Menzies (2007). Smith (1999) suggested

FIGURE 7.4

One-year-old cuttings with a good diameter stem and a vigorous root system with mycorrhizae

FIGURE 7.5

Somatic embryogenesis plants in a misted greenhouse in Chile before being on-grown

that it may be possible to rejuvenate tissue taken from older trees, but this is yet to be confirmed.

Both micropropagation and somatic embryogenesis allow high multiplication rates of valuable genetic material, but capital and production costs are relatively high compared with seedlings and normal cuttings. Plant costs reflect this, but even so the economic advantages are large (Smith, 1999; Carson and Carson, 2011).

CONTAINER PLANTS

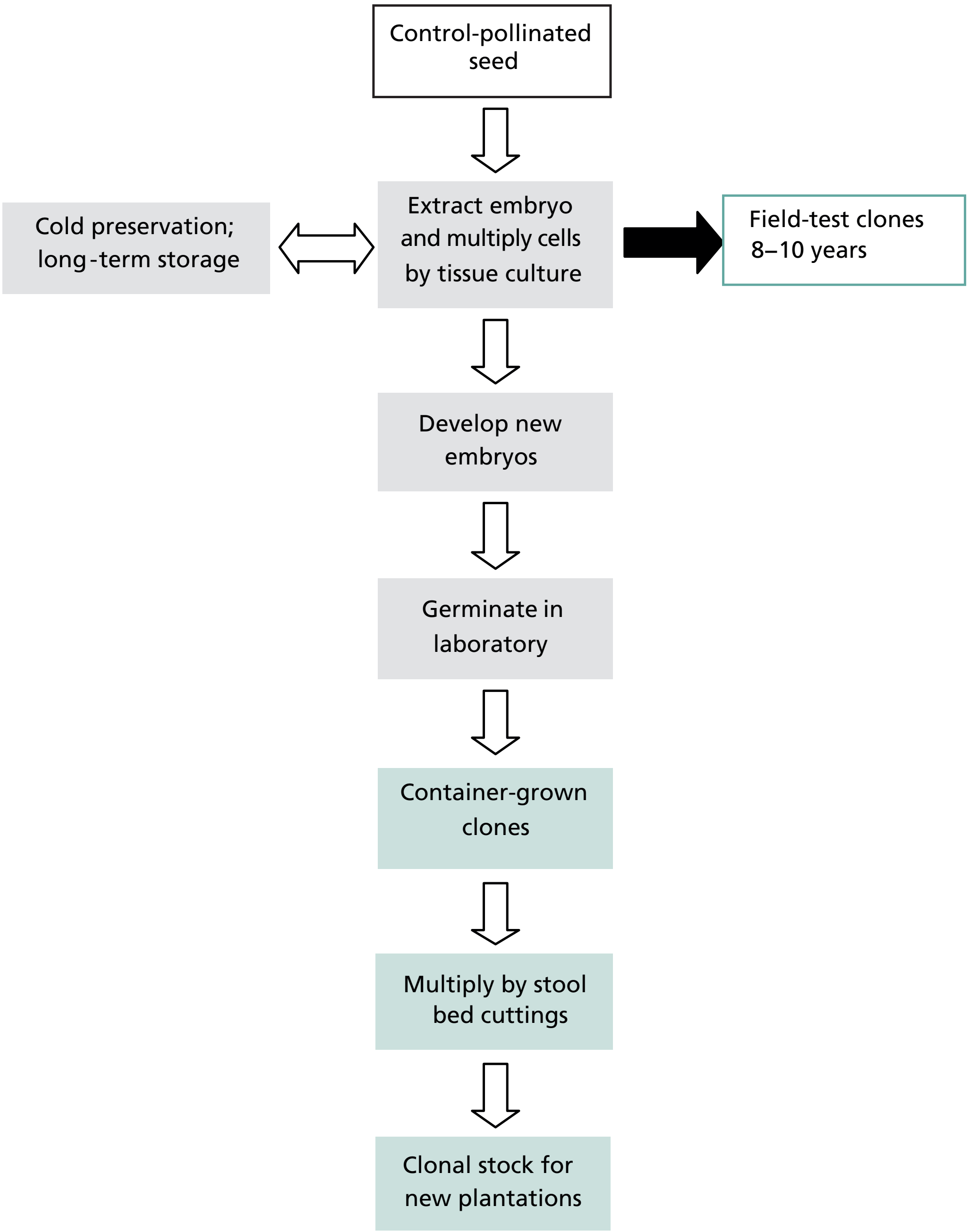
Seedlings, cuttings and tissue culture plantlets may be produced in containers, a practice that is increasingly common in most radiata pine-growing countries. The cited advantages with containers are that they:

- allow slightly quicker production of planting stock;
- possibly extend the planting season;
- may show less transplanting stress and higher survival rates;
- overcome difficulties in obtaining and maintaining sites for bare-rooted nurseries;
- are compact in nature and can easily be mechanized;
- allow the setting of smaller vegetative propagules (1–5 cm long).

The methods are similar to those used for many other tree species. Most growers use polyethylene trays and, for seedlings, sow directly into these rather than pricking out after germination. Where polystyrene trays are used, copper hydroxide paint is needed to prevent roots from binding with them. Container sizes vary between countries, from 80 cm^3 to over 200 cm^3 (Donald *et al.*, 1994; Escobar, Sanchez and Pereira, 2002; Menzies *et al.*, 2005; Ortega *et al.*, 2006). Minimal container depth should be 10 cm. Cells should be tapered, ribbed or have vertical slots to prevent root spiralling, and drainage holes are needed in the bottom to ensure the air pruning of roots. For air pruning, the trays are put on benches (Figure 7.7). There is a good relationship between container size and size of planting stock, and ideally plants should have a diameter of 3 mm or more and not be too tall (Table 7.2).

Potting mixes should have good aeration, readily hold moisture and produce a stable root plug. Thus, many mixtures include peat, composted pine bark, perlite,

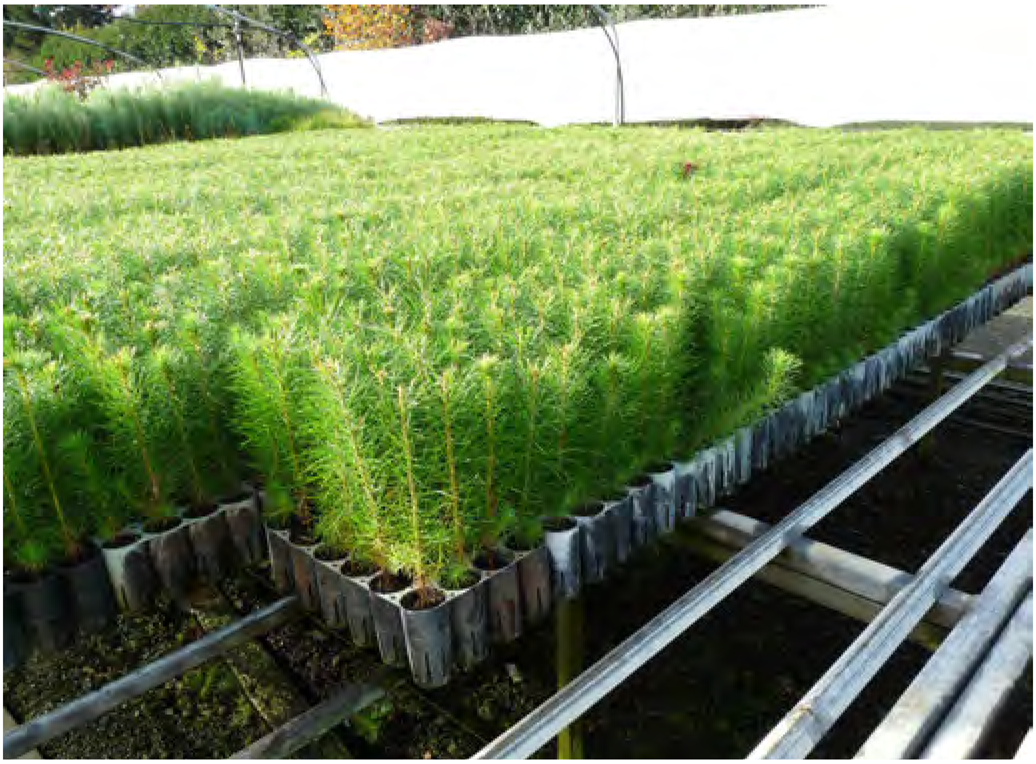
FIGURE 7.6
Typical flowchart of growing clones of radiata pine, starting from control-pollinated seed, through laboratory multiplication and storage to nursery



Note: The stage of laboratory multiplication and storage is depicted in grey and the nursery stage in green. The field test of clones is produced by the same laboratory/nursery system.
Source: Carson and Carson (2011)

vermiculite and pumice in various combinations. Actual potting mixes depend on local sources of suitable material. Composted pulverized pine bark is frequently a major component. Temperatures should reach 65 °C during composting to ensure sterilization (Donald *et al.*, 1994). Slow-release fertilizers are often added to the mix, but additional fertilizers are usually required during the growing season and this may be applied in liquid form. Mycorrhizal inoculation is important (Martinez-Amores, Valdes and Quintosz, 1991; Donald *et al.*, 1994; Escobar, Sanchez and Pereira, 2002). Hardening off is usually done by reducing nutrients and/or irrigation. Machines can be used to assist with filling pots, sowing seed, etc.

FIGURE 7.7
Container grown radiata pine employing air-pruning of roots



Sometimes, small plantlets are started on benches in greenhouses, for example with bottom heat, and subsequently moved outdoors to harden off. In other cases they are grown on raised frames covered with shade. Irrigation is carried out by misting or travelling booms.

PACKAGING AND TRANSPORT OF PLANTING STOCK

The handling and transport of planting stock between the nursery and planting sites should be done quickly and with care. An integrated system ensures:

- minimal handling;
- minimal time between lifting or removal from containers and planting;
- no crushing of the planting stock;
- minimal damage to root systems;
- root systems that are not deformed and are easy to plant;
- capacity to store under cool, humid conditions;
- application of careful planting techniques.

Trewin and Cullen (1985) described the following integrated system for bare-rooted stock in New Zealand:

- in-bed culling of precision-spaced plants to avoid handling at lifting;
- conditioning, as this overcomes planting shock;
- soil loosening by wrenching prior to lifting;
- lifting by hand or machine directly into cartons with the plants laid horizontally (Figure 7.8);
- avoiding root damage or loss of mycorrhizae;
- trimming off roots longer than 10 cm using sharp shears (Figure 7.9);
- closing boxes quickly and placing them in insulated crates;
- storing the boxes in a cool store if they are not going directly to a planting site;
- checking the quality of plants before planting;
- avoiding long storage in the field;
- planting the stock directly from the carton.

FIGURE 7.8
Bare-rooted stock lifted and placed horizontally into boxes

Note: The forest planters take the seedlings direct from these boxes to minimize handling.

Roots may be moistened after lifting in New Zealand, while they are often sprayed with a hydrogel to help maintain moisture in Australia and Chile. However, in dry weather it is often preferable to water the nursery beds the evening before lifting so the trees are fully hydrated and roots retain damp soil particles (A.R.D Trewin, personal communication, 2012). Moisture pads placed over the top layer of the stock in the planting box can also reduce desiccation. Refrigerated trucks are used occasionally to transport stock from the nursery to the field (Escobar, Sanchez and Pereira, 2002).

Container stock may be transported directly to the site in trays. Alternatively, they can be removed from the containers in the nursery and laid on their side in boxes – and thereafter handled much like bare-root stock.

SYNTHESIS AND TRENDS

Based firmly on basic and applied research, *Pinus radiata* plant propagation and breeding has evolved rapidly in the past 40 years, and with recent developments in biotechnology is moving into a new phase. The implications of these recent developments are only beginning to emerge, but it is clear that they offer radiata pine managers improved flexibility, higher production and further economic gains.

Nursery techniques have developed to the point where there is confidence in how to produce and handle both bare-rooted and containerized stock. However, more research on defining and improving the quality of container stock has been advocated, as it is expensive to raise large stock in containers (Menzies, Holden and Klomp, 2001). Recently developed micropropagation techniques, which interact closely with tree-breeding and the need to improve wood quality and crop protection, may lead to the greater use of containerized stock. However, transgenic plants are unlikely to be used widely in the near future because of possible environmental risks, consumer resistance and prohibition by FSC certification.

Research and development on mycorrhizae and other fungi or bacteria to compete with soil pathogens will have an impact on nursery techniques and forest management. There will be continued emphasis, moreover, on integrating the growing of radiata pine from seed orchards through nurseries, to field establishment and silviculture, and ultimately to the production of marketable products.

FIGURE 7.9

Trimming the roots to 10 cm length

Note that shears have been used to cleanly cut this bundle of radiata pine seedlings

8 Establishment and early tending

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

ESTABLISHMENT PLANNING

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

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

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

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

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

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

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

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

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

FIGURE 8.1

Factors affecting the stand at the end of the establishment period

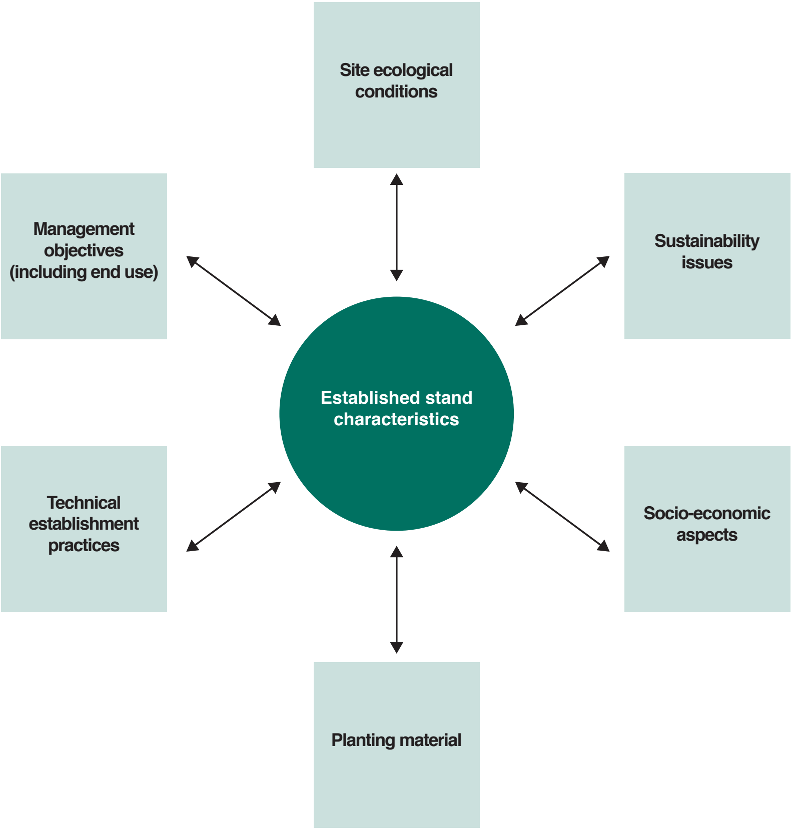


TABLE 8.1
Steps in the establishment planning process

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

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

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

THE BIOLOGICAL LIMITS TO EARLY GROWTH

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

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

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

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

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

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

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

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

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

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

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

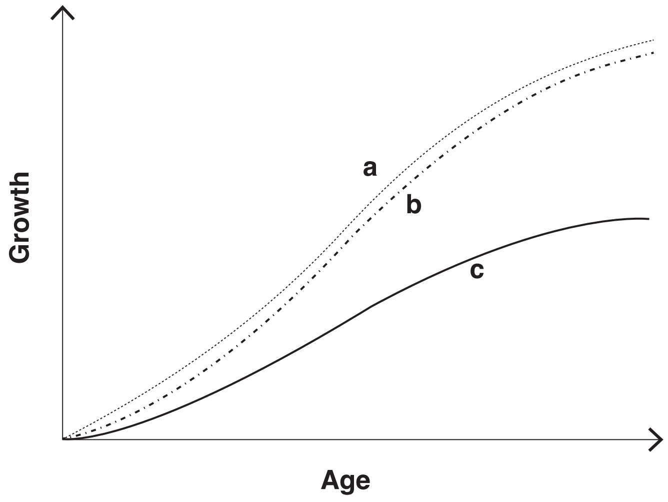
Source: Nambiar, 1990

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

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

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

FIGURE 8.2
Growth responses to silvicultural treatments



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

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

SITE PREPARATION PRINCIPLES

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

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

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

Other general concepts are to:

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

trees that require subsequent higher management costs, or they may result in substantially lower final returns;

- achieve well-stocked, uniform stands at the first attempt, making future silvicultural operations easier;
- employ integrated establishment techniques.

RADIATA PINE SITE PREPARATION METHODS

Five basic methods are used during establishment, often in combination over all or part of the site (Table 8.3). They are:

- hand tool methods;
- machine methods, including harvesting;
- fire;
- chemicals;
- animals or other biotic agencies.

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

Hand tool methods

In countries where labour is scarce, wages are high or planting programmes are large, the use of hand methods is less common than half a century ago. Furthermore, it has been recognized that such methods are limited – for example, they cannot alter the site through cultivation, and the quality of the operation is often poorer than with machines – and the end result may therefore be suboptimal (e.g. Zwolinski, Johnson and Kotze, 2002). Issues with worker safety, supervision requirements and time restraints may be other disadvantages of hand tool methods. Nevertheless, there is a limited role for them (García *et al.*, 2000; Fernández and Sarmiento, 2004; Little *et al.*, 2006). The basic advantages are that they:

- require only small capital outlays;
- often require only simple skills;
- seldom, by their nature, do much damage to the site or cause pollution;
- are applicable in difficult terrain or areas with other restrictions that can limit some alternatives.

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

Mechanical techniques

Mechanical site preparation methods are widely employed in the establishment or re-establishment of radiata pine plantations (Hall, 1995, 2005; García *et al.*, 2000; Fernández and Sarmiento, 2004). However, they are not always required, for example, after harvesting with haulers. Experience and research have shown that machines used prior to planting:

- often give better results, leading to faster, more uniform growth;
- may be used to control some types of weeds (for example, ploughing has been used in Australia to reduce the regrowth of lignotuberous eucalypts, while ripping may reduce the impact of certain weeds);

TABLE 8.3

Site preparation methods commonly used in radiata pine plantations

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

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

Source: Based partly on Hall, 2005

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

The disadvantages are that machines:

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

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

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

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

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

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

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

BOX 8.1

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

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

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

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

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

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

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

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

FIGURE 8.3
Site preparation in South Australia using towed rollers. The resulting mulch assists with moisture conservation, conserves nutrients and makes planting easier.

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

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

FIGURE 8.4
Mounding and ripping provide an excellent cultivated planting site, concentrate nutrients and reduce weed competition.

FIGURE 8.5

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

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

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

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

Fire

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

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

FIGURE 8.6

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

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

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

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

However, there are also many disadvantages. For example:

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

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

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

Chemicals

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

When using chemicals for weed control:

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

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

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

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

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

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

Other weed-control methods

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

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

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

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

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

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

PLANTING

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

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

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

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

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

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

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

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

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

Survival and replacements

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

FIGURE 8.8

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

DIRECT SEEDING AND NATURAL REGENERATION

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

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

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

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

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

FERTILIZER AT ESTABLISHMENT

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

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

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

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

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

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

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

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

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

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

FIRST ROTATION FEATURES

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

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

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

LATER ROTATION FEATURES

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

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

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

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

FIGURE 8.9

Hauler logging leaves a clean site but redistributes nutrients.

SYNTHESIS AND TRENDS

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

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

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

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 eucaplypts. 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):

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

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):

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

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.

10 Productivity changes and sustainability of radiata pine plantation forests

This chapter focuses on the biological and ecological aspects of growing radiata pine, primarily, but not exclusively, for commercial wood products. The on-going domestication of the species, including research on growing radiata pine, has had marked effects on radiata pine's growth rates over the past half-century. These improvements, however, could conceivably be partly offset by biotic and abiotic stresses, including factors that reduce a site's growth potential, and new pests and diseases. There are also ongoing climatic changes, including extreme weather events, that may alter where and how radiata pine grows. Earlier chapters looked at many of these aspects in isolation. This chapter combines the factors that can increase, or which pose risks to, the productivity and long-term ecological sustainability of radiata pine plantations.

CONCEPTS

Sustainability is usually understood as meeting present needs without compromising options or productivity for future generations. For exploited ecosystems, such as forest plantations, ecological sustainability is considered critical (Callicott and Mumford, 1997); the aim is to preserve ecosystem health by considering ecological processes and functions, irrespective of the species performing them. This concept contrasts with traditional forest management for timber, which has focused on sustained yield (long-term equilibrium between growth and timber harvest) and more recently on sustainable forest management, where a wider range of goods and ecosystem services are considered. The focus on ecological sustainability has been reinforced by the concept of "strong" sustainability, which emphasizes that economic and social aspects of sustainability need to be considered within the limits of the earth's biosphere, ecological systems and resources – that is, its natural capital (Ekins *et al.*, 2003). The ecosystem approach is also viewed as a bridge between environmental and human well-being because it recognizes that humans are an integral part of many ecosystems (MEA, 2003).

Evans (2009b) has suggested that it is possible to consider sustainability in a narrow sense – where the focus is on whether forest plantations are biologically viable in the long-term – and in a broader sense, which considers whether using land for plantations is wise and sustainable from an economic, environmental and social point of view. A plantation project may be biologically viable, for example, but could lead to unfortunate social consequences (Menne and Carrere, 2007). Both the narrow and broad outlooks, however, do not necessarily fit into the definition of strong sustainability.

As discussed in Chapter 5, productivity is ecologically defined as the net biomass production per unit area per unit time. Leaf area index and volume growth, which are closely related to biomass production, are often used as productivity indicators. However, for this discussion, net MAI (m^3 per ha per year) has been used because it is most widely reported.

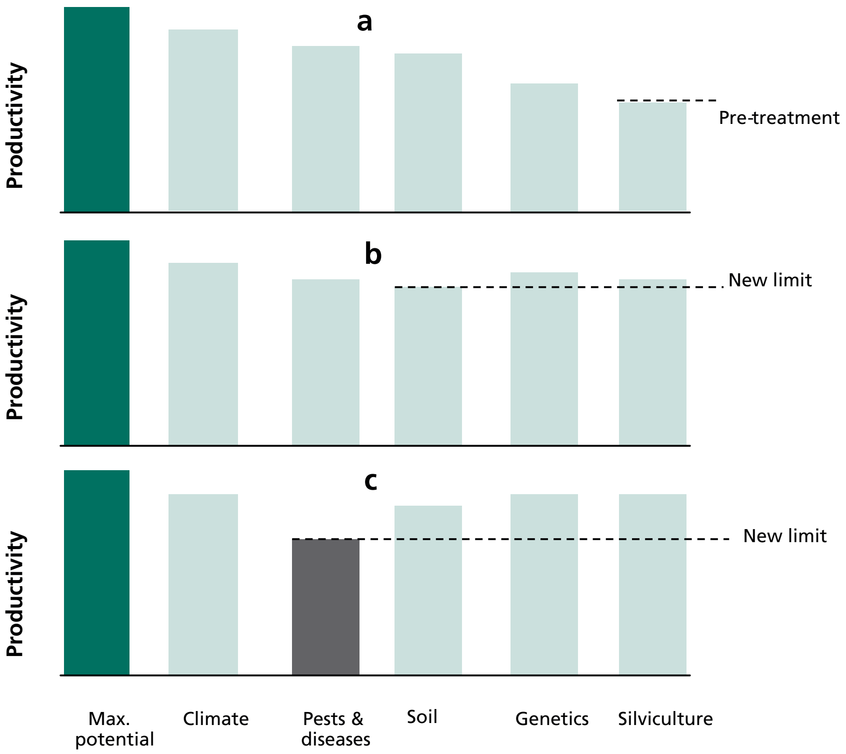
Stand growth depends on climate, site and genetics and on stocking and other silvicultural factors (Mead, 2005a). At any place and time, growth is controlled by the most limiting factor (Figure 10.1). The full potential of a species will not be achieved if it is limited by pests, diseases, silviculture (including tree improvement through breeding), soil and other site factors, or climate. Management is able to control some of these potentially limiting factors.

Figure 8.2 illustrates the concepts of short-term and diverging growth responses (Snowdon and Khanna, 1989). In a short-term response, a change in growth rate is followed by a resumption of the previous growth rate on a parallel trend. Such responses result from temporarily relieving (or increasing) growth limitations such as competition for nutrients or moisture at establishment, although they are not necessarily restricted to the establishment phase. Where growth trends diverge over time, the implication is that the site's resources or the tree's ability to exploit those resources has changed permanently, such as when the fertility status of a site is changed dramatically or the tree genotype has been altered substantially. A third type of response that occasionally occurs is a small change in growth that subsequently becomes undetectable. All three types of response are usually associated with changes in leaf area and sometimes with improved carbon assimilation, nutrient or water use efficiency, or an alteration of other physiological processes (e.g. Sheriff, Nambiar and Fife, 1986). While this classification of growth response types is conceptually helpful, there is actually a gradation between the three types. The changes can be positive or negative.

In discussing changes in productivity over time it is important to specify the baseline from which changes are to be considered. In most discussions on sustainability, the baseline is conceived as the current condition, with a focus on ensuring that future growth is non-declining. It is relatively easy to measure the current status. On some sites, such as those where the soil has severe limitations, the baseline might be measured after these limitations have been overcome. For the purpose of this discussion, however,

FIGURE 10.1

Tree growth is determined by the most limiting factor and some of these factors can be manipulated by forest managers



Note: In (a), growth is limited by poor silvicultural practices such that the genetic, soil and climate potential cannot be achieved. In (b), where silviculture and genetics have been improved, soil is the limiting factor. In (c), increased pest/disease load is reducing growth and perhaps the sustainability of the plantations. This needs to be dealt with to take advantage of the soil potential, improved silviculture and genetics.

the baseline is taken as the growth rate of natural stands of radiata pine, despite the difficulty of quantifying their growth rates during the nineteenth century. This is done to enable the consideration of effects of planting the species outside its natural habitat. Finally, any productivity changes are always highly variable because of site and other factors, so only indicative trends are described.

PRODUCTIVITY INCREASES

Growth rates of radiata pine in natural stands have been poorly reported, but the stands appear to be relatively slow-growing compared with how they grow in plantations outside their natural habitats (McDonald and Laacke, 1990; Burdon, 2001). Lindsay (1932) reported that the height of stands up to 20 years old at Monterey was less than 15 m and that the heights of mature trees were in the range 9–37 m, with the tallest trees occurring on better soils in gullies. In average stands, mature trees were 21–34 m in height at Monterey and a little taller at Cambria, averaging 30–37 m. Typical stands have a site index of about 20 m (height at age 20 years) and seldom exceed 30 m (Burdon, 2001). The tallest trees on Guadalupe and Cedros islands were 33 and 32 m, respectively. A 50-year-old stand with 408 stems per ha at Monterey had a volume of 490 m^3 per ha, which is equivalent to an MAI of 10 m^3 per ha per year. Henry (2005) presented data from four mature natural stands in Monterey and one stand each for Año Nuevo and Cambria. Average stand heights were under 20 m and canopy closure was over 80 percent. Basal area per ha of radiata pine averaged 21 m^2 per ha, which suggests that stand volumes were under 200 m^3 per ha.

These data can be compared to typical MAIs of 12–34 m^3 per ha per year in plantations outside California (Table 1.4) and to 18–25 m^3 per ha per year for unthinned stands in Chile before diseases and advanced silviculture had an impact (Fenton, 1979). Similarly, 35-year-old unmanaged first-rotation stands in central North Island, New Zealand, planted in 1925 at 1 525 stems per ha had a net MAI of 23 m^3 per ha per year and a top height of 42 m at age 35 years (Spurr, 1962).[1] The more than doubling of growth rates of early plantings outside California has often been attributed to the absence of naturally occurring pests and diseases (Gadgil and Bain, 1999; Wingfield, 2004). However, it is likely that part of the increase is attributable to genetic changes resulting from the use of local seed (known as a land race) and the plasticity of radiata pine, which allows it to take advantage of better growing conditions (Burdon, 2001). These changes have produced long-term responses (Table 10.1). The high growth rates were achieved on sites that suited the species; there are many instances where the species has failed because it was planted off-site (see Chapter 2). If radiata pine needs to be tested before it is planted on a large scale, this would take half a rotation and would increase costs. Climate models can assist in deciding if it is appropriate to consider this species (Booth, 1990).

Tree-breeding (Chapter 6) has been very successful in increasing productivity. Provenance selection has been less important for radiata pine than for many other species. Tree-breeding is an expensive, ongoing activity and has been credited with increasing radiata pine productivity by 1–1.3 percent annually (Table 10.1). This is slower than some eucalypt programmes but faster than that achieved with loblolly pine (Mead, 2005a). However, care needs to be taken with tree-breeding because it may lead inadvertently to negative effects. In New Zealand, it may have resulted in inferior corewood properties (see Chapter 5) and increased magnesium deficiency symptoms often seen as as upper mid-crown yellowing (Beets *et al.*, 2004). Tree-breeding may also have reduced the within-tree allocation of resources to defence mechanisms against insects (Kay, 2008).

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[1] The data reported by Spurr show the effects of *Sirex* on deaths of trees aged between 23 and 28 years, but because natural mortality was much lower later in the rotation, this suggests the stands were not affected by the insect later in the rotation. The final crop stocking was 316 stems per ha.

TABLE 10.1
Factors increasing radiata pine productivity, classified by response type and translated to gain at the end of a rotation

Treatment	Gain	Time to harvest gain	Relative cost
Usually long-term (diverging) responses			
Release of natural pests	*****	1 rotation	Very low
Tree-breeding	** to ***	1–3 rotations; ongoing	Very high
Correct major deficiencies	Up to *****	1 rotation	Moderate to high
Rooting volume	Up to *****	1 rotation	Moderate to high
Irrigation (uncommon)	Up to ****	1 rotation	High
Usually short-term responses			
Planting stock and planting	*	1 rotation	Moderate
Stocking level and rotation	**	Up to 1 rotation	Moderate
Weed control	*!	1 rotation	Moderate
Tillage or crushing slash	**	1 rotation	High
Starter fertilizer	*	1 rotation	Low to moderate
Thinning mortality	* or **	>1/3 rotation	Moderate
Nitrogen fertilizer to pole stands	* or **	<< rotation	High

* = < 10%; ** = 10–25%; *** = 25–50%; **** = 50–75%; *****= >75%; ! = larger responses may occur with woody-weed control on some sites.

Source: Mead, 2005a; chapters 4 to 10

Other common long-term diverging responses have been due to correcting major soil deficiencies, irrigation and improving rooting depth (Table 10.1). On very deficient sites, the response to heavy dressings of phosphate fertilizer has been spectacular and long-lasting, and may continue from one rotation to the next (see Chapter 9; Mead and Gadgil, 1978; Turner, Lambert and Humphreys, 2002). Experimentally, irrigation and irrigation coupled with improved nutrition can also result in large responses if the sites are drought-prone and of low nutrient status (Snowdon and Benson, 1992). Treated waste water has been used on a small scale (Myers *et al.*, 1996; Thorn *et al.*, 2000). Ripping or subsoiling may increase rooting depth as well as produce a small weed-control effect. Similarly, draining wet sites allows roots to exploit a greater volume of soil. Mulching instead of burning has been shown to overcome major site deterioration on sandy soils (Figure 10.2). In South Africa, mounding or bedding on poorly drained soils resulted in a 250 percent growth response by age 20 years (Zwolinski, Johnston and Kotze, 2002). However, smaller, short-term responses to ripping and ripping plus bedding have been described for radiata pine on indurated soils in New Zealand (Mason, 2004).

A number of silvicultural treatments commonly result in smaller, short-term responses (Table 10.1). Most of these are associated with the establishment phase, and while they can seem spectacular early on, their long-term impact is relatively small. For example, the control of weeds and the judicious choice of understorey species in silvopastoral systems usually decrease the time needed to obtain the same final crop volume by less than two years over a rotation (see Chapter 11). However, where practices result in high seedling mortality or there is competition from woody weeds, decreases in growth may be more serious. The use of higher initial stockings can increase site productivity but needs to be accompanied by thinning when competition mortality is likely (see Chapter 9). The application of nitrogen to thinned pole stands increases leaf area, results in faster crown closure, and typically boosts growth by 4–6

FIGURE 10.2

The effect of slash burning (top) compared with slash retention (bottom) on radiata pine at age four years on sands in Western Australia

years (Mead, Draper and Madgwick, 1984; Hunter *et al.*, 1986; May *et al.*, 2009a). One reason for the longer, diverging response pattern to phosphorus fertilizer, compared with the shorter-term responses to nitrogen fertilizer, is that the amount of phosphorus added is large compared to the soil reserves and it remains in the ecosystem and cycles efficiently. With nitrogen, the amount applied is small compared with the total amount of nitrogen in the soil. Furthermore, only a small proportion (e.g. 5–20 percent) of the applied nitrogen is taken up by the trees and a large proportion is incorporated into the soil organic matter or lost from the ecosystem in the first year after application (Mead, Chang and Preston, 2008). A small part of this loss (<10 percent) is from the leaching of nitrate, although this can be higher on sandy soils or in high-rainfall areas (Davis *et al.*, 2012). Volatilization is also possible for urea fertilizer under some conditions (see Chapter 9; May *et al.*, 2009a). Splitting fertilizer applications within the season does not increase tree uptake, although it can reduce nitrate leaching (Thomas and Mead, 1992).

In summary, radiata pine has grown much better in many plantations than in natural stands and it has been possible to substantially increase productivity with intensive silvicultural techniques. An encouraging study in New Zealand, which used historical permanent plot data, found that there had been an increase in MAI in recent years, with stands established during the 1980s growing 25 percent faster than those established in the 1930s (Palmer *et al.*, 2010). The time taken to achieve these gains needs to be taken into account in evaluating the impact on plantation management (Table 10.1). Fertilizer applications and thinning to avoid mortality are the only options available to increase merchantable wood later in a rotation. Furthermore, Mead (2005a), who surveyed managers about how well they achieved trial results in practice, found that the median reduction between trial and operational responses ranged from 15 percent to 25 percent; there was high variability among managers.

PRODUCTIVITY DECREASES

Invasive species

There are several ways in which productivity can be reduced. Pests and diseases pose the greatest threat, although to date their increasing incidence has only prevented the use of radiata pine when the species has been used on sites that were far from optimal (see Chapter 4). Integrated pest management coupled with the retention of a wide genetic base has been able to keep decreases within “acceptable” levels. It is difficult to evaluate the overall impact of individual pests and diseases on productivity or what will happen in future, particularly as ecosystems are changing and often include novel combinations (see Chapter 4). Nevertheless, it is expected that some pests and diseases will contribute to long-term declines in productivity.

Changes in the weed spectrum from one rotation to the next may also have an impact on productivity if new weeds are not controlled. This may have occurred between the first and second rotations on some sites in the Nelson region of New Zealand. A study by Whyte (1973) found short-term decreases of 10–20 percent in height and volume growth between rotations on upper slopes, but faster growth was observed on lower slopes; it is difficult, however, to pin down the actual cause of these changes.

Soil fertility changes

Soil fertility can also be reduced by the removal of nutrients in harvested trees or because of erosion or poor establishment practices, unless such losses are offset by weathering or other inputs. Radiata pine afforestation can reduce soil pH and soil nutrients because of uptake by the trees (see Chapter 11; Berthrong, Jobba and Jackson, 2009; Rigueiro-Rodríguez, Mosquera-Losada and Fernández-Núñez, 2011). The contention that radiata pine plantations always lead to soil degradation has not been substantiated (Will and Ballard, 1976; O’Hehir and Nambiar, 2010; Powers, 1999; Fox, 2000; Evans, 2009b). Indeed, establishing plantations on degraded sites has long been regarded as a good way to restore such sites. Soils are usually improved faster by intensive management practices. Further, long-term research in the western United States has found that intensive weed management, while substantially improving growth rates, did not decrease soil C storage (Powers *et al.*, 2013).

Madgwick (1994) summarized Australasian research data for radiata pine on the removal of nutrients over a rotation. While stem-only harvesting comprised 80–90 percent of whole-tree above-ground dry weight, the removal of nutrients was considerably lower because of their accumulation in the crowns. Stem-only harvesting typically removes 40–50 percent of the nitrogen, 45–60 percent of the phosphorus, 60–65 percent of the potassium, 60–70 percent of the calcium and 65 percent of the magnesium in the entire tree. Actual nutrient removals vary with site, length of rotation and harvesting practice (e.g. whole tree, normal logs or debarked logs) and whether production thinnings are conducted. For example, short-rotation pulpwood crops will remove more nutrients per year than long-rotation sawlog crops.

These harvesting losses need to be compared with net inputs from other sources and other losses (Table 10.2). On sites where there is negligible air pollution or other point sources of atmospheric nitrogen, nitrogen inputs from rainfall are usually 1–5 kg per ha per year. Even so, several studies have shown that plantations can accumulate up to 25 kg of nitrogen per ha per year, in some cases without the presence of legumes (Turner and Lambert, 2011). Legumes, such as lupins, can fix large amounts of nitrogen. The sand-dune forest data from New Zealand in Table 10.2 illustrate the build-up of

TABLE 10.2

Typical nutrient balance sheets for selected contrasting sites and harvesting practices, New Zealand

Plantation		Biomass	N	P	K	Ca	Mg
		t/ha/yr	kg/ha/yr				
Recent sand dune 42-year-old stand	Whole tree*	9.6	6.8	1.6	11.0	8.4	2.8
	Stem only	8.6	3.0	0.9	5.2	5.5	1.7
	Weathering	-	-	1.1	9.2	12	7.2
	Other inputs	-	37**	0.2	3.5	5.0	3.2
	Other losses	-	0.2	0.1?	NA	NA	NA
		t/ha	kg/ha				
	Forest floor	36	462	NA	76	272	148
	Soil***	-	836	516	905	3 275	1 655
	Total site*	-	1 655	-	-	-	-
		t/ha/yr	kg/ha/yr				
Pumice soil 29-year-old stand	Whole tree*	14.7	15.0	2.3	16.0	11.5	3.5
	Stem only	12.8	7.5	1.1	9.8	7.6	2.3
	Weathering	-	-	0.5–2	5.4	14	5.0
	Other inputs	-	4-5	<0.1	7.6	1.4	1.6
	Other losses	-	0	0.01	4.2	1.6	5.7
		t/ha	kg/ha				
	Forest floor	33	302	33	150	177	38
	Soil total (available)****	-	3 049 (593)	2 574 (60)	131 718 (2 874)	171 600 (853)	35 100 (245)
	Total site*	-	3 817	2 876	136 144	173 238	35 537

Note: Tree data are on an annual basis to compare with annual weathering and precipitation, while the reserves are on a per ha basis at the end of the rotation; NA = data unavailable; * = whole tree excludes pine stump and roots but these are included in the total site reserves; ** = this site began as raw sand and accumulated 1 655 kg N per ha over 45 years, mainly coming from N fixation by legumes, although about 5 kg N per ha per year is obtained from rainfall. The rate of fixation can be as high as 160 kg N per ha per year; *** = based on available P, K, Ca and Mg are from Dyck *et al.*, 1991. Totals NA; **** = bioassay by Will and Knight (1968) for a similar soil.

Sources: Dyck *et al.*, 1991; Dyck and Beets, 1987; Smith *et al.*, 2000; Barker, Oliver and Hodgkiss, 1986; Zabowski, Skinner and Payn, 2007; Parfitt, Baisden and Elliott, 2011; Knight and Will, 1977 ecosystem nitrogen over a single long rotation of radiata pine, aided by the presence of lupins. Another study on these sands found that, by age 14, lupins used during the establishment phase had increased the ecosystem nitrogen by approximately 50 percent (Barker, Oliver and Hodgkiss, 1986). While rainfall also brings in nutrients, the weathering of soil minerals is the major source of phosphorus and cations (Zabowski, Skinner and Payn, 2007). A certain amount of most nutrients may be lost via groundwater to streams; nitrogen can also be lost through denitrification. Leaching is often higher immediately after harvesting until re-vegetation occurs.

As illustrated in Table 10.2, the net balance differs greatly, depending on:

- soil type, rainfall and location;
- harvesting intensity and frequency;
- removal or conservation of the litter layer, itself a major pool of nutrients;
- the nutrient concerned;
- possible fertilizer additions.

In general, harvesting sawlogs from radiata pine plantations will not – or will only marginally – deplete the nutrient store and thus is sustainable (Table 10.2). There is some risk on sites that begin with low reserves and with whole-tree harvesting, very short rotations or where the litter is not conserved (O'Hehir and Nambiar, 2010; Fox, 2000). Other nutrient balance studies have been carried out in a number of countries and are in general agreement, although, as in Table 10.2, there are site differences. In Spain, for example, on a site that was low in phosphorus, whole-tree logging depleted the soil reserves to the extent that it might threaten sustainability if the rate of weathering is low (Ouro, Pérez-Batallón and Merino, 2001). Other studies also indicate that phosphorus is often a critical nutrient (Schlatter, Gerbing and Oñate, 1998; Zabowski, Skinner and Payn, 2007).

Poor re-establishment practices can reduce productivity substantially. In South Australia, the use of intense burns or heaping and burning caused a marked reduction in radiata pine growth in the second rotation (Box 10.1), with dramatic effects on these sandy soils (Figure 10.2). Similarly, windrowing can also reduce site productivity because it redistributes slash, forest litter and, often, topsoil (Dyck, Mees and Comerford, 1989). Intense burns and windrowing can have long-term impacts on site organic matter and nutrient status (Smith *et al.*, 2000; Smaill, Clinton and Greenfield, 2008; Jones *et al.*, 2011). Results from these studies found that on infertile sandy sites, there were long-term reductions in productivity, but on more fertile sites the growth decreased for only a few years.

Logging can have other adverse effects. The worst of these can be found on log loading areas (skid sites) where the topsoil is removed and the soil becomes very compact. Such areas cover only 4–6 percent of the site and can be partly rehabilitated by ripping, applying fertilizer or returning the topsoil; however, those treatments can be expensive (Maclaren, 1996). Ground-based harvesting equipment often traverse more than two-thirds of a logging site and significantly affect 5–25 percent of the site, depending on the equipment used (Murphy *et al.*, 2009). Soil compaction and the displacement of litter and topsoil are common – they are greatest with skidders on wet soils and much less common in animal- and helicopter-based logging systems. Soil compaction and increased bulk density to a depth of 30 cm usually occur after a few machine passes (Greacen and Sands, 1980; Gayoso and Iroumé, 1991). In a rotation-length experiment with radiata pine on a clay soil, litter removal and litter removal plus light compaction caused a small short-term reduction in growth that had become statistically insignificant by later in the rotation (Murphy *et al.*, 2009). Topsoil removal combined with either moderate or high compaction showed a long-term growth reduction, with decreased growth at the end of the rotation of 28 percent (moderate compaction) and 38 percent (high compaction). The short-term nature of litter removal and light compaction has been noted in other research (Powers *et al.*, 2005), but longer-term effects of light compaction can occur on some soils (Greacen and Sands, 1980).

MANAGING INVASIVE SPECIES

Pests and diseases present perhaps the greatest threat to the sustainability of radiata pine plantations. Once fully established, they can have long-term and costly impacts on productivity.

The impact of new weeds can be reduced by vigilance against introduction and spread. Initial introductions are often human-initiated. Potential vectors include machinery, road-building material, animals and birds, although wind-aided seed dispersal is also common. The spread of weeds can be reduced by regularly monitoring plantations for potential weeds and ensuring a rapid response to eradicate them. Good management systems are essential to reduce risk. Reducing the impact of established difficult-to-control weeds may require research support (see Chapter 8). A good example of a preventable weed problem is the introduction and spread of pampas grass (*Cortaderia* spp.) in radiata pine plantations in Northland, New Zealand. The initial introduction occurred during the upgrading of roads for logging in the first rotation. Pampas appeared along roadsides and was not controlled, so its wind-blown seed spread quickly onto the logged sites, which provided ideal seedbeds.

BOX 10.1

Second rotation radiata pine decline in South Australia reversed

Most South Australian radiata pine plantations are on low-fertility podsolized sandy soils where moisture is frequently limiting. In the 1950s, inventories found that productivity between the first and second rotations had declined. This occurred on about 85 percent of the forest estate, with reduced volumes of 25–65 percent (3–8 m^3 per ha per year).

The first rotation had been planted with unimproved seed on hand-cleared eucalypt woodlands. They were hand-weeded and fertilized with small amounts of phosphorus and zinc. This crop was logged down to 10–15 cm small-end diameter. The high amounts of slash were either burnt and then heaped or were first windrowed and then burnt. Sites were ploughed before replanting and again were hand-fertilized with superphosphate. Additionally, two intense wildfires led to the loss of organic matter and to wind erosion.

Research showed that intense burns could reduce nitrogen by 570–930 kg per ha and annual rainfall inputs were only 1.5–2.0 kg per ha. Windrowing and burning often reduced total nitrogen reserves on the site (to 50 cm soil depth) by up to 70 percent. Burning also reduced site phosphorus, potassium, calcium and magnesium reserves by 8, 21, 123, and 13 kg per ha, respectively. Research found that mulching slash and litter maintained nutrients on the site, improved soil water availability and produced good tree growth.

Based on this research, the third rotation, beginning in the 1980s, avoided burning and prioritized the conservation of site resources; weed control also improved (see Box 8.1 for current silviculture) and genetically improved stock was used. The third rotation is now growing very much faster than the second and even better than the first, with growth-rate improvements of 60–230 percent and 4–30 percent higher than the second and first rotations, respectively. In the 1960s, about 75 percent of new plantations were of low site quality (MAI 18–22 m^3 per ha per year) and only 5 percent were fast-growing (MAI 26–33 m^3 per ha per year). From the 1990s, the higher site quality accounted for 80 percent of the area, and low-quality sites were becoming rare.

On these fragile sites, establishment practices can have large impacts on productivity but, with appropriate management, radiata pine can be grown sustainably. This is an example of successful adaptive forest management.

Source: O'Hehir and Nambiar, 2010

As discussed in Chapter 4, the spread and establishment of new insects and fungi is a growing threat to plantation forests. Sweet (1989) argued that the health of radiata pine in New Zealand had deteriorated since the 1950s. The first line of defence is quarantine measures, coupled with systematic monitoring systems to quickly detect new introductions that cross borders. If pests can be detected before they become well-established, eradication may be possible. Once established, however, the only option left is integrated pest management (see Chapter 4). This may require decisions on what constitutes an acceptable level of productivity loss before active intervention is undertaken (Evans, 2009b).

Radiata pine is usually grown as a monoculture and there has been considerable dispute about whether this increases the threat of pests and diseases (see Chapter 4; Sweet, 1989; Evans, 2009b). A recent review found that mixed forests may reduce insect problems, although this depended on species' composition and the insects involved (Jactel and Brockerhoff, 2007). Forest plantation monocultures may increase risk because of the large amount of food available, particularly when grown at high stand densities or where there is a narrow genetic base or the species is planted off-site (Wainhouse, 2005). Tree-breeding strategies (see Chapter 6) need to ensure that genetic diversity is maintained, and they can also be used to reduce the impacts of specific diseases.

It should be noted that radiata pine commonly occurs in almost pure stands in its native habitat, although often with a coast live oak (*Quercus agrifolia*) component (Lindsay, 1932; Burdon, 2001; Henry, 2005). There are also stands where radiata pine intergrades with this oak or with Douglas fir. Having oak present has not prevented the natural stands from being attacked by the exotic pitch pine canker. However, the disease, together with fire suppression, may have been partly responsible for an increased live oak component in recent years (Henry, 2005).

MANAGING NUTRIENT SUSTAINABILITY

Mead and Smith (2012) described ten principles to guide nutrient management to ensure biological sustainability. These are based on current knowledge but also on the recognition that knowledge is incomplete and advancing rapidly. By extension, practices must be able to adapt to new research and changing ecological conditions. The ten principles of sustainable nutrient management are:

1. define management objectives;
2. quantify management risks to maintaining soil fertility in the long term;
3. map and evaluate sites;
4. decide on the level of monitoring;
5. include independent auditing;
6. conserve resources;
7. develop site-specific nutritional management plans;
8. consider off-site impacts;
9. use decision-making aids, including models, economic and energy analysis/life-cycle analysis;
10. apply adaptive management.

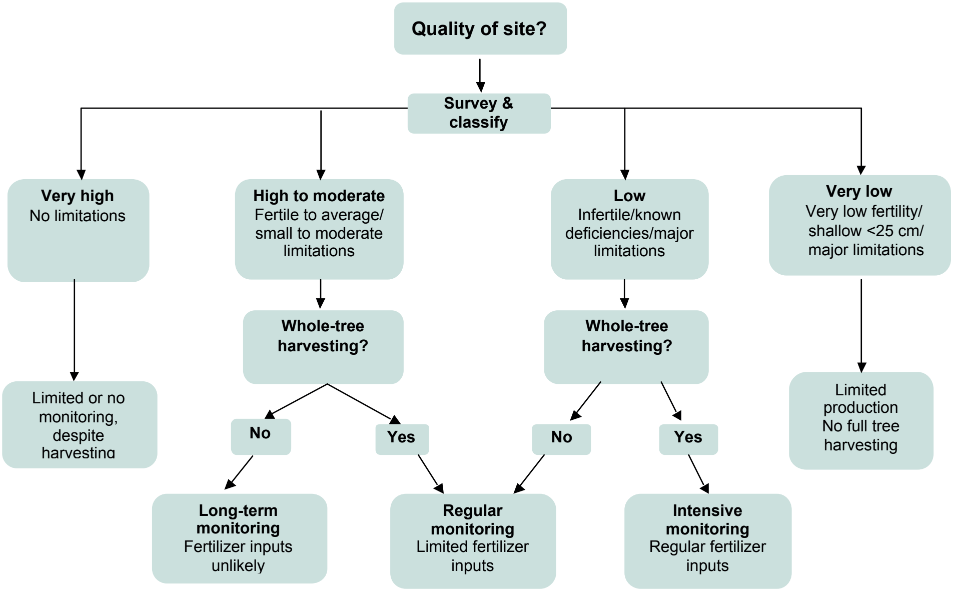
The importance of defining management objectives (principle 1 above) is stressed in earlier chapters. This is also critical for nutrient management because it influences decisions on growing and harvesting methods and their intensity. This principle thus helps define likely nutrient risks. Principle 2, to quantify management risks, includes considering factors discussed earlier, such as nutrient budgeting in relation to soil reserves and other inputs (e.g. Table 10.2), and evaluating whether establishment, silvicultural and harvesting practices could degrade the site or increase erosion.

The third principle, mapping and evaluating sites, recognizes the need for site-specific management because of the range of factors affecting productivity and differing sensitivity to degradation (Burger, 2002; Fox, 2000; Mead and Smith, 2012). Although methodologies are evolving rapidly, they mostly involve subdividing plantations into areas that can be treated uniformly based on landscape, soil type and vegetation. Plantation crop types, harvesting methods, roading and streamside protection should be part of this spatial database. The management units need to be of practical size so that nutrient management plans can be allocated to each site unit. This allocation flows from the risk analysis in principle 2. In Figure 10.3, four site groupings are suggested by way of illustration. On very fertile sites there will be few risks to nutrient status, but at the other extreme will be sites that are so poor or have other limitations that they would not be considered for intensive forest management. In addition, there will be areas such as riparian buffers or reserves where no plantation management would be applied. While such a grouping is subjective, it could be altered over time based on experience. Fox (2000) suggested that site-specific management and associated mapping may result in a mosaic that includes intensively managed and extensively managed stands. It could also include agroforestry options.

The need for monitoring is linked to these site groups. Mead and Smith (2012) suggested four levels of monitoring based on fertility and the degree of harvesting intensity or other factors. They are nil, long-term, regular and intensive monitoring (Figure 10.3). Long-term monitoring could include those parameters identified during the Montreal Process for ensuring that soil quality and net production are not being compromised (Anon, 1995). The top three radiata pine-growing countries are part of this international sustainability process. Often, such monitoring is based on soil properties such as texture, soil strength, nitrogen mineralization rates and organic matter and soil depth or indices based on these (Fox, 2000). In New Zealand, the current recommendation for radiata pine plantations is to measure total soil phosphorus, the carbon:nitrogen ratio and total porosity (Watt *et al.*, 2008a). With 'regular' monitoring, in addition to these long-term measurements there would be more intensive measurements at the forest management unit level. The range of measurements would depend on site limitations and current knowledge; where knowledge is lacking, a wider range of analyses would be appropriate (Mead and Smith, 2012). Where trees are present, foliage analyses (see Chapter 2) should be considered in

FIGURE 10.3

Overview of site assessment, level of monitoring in relation to harvesting impacts and the need for nutrient amendments



Source: Mead and Smith, 2012

addition to soil analyses. Foliage samples collected at the time of canopy closure would correspond to the time of greatest nutrient demand, and samples collected from stands showing deficiency systems would assist in diagnosis. Leaf area measurements can also be helpful (May *et al.*, 2009a). The most intensive monitoring programme is appropriate where there is low nutrient soil status and active management for deficiencies (Mead, 1984; Payn *et al.*, 1999). Sampling strategies need to be robust and efficacious.

Independent auditing (principle 5) of classification and monitoring systems will ensure that they are robust. Third-party auditing is also required for forest certification.

Sustainability, moreover, depends partly on managers making wise use of resources (principle 6), particularly those that will be limited in the longer term or which can be linked to other adverse environmental or social impacts. In terms of nutritional management, this means there is no need to apply nutrients where they are not being depleted at a faster rate than inputs from weathering, the atmosphere or other sources. For example, calcium has often been suggested as a potential concern (Burger, 2002), but radiata pine responses to calcium have been very rare, and weathering and atmospheric deposition usually exceed demand (Table 10.2; Zabowski, Skinner and Payn, 2007).

Phosphorus is of greater concern, particularly where whole-tree harvesting is used, since multiple crops are likely to lead to a decline in soil phosphorus on some sites in the longer term (Payn and Clinton, 2005; Zabowaski, Skinner and Payn, 2007). Furthermore, the use of phosphate fertilizers is common on low-phosphorus sites (see Chapter 9). Although the quantities are small compared with agricultural application, their use needs to be weighed against the reality that world phosphate resources are finite and there are indications that peak phosphorus (equivalent to peak oil) may soon occur (Cordell, Drangert and White, 2009). The price of phosphate has also increased rapidly in recent years. While phosphorus applied to forests seldom causes pollution, fertilizer application should be carefully controlled and limited to the areas where it is needed (i.e. site-specific management), and the application should be precise spatially.

Energy use and potential greenhouse gas emissions from the use of fertilizers should also be considered in decision-making. For example, the application of nitrogen fertilizers in plantations has a relatively poor energy output:input ratio compared with other methods of increasing productivity (Mead and Pimentel, 2006).

As most tree nutrients are in the foliage, small branches and bark, it is important that where stem-only harvesting is being undertaken, these resources are kept on the site and not heaped at landings or elsewhere. When these residues are used as fuel, the ash can be returned to the site to help maintain nutrient levels (Augusto, Bakker and Meridiue, 2008). The application of wood ash to very acid, high-organic-matter soil in Spain led to increased pH and available cations, which resulted in increased radiata pine growth ascribed mainly to improved calcium and magnesium status (Solla-Gullión *et al.*, 2008).

The development of site-specific nutrient management (principle 7) should consider the prospect of reducing the removal or redistribution of nutrients, lengthening rotations to allow for greater natural replacement, and the use of fertilizers. There are four basic situations in which these management strategies can be applied (Figure 10.3; Mead and Smith, 2012):

1. where problems are unlikely (fertile sites);
2. when risk assessment and monitoring indicates that possible problems are developing on average-to-marginal fertility sites;
3. where there are known problems;
4. when correcting gross nutrient deficiencies, particularly when establishing first-rotation plantations on infertile sites.

Nutrient diagnosis is covered in Chapter 2 and fertilizer principles and practice are covered in chapters 8 and 9 and by Mead and Smith (2012). Monitoring procedures are an important part of these management strategies. It is often ecologically and economically wiser to alter the silviculture or harvesting practices that are degrading the site rather than adding fertilizer. Similarly, encouraging nitrogen-fixing plants may be a preferable approach to applying nitrogen fertilizer.

Off-site impacts should be minimized (principle 8). These include the contamination of waterways and groundwater. The use of riparian buffer zones can reduce the impacts of logging and establishment practices (see Chapter 2). Fertilizer contamination of waterways in plantation forestry is small and short-lived, and because it is often associated with direct application to waterways can be reduced by using buffer zones along streams and by precision application techniques (Neary and Leonard, 1978; May *et al.*, 2009a). Fertilizer leaching is related to soil properties, vegetation uptake and fertilizer rate and formulation (see Chapter 9).

A range of tools can be used to ensure that decisions are based on the best information and assist with site-specific management. Nutrient balance models have been developed to explore the impact of forest operations, including harvesting, on sustainability on different sites (Payn and Clinton, 2005; Smaill, Clinton and Hock, 2011). Some radiata pine stand growth models may include fertilizer response data. Expert systems have been developed for South African and South Australian radiata pine plantations to assist in fertilizer-related decisions (Payn, Grey and Donald, 1989; May *et al.*, 2009b). Management decisions also usually involve cost–benefit analysis (see Chapter 3). In terms of sustainability, the expense involved in maintaining productivity should not be seen as an option but rather as an integral part of the project (see Chapter 9 and Mead and Smith, 2012). Energy and life-cycle analyses can also assist decision-making (Mead and Pimentel, 2006).

Adaptive management was the final principle identified by Mead and Smith (2012). Adaptive management is a cyclic process that seeks continual improvement and sustainability through planning, implementation, monitoring and evaluation outcomes, and reviewing practices. New research may suggest management improvements that can be incorporated in this process.

SYNTHESIS AND TRENDS

The increased productivity of radiata pine plantations observed over the past half-century is likely to continue as emphasis is placed increasingly on site-specific management. Tree-breeding, coupled with clonal forestry techniques, will facilitate this as well as increase the overall productivity of the species.

The pressure on the world's resources, however, including that created by climate change, is increasing the need for forest managers to ensure and to show that their radiata pine plantations are being managed sustainably. In some countries, this is being supported by research, as knowledge is still incomplete. Sustainable forest management, which aims to maintain and enhance the economic, social and environmental values of all types of forests for the benefit of present and future generations, is a major focus of international forestry. It covers many of the social and ecosystem services discussed in Chapter 3, such as carbon sequestration, biodiversity conservation, employment and water issues, but also considers food security, indigenous peoples and gender.

The biggest threats to the sustainability of radiata pine plantations are climate change and the prospect of increasing diseases or pests. Climate change (see Chapter 2) is likely to make some current plantation areas marginal in the long term. New biological pests may also limit the areas in which the species can be grown profitably. However, an emphasis on maintaining a broad genetic base in breeding programmes, breeding for disease and pest resistance or particular sites, and quarantine and monitoring will likely ensure the viability of radiata pine plantations in most areas. Nevertheless, as research increasingly points to genetic diversity as an important buffer against invasive organisms, growers of radiata pine plantation forests must not be complacent.

Nutrient sustainability issues are likely to mean that some sites cannot be managed using whole-tree harvesting techniques and that some very poor sites may need to be planted with other, less-demanding tree species or used for other purposes. The use of both nitrogen and phosphorus fertilizers is likely to become restricted because of dwindling supplies and increasing prices. On the other hand, there are good arguments for increasing the planting of radiata pine to offset greenhouse gases (see Chapter 3), for erosion control and as part of integrated farm-forestry solutions (see Chapter 11). Planting trees to capture carbon and the need to reduce the danger of nutrient depletion and improve radiata pine wood quality (see Chapter 5) point to higher stockings and longer rotations in the future. The nature of radiata pine silviculture and resources can be expected to change accordingly.

11 Radiata pine on farms

While radiata pine can be grown in large parts of New Zealand, it has a much more limited potential distribution in Australia, Chile, South Africa and Spain, where climatic conditions are much more variable. The range of tree species and agroforestry systems in these countries are thus far greater than in New Zealand. Where it is grown on farms, radiata pine is most commonly used in silvopastoral systems, as windbreaks or planted in woodlots, primarily for timber production. Even in areas suitable for radiata pine, it is only one of several species commonly planted on farms, but farm-grown radiata pine is often an important regional timber resource. In New Zealand, for example, almost 15 000 owners have about 20 percent of the radiata resource in scattered woodlots on farms. A survey of these farms found that ninety percent of their woodlots were in radiata pine, and they averaged 9 percent of the farm area (Rodenberg and Manley, 2011). In Australia, about 9 percent of the plantation resource is on farms (Nuberg, Reid and George, 2009). In Spain, most of the radiata resource is in small holdings and community forests (Rodríguez *et al.*, 2002a). Some 6 percent of the radiata pine plantations in Chile are less than 100 ha in size, making up 84 percent of landowners growing radiata pine (Censo Agropecuario, 2007). Many of these smallholders grow their trees under contract for larger industrial companies.

Growing trees on farms can help improve farm production. When farming profitability is considered on a reasonably long time-frame, trees can play a critical role. Trees can ameliorate the climate, reduce erosion, harness water runoff, improve water quality and increase biodiversity, as well as provide additional revenue and recreation and amenity benefits (see chapters 2 and 3). The planned use of trees can diversify farm income and spread the risks that arise from commodity price fluctuations. Furthermore, while the broad landscape is governed by the underlying topography, the size, colour, texture, variety and placement of trees can markedly alter perceptions and enhance landscape values.

This chapter focuses on the ecological processes that underlie agroforestry and the experience of radiata pine as a farm forestry and agroforestry tree. It covers the use of radiata pine:

- in windbreaks and as a shelter tree;
- as widely spaced trees with pasture beneath or as belts with pasture between them;
- in woodlots, including stock havens.

Farm planning issues and guidelines are also covered.

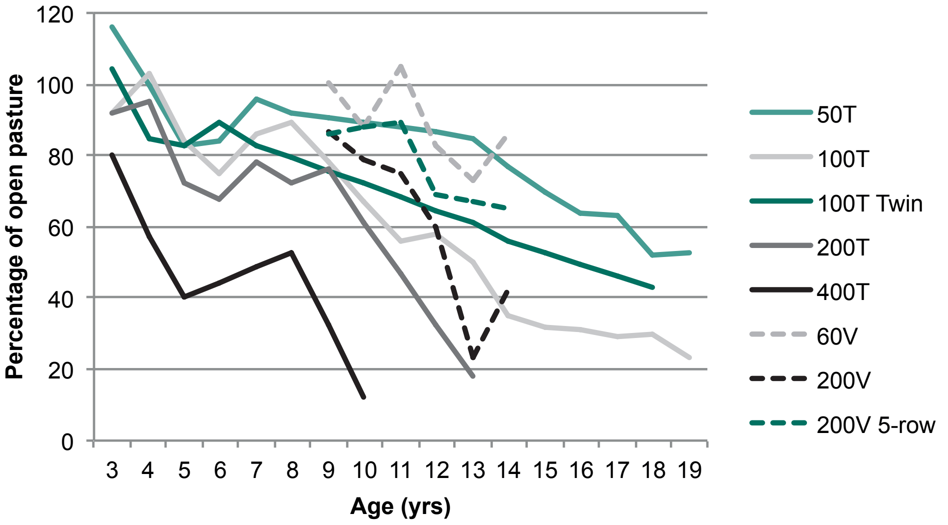
ECOLOGICAL PROCESSES IN RADIATA PINE SILVOPASTORAL SYSTEMS

Agroforestry systems should be based on a firm understanding of ecological processes. Silvopastoral systems have five main components that can readily be manipulated: trees, pastures, animals, soil and, to a lesser extent, water use. There is also a strong time element because interactions between trees and agriculture change as the trees grow and are harvested.

Light competition

Light becomes the dominant competitive process between widely spaced radiata pine and pasture after 5–10 years (Mead, 2009). The amount of shade cast by trees is related to canopy density, which changes with tree vigour, stocking, the pattern of planting and age as the canopy closes. On the fertile Tikiteri site in New Zealand, for example, pasture disappeared after 14–15 years under evenly distributed radiata pine

FIGURE 11.1
Pasture production under radiata pine trees, as influenced by final crop stocking, stand arrangement and site



Note: T = Tikitere, New Zealand (site index = 33 m), for stockings of 50, 100, 200 and 400 stems per ha, plus 200 stems per ha in twin rows; V = Victoria, Australia (site index = 20 m), for stockings of 60, 200 and 200 stems per ha in 5-row bands 33 m apart.
Sources: Hawke, 2011; Bird *et al.*, 2010.

at a final crop stocking of 200 stems per ha (Figure 11.1). On a slower-growing site in Victoria, Australia, the disappearance of pasture was delayed by 3–4 years (Figure 11.1), while at a higher-latitude site in New Zealand, the pasture production decrease was delayed for 6 years (Hawke, 1997; Hawke and Knowles, 1997). Studies in Western Australia confirmed that reduced pasture growth is the result of shading as the trees age (Anderson, Moore and Jenkins, 1988). Reducing tree stocking to 100 stems per ha or less allows pasture to persist longer into the rotation (Figure 11.1). Pasture growth and retention can also be helped by planting trees in double rows or strips, or even more widely apart as shelterbelts. At the Victorian site, at age 25 years there was still some pasture between bands of trees spaced at 33 m (Bird *et al.*, 2010). For a given age and stocking, canopy closure is usually greater in radiata pine than for many other tree species (Rozados-Lorenzo, González-Hernández and Silva-Pando, 2007). The degree of canopy closure at which pasture disappears (70–85 percent) does not vary greatly between species (Knowles *et al.*, 1999; Mead, 2010b). Pasture productivity under radiata pine has also been related to stand basal area and site index (Pasalodos-Tato *et al.*, 2009).

Associated with decreased pasture productivity under trees is a reduction in pasture leaf area, fewer stems or tillers per plant, greater etiolation due to a decrease in ratio of red to far-red light, and lower bulk densities (Peri *et al.*, 2001; Peri, Lucas and Moot, 2007). Foliage nitrogen concentrations and crude protein increase slightly in temperate grasses but not lucerne (*Medicago sativa*). However, the reduction in productivity is more important than these small compensatory responses.

Pruning and thinning slash and tree foliage litter also smother pasture and interfere with grazing (Hawke, 1991, 1997; Hawke and Knowles, 1997). For radiata pine, litter fall becomes important after age 10–12 years, while most thinning and pruning occurs before this age. The decay of thinning and pruning slash is relatively rapid for the first two years. Heaping thinning and pruning slash will also assist pasture growth and use by animals. Green radiata pine foliage is not particularly palatable, with fresh young needles equivalent to oaten hay (Anderson, 1985). To reap any benefit from foliage on pruned branches, stands should be heavily stocked. The heavy grazing of slash and the understorey also reduces the risk of fire, a factor that is considered very important in Spain (Pasalodos-Tato *et al.*, 2009). Slash can be reduced by using the best genetic material and by timely pruning and thinning (Hawke and Knowles, 1997).

Shade tolerance varies with pasture species. Nitrogen-fixing clovers (*Trifolium* spp.) and some grasses, such as perennial ryegrass (*Lolium perenne*), are light-demanding. Light-demanding grasses are often replaced with more shade-tolerant, less valuable species such as Yorkshire fog (*Holcus lanatus*) or native grasses (Hawke and Gillingham, 1997; Kellas *et al.*, 1995; Mead, 2010b). Although cocksfoot (*Dactylis glomerata*) is relatively shade-tolerant, research comparing it with light-demanding lucerne found that lucerne grown under radiata pine was the more productive species (Peri *et al.*, 2001). The cocksfoot became nitrogen-deficient after the clover had died out, but this did not occur with lucerne because it is a nitrogen-fixing legume.

Moisture competition

Moisture competition is usually the second most dominant factor after light (Mead, 2009). The extent of moisture competition is related to climate, soil moisture storage potential and the pastures used. In the establishment phase, moisture competition can result in tree mortality and reduced tree growth unless pastures and weeds are controlled with spot or strip weedicide spraying (see Chapter 8). Some pasture species compete more than others with trees for moisture (Pollock and Mead, 2008). In an experiment in Canterbury, New Zealand, lucerne and phalaris (*Phalaris aquatica*) roots also exploited the sprayed zone more than species such as ryegrass or cocksfoot (Mead, 2010b). Animals can benefit when used to control weeds such as pampas grass (*Cortaderia* spp.), while controlling the pampas decreases the moisture competition that reduces radiata pine tree growth (see Chapter 8).

As the trees grow and are tended, their roots spread laterally and their changing crowns intercept rainfall, causing fluctuating zones with lower throughfall (rain shadows). Pastures under older trees receive less precipitation than open pastures (Sotomayor and Teuber, 2011). Throughfall patterns, tree root expansion and other shelter effects influence pasture growth. In young silvopastoral stands there may be complementarity, where pasture production is greater with trees than where pastures and trees are grown separately. In the Canterbury experiment, this moisture complementarity disappeared after age 4–5 years (Pollock and Mead, 2008). However, differences in stocking, site, climate and year-to-year variation will alter these patterns and be reflected in pasture dry matter production (Figure 11.1). Rain shadows and tree root competition are also important for shelterbelts (Mead, Millner and Smail, 1999).

Nutrient competition

Although nutrient uptake is facilitated by soil moisture, nutrient competition is usually less important than moisture.

The reduction of clover under trees may result in nitrogen stress in both pastures and trees (Mead, 2010b). In addition, forage harvesting may remove more nitrogen than is fixed by pasture legumes, even when the legumes grow vigorously (Goh *et al.*, 1996). When animals graze the pasture they recycle most of the nutrients, and nitrogen stress is less evident. The results of foliage vector analysis in the Canterbury experiment confirmed that both moisture and nitrogen stress occurred with the more competitive lucerne and phalaris-clover pastures (Mead, Scott and Chang, 2010). Furthermore, understorey competition resulted in an accumulation of phosphorus in the pine needles, probably due to changes in soil phosphous availability.

Animals using shelterbelts, shade trees or woodlots for protection often transfer fertility from the open field to areas where they congregate (Hawke and Gillingham, 1996).

Soil–plant interactions

As discussed in Chapter 2, plantation forests and other types of tree-planting can markedly reduce erosion and alter stream flow and water quality. Tree-planting and earthworks on farms can also increase water infiltration while reducing soil erosion; this is particularly useful in lower-rainfall areas (Figures 11.2 and 11.3; INFOR, 2008). Both trees and pastures can alter soil-nutrient capital, depending on the amounts removed from the site compared with replacements from weathering, aerial deposition, nitrogen fixation and fertilizers (see Chapter 10). The establishment of trees may also reduce moisture movement through the profile, which together with the uptake of nutrients by deep tree roots can lead to lower leaching losses of soluble ions such as nitrates than in open pastures (Mead, Scott and Chang, 2010). In Western Australia, radiata pine agroforestry plantings lowered water tables and reduced salinization (Bari and Schofield, 1991).

Growing radiata pine on improved pastures or abandoned agricultural land often leads to reductions in pH, nitrogen, organic phosphorus and sometimes total carbon and exchangeable cations (Perrott *et al.*, 1999; Ross *et al.*, 2002; Rigueiro-Rodríguez, Mosquera-Losada and Fernández-Núñez, 2011). In contrast, the establishment of radiata pine silvopastoral systems on former arable land has been shown to increase carbon, nitrogen, the carbon: nitrogen ratio, organic phosphorus and pH (Mead, Scott and Chang, 2010). The direction of soil changes depends on the starting point as the ecosystem moves towards a new equilibrium.

Animal–plant interactions

Animals often damage young trees, particularly close to gates, so sheep must be monitored closely in radiata pine stands less than 2–4 years of age (Hawke and Knowles, 1997; Mead, Millner and Smail, 1999). Shelterbelts and individual trees in paddocks also need to be protected from animal grazing. Animal live-weight production, including wool production, is related to the availability of feed and so decreases over time and

FIGURE 11.2

Contour soil bund to collect runoff in a low-rainfall area in Chile

A. Sotomayor

with higher stockings (Hawke and Knowles, 1997; Peri *et al.*, 2001; Bird *et al.*, 2010). Decreased animal bite size offsets any improvement in palatability under trees. There can be higher parasite loads in sheep grazing under radiata pine stands (Hawke, 1991).

Trees can alter the microclimate through shelter and shade, which can be advantageous to animal health and performance, especially at critical times (Mead, Millner and Smail, 1999; Fisher, 2007; Sotomayor and Teuber, 2011). Trees typically reduce wind speed and wind chill compared with open pastures. General animal performance is reduced when the temperature is outside the optimal thermal well-being zone for an animal species. Both cold and heat stress reduce animal production. With cold stress, feed intake is increased to maintain body temperature, while heat stress leads to a reduction in feed intake. Thus, trees can be used to optimize animal productivity as well as to protect newborn animals from storms or prevent sunburn or cold stress in shorn sheep.

Tree age effects

With widely spaced trees in pastures, the net effect is frequently to increase pasture productivity compared with open pasture for the first few years after planting (Figure 11.1). However, pasture growth and quality decrease as the trees close canopy following final pruning and thinning.

Shelter effects tend to improve with time. With shelterbelts, the amount of shelter is related directly to tree height, so shelter benefits increase with time (Mead, Millner and Smail, 1999). Young trees provide only limited shelter and, because they displace pasture, the net effects are usually negative. However, net effects improve as the shelterbelts increase in height.

FIGURE 11.3

Radiata pine in Chile, at age 5 years, planted in twin rows spaced 7m apart. The ripping rows follow the contour to encourage water infiltration

WINDBREAKS

When Europeans first settled in Canterbury, New Zealand, the combination of wind and a lack of native trees prompted settlers to use radiata pine as a shelter tree (see Chapter 1). Hall (1898) vividly described the need to plant seven-row-wide radiata pine shelterbelts at 2.74 × 2.74 m spacing (1 330 stems per ha). He described those shelterbelts as increasing crop and grass growth, as well as being extremely valuable for stock shelter. Incidentally, Hall also used these belts as stock havens when the trees were big enough. Indeed, it is still possible to find shelter trees planted in Canterbury between the 1870s and 1900, a living testimony to the species' potential as a windbreak. It also demonstrates that when the tree is grown deliberately for shelter it can be stable, contrary to its performance in plantations.

Wind can reduce plant growth through mechanical damage, sand blasting, suboptimal temperatures, increased moisture loss and the loss of topsoil from potentially erodible soils (Nuberg and Bennell, 2009; Mead, Millner and Smail, 1999). The consequences are lower crop yield and lower crop quality, particularly in horticultural crops and to a lesser extent in cereal crops and pastures. Some effects may be infrequent but severe, while complex microclimatic changes can result in variable growth and fluctuations in the time of crop maturity, lodging, etc., making economic assessments of shelterbelts difficult. The effect of cold wind on animals include increased heat loss and higher critical cold temperatures (because of wind chill), which increases the mortality of newborn lambs, calves and recently shorn sheep (Reid, 2009). Newborn lambs are particularly susceptible to hypothermia induced by wet, windy weather. Shelterbelts can also protect animals from snow. While the effects of shelterbelts on reducing lamb mortality are variable (Pollard, 2006), research has confirmed the importance of shelter and shade for animal welfare (Fisher, 2007; Reid, 2009). Shade from trees is important for keeping animals cool in hot weather, especially so when stock is concentrated in yards for long periods in hot weather.

However, shelterbelts and shade trees also compete with adjacent pastures and crops for light, moisture and nutrients. These competitive effects may extend on either side of a shelterbelt for a distance of one to two times the height of the windbreak and can be exacerbated by the rain shadow in the lee of the windbreak. Thus, it is important to take into account the effects of shading and rain shadows when planning where to establish shelterbelts and to acknowledge that tree roots will invade the field. There can be reduced frost close to the trees. Stock will also transfer fertility nearer to the shelterbelts or shelter trees when they congregate around them (Hawke and Gillingham, 1996).

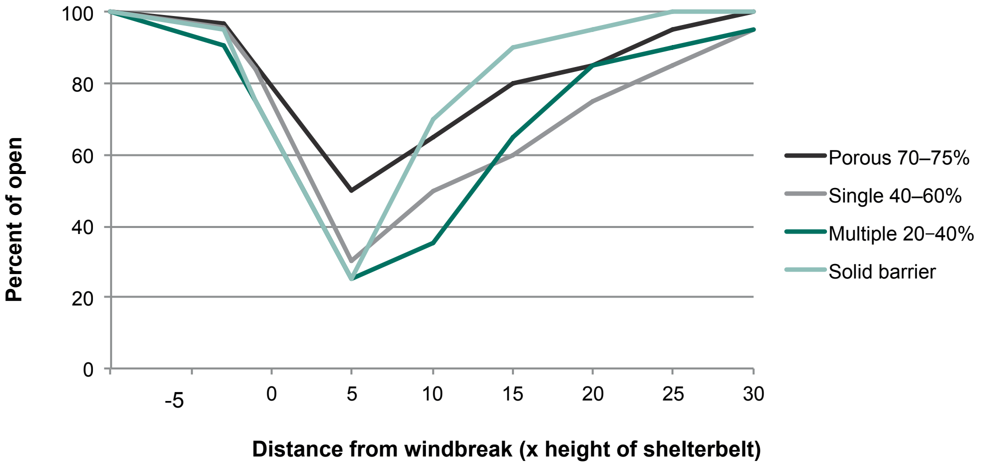
Shelterbelts are only one way of protecting animals or crops, and so their use should be evaluated as part of an overall farm strategy. Other plants, topography, artificial shelter, animal management and diet can all play roles in ensuring animal health (Fisher, 2007). Shelterbelts may also be used to improve working conditions and energy conservation in buildings, as well as protecting roads on farms. Models have been developed to assist decision-making.

The basic principles of shelterbelt design are (Nuberg and Bennell, 2009; Mead, Millner and Smail, 1999):

- The area sheltered to the lee is in direct proportion to the height of shelter.
- For shelterbelts to be effective, they need to be long and free of gaps.
- Shelterbelts should be green to their base so that wind does not funnel under them.
- For windbreaks, 30–70 percent porosity is preferred over very dense belts.
- The shelterbelt should be oriented so that it is at right angles to the direction of the most damaging wind, although there is some leeway with orientation. Sometimes the damaging wind(s) is not the predominant wind of an area. Topography needs to be considered in shelterbelt orientation. If wind funnels along a valley, then the

FIGURE 11.4

The effects of windbreak porosity on windflow at different distances from the windbreak for porous, single-row and multiple-row conifers and for a solid barrier



Source: Brandle, Hodges and Zhou, 2004

trees should be planted up and down the slope. Planting on ridgelines and where topography concentrates the wind is often recommended (Cleugh and Hughes, 2002). However, soil depth and fertility may limit tree growth and stability on ridges.

- Continuity over time needs to be designed for.
- Mixed tree species can be used to increase biodiversity and amenity, to provide forage for bees and to supply other non-wood products. They may also reduce certain risks.

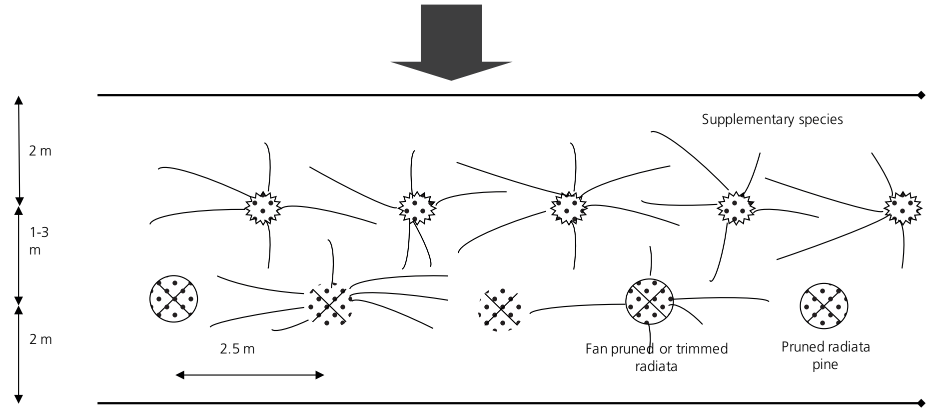
Shelterbelts deflect wind upward, causing reduced wind speed in the lee. The quiet zone is 2–8 times the height of the shelterbelt, with the lowest wind speeds at 4–6 times the height; there is less effect in the wake zone beyond the quiet zone up to 20 –30 times the height (Nuberg and Bennell, 2009). A porosity of 30 percent will reduce wind speeds by up to 70 percent in the most sheltered location, while a higher-porosity (less-dense) shelterbelt has a lesser effect (Figure 11.4). A solid barrier creates a very sheltered area immediately behind it but causes increased turbulence further away. Thus, where a high degree of shelter is required, as with horticultural crops, shelterbelts should be closely spaced and have relatively low porosity. For pastures, they are frequently spaced at 15–20 times the shelterbelt height.

With species like radiata pine it pays to manage the crowns to prevent large branches from developing and from leaning out and shading the pasture or crop. If necessary, root spread can be controlled by deep ripping at 3–5 m from the shelterbelt. It is also possible to manage shelterbelts for timber, and indeed there are designs, called timberbelts, where the provision of timber is given higher priority than sheltering effects (Maclaren, 1993; Hawke and Knowles, 1997).

For porosity control and the provision of wood, single or double-row shelterbelts are usually more effective, as well as more stable, than wider, multi-row belts. With two-row belts, a proven design is to grow slower-growing species such as *Cedrus*, *Cryptomeria*, *Cupressus* or *Thujia* species to windward, with the faster-growing species (radiata pine) on the leeward side (Figures 11.5 and 11.6). This design allows for species with different rotation lengths; thus, when the pine is felled for timber the shelter continues. The slower-growing windward species are usually not high-pruned and are given only minimal tending. Mechanical side-trimming up to 12 m of the radiata pine every few years controls branch development and porosity. It is also possible to high-prune alternate radiata trees, although it is likely the wood will not be as good as in normal plantations. Another alternative to side-trimming is to fan-prune. With

FIGURE 11.5

Representation of a two-row shelterbelt layout, with supplementary species to windward



Note: In this example, every second radiata pine is high-pruned, but some growers prune them all.

fan-pruning, all branches, except those parallel to the tree row, are removed. The trees should not be topped.

High-quality establishment practices, including weed control and the correction of nutrient deficiencies, are essential for shelterbelt trees to ensure even growth and avoid gaps. It is advisable to use good genetic stock; with radiata pine, physiologically aged cuttings taken from 3-4-year-old trees are ideal. If animals are being grazed, good

FIGURE 11.6

A porous two-row radiata pine and deodar cedar shelterbelt that has been side-trimmed and in which every second radiata pine tree has been high-pruned

fencing is essential, and fences need to be at least 1.5 m from the trees. Thus, a single-row shelterbelt would remove a strip of 3–4 m from grazing and a double row of trees would be 4–7 m wide. Radiata pine is usually planted at 2.5 m spacing along the rows, and where there are two rows the two species would be planted so that they alternate (Figure 11.5).

It is possible to design shelterbelts that trap snow, leaving a snow-free area for animals in the lee. One design used in New Zealand is a multi-row radiata pine belt (4–6 rows) in which the leeward row has branches to their bases (trimmed or fan-pruned) and the windward rows are high-pruned. The snow accumulates under the high-pruned trees, leaving a snow-free area in the lee of the belt (Figure 11.7). Such belts can also provide income from wood. Other designs are used in North America (Brandle, Hodges and Zhou, 2004).Woodlots are another alternative to protect animals from snow (stock havens).

Shelterbelts can have adverse effects on highways. The shading of highways may increase the risk of road icing, while there can be reduced visibility at crossroads, and gaps may increase buffeting wind gusts. They can also create problems if they are close to telephone and power lines.

WIDELY SPACED TREES OVER PASTURE

Radiata pine use in this form of agroforestry has been studied in depth in Australasia and to a lesser extent in other countries (Hawke, 1997). The overall conclusion is that radiata pine is not easy to employ in this role because it is too competitive with pastures, the wide spacings result in reduced wood quality and quantity, and it increases the complexity of management. Due to decreased pasture productivity, grazing returns may not cover the increased costs of fencing and the provision of water to silvopastoral blocks (Hawke, 1997). Because of fluctuations in feed supply it is more difficult to match animal needs to feed supply. While radiata pine has seldom been accepted as an agroforestry species at a large scale (Bartle, 2009), there may be ways of improving its use in this role.

The following summary of research is based largely on three major Australasian experiments involving radiata pine and, to a lesser extent, on a Chilean experiment. The Tikiteri experiment near Rotorua, New Zealand (rainfall 1 600 mm), studied final crop stockings ranging from 50 to 400 stems per ha for 25 years (Hawke and Knowles,

FIGURE 11.7
A radiata pine shelterbelt designed to catch snow

Note: The windward rows are pruned to allow snow to accumulate under the trees.

1997; Hawke, 2011). This good site had a site index of 33 m and a 300 index of 33 m^3 per ha per year. A similar experiment, but with lower rainfall (620 mm), performed at Carngham, Victoria, Australia, compared five planting systems over 25 years (Bird *et al.*, 2010). The site index was estimated to be 20 m and the 300 index was 16 m^3 per ha per year. The Lincoln University experiment at Canterbury, New Zealand (rainfall 660 mm), studied competition processes from different pasture understories, including nil understorey, over 16 years (Mead, 2010b). The experiment was established on arable soil and had an estimated site index of 26 m and a 300 index of 24 m^3 per ha per year. The Chilean experiment, in an area with 700 mm annual rainfall and a dry period of eight months, used natural and improved pasture (subterranean clover and phalaris) and compared silvopastoral treatments with a typical radiata pine plantation and non-tree treatments (Sotomayor and Cabrera, 2008). The estimated site index was 27 m and the 300 index was 23 m^3 per ha per year, similar to the Lincoln University experiment. All four experiments involved grazing by sheep.

Generally, pasture production under radiata pine is better than in the open for only 2–3 years in the early years of the stand (Figure 11.1; Hawke, 1997; Mead, 2010b). Animal management needs to be tightly controlled while the trees are small, so some managers prefer to cut the pastures for silage or hay in the first 2–3 years after planting (Hawke and Knowles, 1997; Maclaren, 1993). Animal damage to young trees varies widely, and caution is recommended when introducing sheep in the first few years; with cattle it is best to wait until the tree bark becomes corky (Reid, 2009). In these first few years, the lax grazing used to prevent tree damage works against maintaining good pasture quality. For large-scale operations, the use of individual tree protectors is too expensive and repellents are too labour-intensive, although they may be used on a small scale (more so with fruit and amenity trees). Slash from pruning or thinning and later from litter fall decreases the value of the pastures, as do other changes in pasture quality (Hawke, 1997; Hawke and Knowles, 1997; Mead, 2010b). Cattle forage among slash better than do sheep. Unless tree stockings are very low, grazing is generally restricted to less than half the normal rotation (Figure 11.1).

Individual tree diameter and crown growth is faster at low radiata pine tree stockings, but height growth can also be reduced (Box 9.1). In the Tikiteri experiment, log quality and grade outturns were poorest with the lower stockings because of the large branches and the high amount of low-density core wood; pruning was unable to offset these losses (Hawke, 2011). In this particular experiment, the low-density corewood was exacerbated by tree-breeding (see also Chapter 6).

In the Victorian experiment, where growth was much slower than at Tikiteri, only the trees at 60 stems per ha were large enough for logging at age 25, and only the pruned butt logs were suitable as sawlogs because the top logs were too heavily branched (Bird *et al.*, 2010). The higher stockings in this trial were suboptimal for sawlogs at age 25 and a longer rotation was necessary. Belts of trees had several advantages. Apart from greater pasture productivity (Figure 11.1), it is easier to exclude stock while young; the radiata pine trees also had similar growth characteristics to those grown in normal plantations. Belts of trees are probably better suited for cropping.

The Canterbury experiment had a uniform final crop stocking of 200 stems per ha and included comparisons of physiologically aged clones with seedlings (Mead, 2010b). Growth rates, tree taper, tree form and butt sweep, DOS of the pruned butt logs and branch index were all reduced by understorey competition during the first 10–12 years. Following suppression of the understorey, growth rates were similar; the most competitive understories would have increased rotations by two years to obtain the same volume at harvesting but the trees would have improved wood properties. There were distinct differences between radiata pine seedlings and clones. Seedlings were less affected than clones by competition and had higher taper, although differences between the two types were less at mid-rotation.

The clones were less susceptible than the seedlings to toppling (Gautam *et al.*, 1999).

A key lesson from the Canterbury experiment is that managers can control tree growth and form by their choice of understorey pasture. Lucerne under the radiata trees performed well in this summer-dry environment, but it would not be suitable where winter feed is important because it has lost its palatability by that time of year. Cocksfoot/clover pasture was a good compromise between growth rates, tree form and pasture production. A second important lesson is that clonal radiata pine has advantages. Now that highly improved clones with better corewood properties are becoming commercially available, these may overcome the problems associated with poor wood properties on farms (Carson and Carson, 2011; Figure 6.1).

In the Chilean experiment, where the final crop stocking was 200 and 435 stems per ha for the silvopastoral and forest treatments, respectively, total volume at age 24 years was 20 percent lower in the silvopastoral treatments (Sotomayor and Cabrera, 2008). However, as the diameters in the silvopastoral treatments were over 50 cm, compared with 41 cm in the forest treatment, there was a considerably higher volume of more valuable pruned logs under the silvopastoral treatment. While this study did not include assessments of stem or log quality, animal productivity was included in the analysis. In economic terms, the silvopastoral treatments with natural pasture were slightly more profitable than the forest treatment, but the silvopastoral treatment with improved pasture was less profitable in this dryland situation. The traditional grazing of open pasture was reasonably profitable, but using improved pasture was not at all remunerative. IRRs of the better treatments, without land costs included, were between 9.7 and 11.5 percent.

In summary, the future use of widely spaced radiata pine (e.g. final crop stocking of 100 stems per ha) over pasture may be improved by planting specially selected clonal materials and choosing pastures other than ryegrass/clover to control tree growth and form. The correct combination could ensure that pasture is available for most of the rotation while at the same time producing large-diameter trees of acceptable quality timber. However, as this will not overcome the increased management difficulties with this type of system, there need to be additional benefits to justify this silvopastoral practice. Erosion control, the use of plantings as stock havens under adverse weather conditions or when animals are giving birth, fire control and other social advantages are all possible reasons that could tip the balance in favour of silvopastoral systems (Mead, Millner and Smail, 1999; Pasalodos-Tato *et al.*, 2009). In Chile, silvopastoral systems are favoured by over 90 percent of small farmers, who see it as a way of increasing income, improving their quality of life, reducing erosion and providing fuel (Sotomayor *et al.*, 2009).

WOODLOTS

Planting woodlots is a common practice on farms and small holdings. On farms, woodlots are often planted in areas that produce poor pasture or have other limitations that need to be addressed (Hawke, 1997; Mead, Millner and Smail, 1999; Nuberg, Reid and George, 2009). In Galicia, Spain, radiata pine woodlots have been supported by the European Union's agricultural policies (Rigueiro-Rodríguez, Mosquera-Losada and Fernández-Núñez, 2011). Plantations are frequently grazed, sometimes as an aid to weed control (see Chapter 8), and, particularly in Spain, as a fire protection measure (Pasalodos-Tato *et al.*, 2009).

The management of these woodlots usually follows normal management options for radiata pine (see Chapter 9). Thus, the recommended thinning and pruning schedules correspond to the typical schedules for radiata pine management (Maclaren, 1993; Sotomayor, Helmke and Garciá, 2002; Private Forests Tasmania, 2004). Many farmers, driven by profit and the wish to diversify income, may attempt to keep costs under control by doing the silviculture themselves. Environmental reasons are often also important in the establishment of woodlots on farms, but recreation and landscape aesthetics less so, at least in New Zealand (Rodenberg and Manley, 2011). However, the choice of site for woodlots is critical (Maclaren, 1993). Factors such as topography, roading, harvesting requirements and transport, a small woodlot size and lack of good markets can easily make a project unprofitable.

A radiata pine woodlot can play a major role as a stock haven, much like a block of widely spaced trees in pasture. For this role to be effective, the location of the woodlot needs to be planned (Mead, Millner and Smail, 1999). For example, if animals are to be kept under trees after shearing, the woodlot needs to be close to shearing sheds. Where protection is required during winter storms or at lambing, the location should allow ease of access from several paddocks. Woodlot stock havens should be located on warm sites. To minimize cold drafts, the outer row should not be pruned, although access to the interior should be sufficient to allow the distribution of feed.

FARM PLANNING

The integration of tree-based systems into farms is best achieved through whole-farm or catchment-based planning. In Spain, a common problem is the small size of landholdings; in this case, establishing some form of land management cooperative might be needed (Fernández and Sarmiento, 2004). For many catchments, the best outcomes will involve all farmers jointly planning their approaches.

The diagnosis and design process begins with defining the important roles for trees in the area, followed by design, priority setting and financial planning. The adopted design must be integrated into the owner's objectives. Planning may be assisted by experts, consultants or extension workers. A number of decision-making tools such as models have been developed, and in Australia the Master Tree Grower programme is available to assist farmers (Knowles, 1994; Nuberg, Reid and George, 2009). In Chile, the Instituto Forestal provides advice on agroforestry models (INFOR, 2008).

In an example in New Zealand (Box 11.1), the diagnosis and design process began with experts in science and policy and local Maori and farmer leaders reviewing farm characteristics and the problems being experienced in this high-country farming catchment and setting goals. The next step explored options to achieve increased profitability and sound environmental outcomes. This was supported by the use of a radiata pine agroforestry model that enabled various scenarios to be explored. Finally, the project was implemented and its outcomes monitored. In this case, radiata pine woodlots played a major role in stabilizing the steeper hills and providing for eventual timber income, while streams were protected by native trees and shrubs. Grazing was restricted to gentle slopes, fertile soils where animal management could easily be intensified.

TRENDS

Farm forestry involving radiata pine was popular with farmers and small investors in Australasia 15–25 years ago. It was supported by government extension workers, subsidies, strong farmer leaders, the prospect of good returns and the perceived need for income diversification. However, this supportive environment was followed by the dissolution or downsizing of state agencies and the sale of their forests and thus a loss of farmer confidence, first in New Zealand and later in many Australian states. Subsidies were withdrawn in New Zealand, except in special erosion-control situations, but advantageous tax treatments continued in Australia. However, in Australia there was also a switch towards growing short-rotation eucalypts for pulpwood. Coupled with this were decreased returns to growers and the realization that growing radiata pine at low stockings on improved grasslands was not as beneficial as previously assumed. More recently in New Zealand, dairy farms have been expanding on better land at the expense of sheep and beef farms. These and other factors have contributed to a decline

BOX 11.1

Catchment diagnosis and design planning in New Zealand hill country

An evaluation of this 296 ha hill farm catchment found that since the forest was felled in the 1920s, 11 percent of the area had been subjected to landslips and that up to 80 percent of the area was potentially prone to landslips. Further, sediments were high in unprotected streams compared with those coming from remnant forest areas, and 39 percent of the land area was covered with low-quality, difficult-to-manage pastures. Land managers, policy agencies and biophysical scientists worked together to identify the following main economic and environmental goals for the property:

- developing viable businesses;
- maintaining/restoring healthy ecosystems;
- protecting landscape values;
- improving environmental performance.

Various scenarios were explored using the agroforestry estate model (Knowles, 1994) and expert stakeholder knowledge. These scenarios included radiata pine plantations, riparian re-vegetation, native forest restoration, pastoral land stabilization, and livestock intensification. Time scale and economics were also considered. Priorities for action were determined, along with a timeline for implementation. The final plan called for radiata pine woodlots covering 153 ha in the upper catchment; 7 ha of native forest planting, primarily as riparian strips; and 131 ha in the lower catchment for improved sheep and beef farming. Planting 1 000 widely spaced poplar poles were also prescribed. About 20 km of steam fencing was undertaken. The pine were planted at 1 200 stems per ha and designed to have a final crop stocking of 400 stems per ha. Sheep grazing began under the trees at age 4 years.

Early assessments of the project found a large decline in stream sediments (76 percent), phosphorus (62 percent) and faecal coliform, while the native forest had started to recover. Lambs increased productivity by 87 percent per ha and beef cattle by 170 percent per ha. Overall, however, a big input of capital was needed to establish the forest, and this is causing cash-flow problems. It is expected that in the longer term the project will prove very profitable.

Sources: Dodd *et al.*, 2008a, 2008b, 2008c

in interest in planting radiata pine on farms in Australasia.

This trend away from radiata pine farm forestry in Australasia could change. A better understanding of the problems associated with growing radiata pine on improved grasslands has been discussed above but is yet to be translated into improved farm forestry confidence. Of greater importance, however, are the rapidly changing attitude on how markets and urban populations wish to see farming undertaken and the impacts of climate change and resource overuse. There is growing recognition that farming should follow a better ecological model, where the environment is protected and multiple objectives are emphasized. Whole-farm, catchment and landscape planning are part of this trend. Climate change mitigation, the need to move away from fossil fuels, and the implementation of greenhouse gas emission trading schemes are also raising the prospects of more large-scale tree planting, although it is unclear what role radiata pine will play compared with other species (see Chapter 3).

In Chile, small radiata pine plantation growers have been supported by various government programmes, including research, but they are also occasionally involved in contract growing for the timber industry (Morales, 2005). Subsidies are still available for small growers for woodlots, agroforestry systems and shelterbelts. For woodlots and widely-spaced trees in pasture, such subsidies can increase internal rates of return by 5–8 percent (Sotomayor, Helmke and García, 2002; Sotomayor and Cabrera, 2008). However, farmers are often keener on planting short-rotation eucalypts than pines.

In Spain, radiata pine forestry has taken place on abandoned agricultural land, often supported by European Union policies and with the help of local forestry associations (Michel, 2000; Rigueiro-Rodríguez, Mosquera-Losada and Fernández-Núñez, 2011). Grazing in silvopastoral systems is also seen as a way of reducing the risk of fire and increasing biodiversity. Research in agroforestry has been increasing in recent years and should assist with better implementation in years to come.

12 Conclusions

This book has reviewed the development of radiata pine plantation forests as well as current management practices. It has illustrated how global experiences in growing the species and a wealth of research have contributed to building current-day management practices. The expansion of radiata pine plantation forests into the most widely planted non-indigenous conifer did not occur by accident but, rather, was the result of persistence by visionary people and societies. It is an inspiring story that has been an encouragement to those seeking to plant trees to provide for the needs of people in the widest sense. Although beyond the scope of this publication, it is important to note that the steps taken towards the domestication of radiata pine did not happen in a vacuum but unfolded in parallel with work on other species; this undoubtedly assisted in the establishment of today's radiata pine plantations.

LESSONS FROM THE RADIATA PINE EXPERIENCE

There are many ways in which forest managers and the wider community can benefit from the experience with radiata pine forest plantations. The major lessons learned are given below.

Growth characteristics

Compared with many other pine species, radiata pine is:

- fast-growing and able to produce large logs in under 30 years;
- flexible in growth habit, so can take advantage of a range of climates;
- a nutrient-demanding species;
- a versatile (although not exceptional) general-purpose timber.

Species niche

A major lesson from experiences in growing radiata pine is that it is vital to recognize its ecological niche (see Chapter 2), and planting outside this niche should be avoided. The radiata pine niche is:

- Regions with temperate maritime environments with a relatively dry summer period and certainly not humid summers. An annual rainfall greater than 600 mm suits the tree best. Suitable rainfall distributions are winter-biased or near uniform. Sites with the possibility of very low temperatures, hail or heavy snow should be avoided.
- The species is generally grown between latitudes 34° and 44° and below 1 000 m altitude (although the native Mexican island populations are outside this latitude range).
- The species has occasionally been grown at high altitudes in some low-latitude sites and in summer-rainfall areas with low humidity, but this could be risky because of pests.
- Planting on shallow, waterlogged or highly alkaline soils is not recommended, unless these limitations can be improved.
- Radiata pine is moderately tolerant of salt spray.

Climate change may alter the locations where radiata pine can be grown successfully. To date, however, information on the impacts of climate change or on radiata pine's resilience is scanty. Further research is being undertaken in this field.

Radiata pine forests and societal values and needs

The expansion of radiata pine plantations occurred in Australia, Chile, New Zealand, Spain and South Africa because of the demand for wood products (see Chapter 3). For the most part, governments were instrumental in promoting and supporting these programmes, but as private-sector investment in tree-growing and wood industries has matured, direct financial support from governments has decreased. Some direct and indirect support has continued, primarily through the provision of an enabling policy framework for investment and supportive research and education. Wealth creation has been an important consequence for countries or regions that have developed large-scale radiata pine plantation forests. Owners have generally obtained satisfactory economic returns from radiata pine plantations, although returns have decreased in recent years.

In addition, other societal benefits (see Chapter 3) are increasingly being recognized, including the effects of radiata pine plantations on:

- Generating employment, although the amount of employment changes over time. Employment increases with the development of associated industries but can also fluctuate with the rates of new planting, silvicultural practices, changes in company structures and innovations. About 30 jobs are supported for every 1 000 ha of radiata pine plantation, although most of these are outside the forest itself.
- Increasing biodiversity conservation compared with some alternative land-uses and reducing the use of natural forests for wood production. Radiata pine forests can also be important habitats for some native species.
- Mitigating climate change by reducing CO^2 emissions. This can result from using plantations to sequester and store carbon, and by reducing the carbon emissions arising from construction and fossil energy sources.
- Controlling erosion and regulating water quantity and quality.
- Developing more sustainable farming systems by integrating trees into landscapes (see Chapter 11).
- Furnishing rural landscapes valued for recreation and amenity.

Some negative issues with large-scale radiata pine plantations have emerged, however, and these need to be actively managed (see Chapter 3). These include landscape issues, wilding spread, reduced water flows in streams and changes to, or impacts on, existing local communities. Active engagement by forest managers with stakeholders has proved beneficial to both communities and forest enterprises. Forest managers have generally embraced environmental standards to reduce impacts and increase other societal benefits.

Radiata pine's wood uses

Radiata pine plantations have become important sources of wood and fibre; this has stimulated the development of wood-using industries (Figure 12.1). Radiata pine is a versatile, medium-density softwood but is not suitable for all end uses (see Chapter 5). Its strengths are its even texture, long fibre length and ease in machining and painting. Its limitations include low-strength corewood, poor natural durability, poor surface hardness, frequent large knots and other defects. It is a commodity species rather than a high-value, special-purpose species.

It has also proved a difficult species to grow for poles or as widely spaced trees on fertile pasture sites in agroforestry, and in both cases care is required to achieve desired results (see chapters 9 and 11). An important lesson from experiences with radiata pine is the need to recognize a species' end-use advantages and limitations and decide how to maximize the use of its good features. This can influence the scale of planting as well as silviculture and management, as has occurred in the main radiata pine-growing countries. Another lesson is that site and silviculture, including tree-breeding, can alter the quality of the wood produced and hence affect end use (see chapters 6, 8 and 9).

FIGURE 12.1
Radiata pine logs on their way to the wood-using industry

Tree-breeding and silviculture

As a result of advances in tree-breeding and silviculture, researchers and managers have increasing confidence to successfully grow the species on a range of sites and with varying management objectives and end-use potential. The key lessons from these experiences are as follows:

- Radiata pine has considerable genetic variability that can be exploited through tree-breeding (see Chapter 6).
- Tree-breeding knowledge and systems have developed substantially and become much more sophisticated. This is ongoing, as technology developments are providing new options. For example, it is now possible to select tested clones for specific sites and wood properties.
- Tree-breeding and propagation systems are closely related.
- The choice of traits to improve has not been straightforward. This is shown by the inadvertent reduction in some wood properties in early breeding programmes.
- Tree-breeding has resulted in substantial improvement in tree form and growth rates.
- Radiata pine is flexible in its response to silviculture and thus in its response to management objectives and other requirements. There is a range of ways in which managers can grow this species (see chapters 8 and 9).
- Nursery practices, site preparation, establishment and later tending should be seen as components of an integrated system linked to management objectives.
- Improved tree breeds and nursery and establishment techniques have allowed managers to plant on more difficult sites and at lower tree stockings (see Chapter 8). Replanting after logging is also influencing establishment practices.
- Forest management decisions have become site-specific. This has been assisted by the development of a range of decision-support systems (see Chapter 9).
- The use of complex modelling support systems should be treated with caution. They can (and have in the past) inadvertently led to suboptimal decisions.
- The silviculture of radiata pine continues to change. In the 1980s there was a trend by growers to use pruning to grow clearwood. Some managers are moving away

from this approach aimed at improving wood quality in favour of a factory-based approach. The development of carbon-trading markets or the use of radiata pine as an energy source may see further changes in silviculture.
- The use of fertilizers has been successful in overcoming nutrient deficiencies as well as increasing the growth of apparently healthy stands with hidden hunger.

The domestication process of radiata pine, and the improvements in the way it is grown, has been based on a concerted 40–50-year research effort.

Sustainability

The two main issues affecting the ecological sustainability of radiata plantations are the possibility of soil degradation and the increasing risk posed by invasive organisms (see chapters 4 and 10). The evidence and research suggests that:

- The productivity of the first planted radiata pine plantations was generally higher than the natural forests because of the release from natural predators, the flexibility of the species to adapt to new environments, better sites, and to a lesser extent, the use of seed adapted to the new environment (land races).
- In general, later rotations have grown faster than earlier rotations because of improved genetics, planting stock and establishment practices. This is an ongoing process. New breeds, clones and silviculture are now being developed for specific sites and wood properties.
- With the exception of Spain, there has been wide acceptance of the use of fertilizers on nutrient-deficient sites.
- In the rare cases in which there was a decline in growth rate between rotations, the decline was due to poor management practices such as the removal of topsoil or the burning of slash.
- Nutrients extracted in logs will usually be offset by natural inputs. Whole-tree harvesting and short rotations pose bigger risks on some sites.
- The number of invasive organisms has increased (see Chapter 4). In some cases, particularly where radiata pine had been planted on unsuitable sites, invasive species have led to the abandonment of trees. In most cases, the problems have been ameliorated and can be lived with. For example, biological control has helped to control some insect pests.
- In general, growing healthy, vigorous trees should be the goal, since these are likely to be least affected by invasive organisms.
- There is recognition that quarantine and monitoring procedures need to be strict and that tree-breeding programmes should keep a wide genetic base.
- However, managers now face novel ecosystems in a changing environment and this makes it difficult to predict the future risk to radiata pine posed by biological threats.
- Abiotic damage from drought, wind, frost, snow and fire can be limited by careful site selection and stand management. However, climate change may increase such risks.

Sustainability is also about working with communities to ensure that societal needs are met and that negative aspects are reduced or mitigated (Figure 12.2; see Chapter 3). Forest managers also need to be mindful of the need to use global resources carefully. Many radiata pine plantation growers have embraced environmental standards, including independent certification, and this has assisted in obtaining a balance between productive and other ecological or societal services.

Radiata pine plantations have been sound economic investments to date, creating wealth for countries and communities. Further investment in the main areas that can grow radiata pine forests should make reasonable returns, provided that market acceptance remains buoyant and governments maintain consistent policies. In some places, land costs may limit expansion.

FIGURE 12.2

Radiata pine, other introduced trees, native areas and farming create an attractive landscape

Uncertainties

- The effects of climate change on radiata pine plantation forests are still insufficiently known, despite initial modelling on the topic.
- Associated with climate change mitigation is the use of afforestation to store carbon or to provide a renewable energy source. How governments will encourage or discourage these options, however, is yet to be seen.
- There is ongoing discussion and research on how to value the wider environmental benefits of plantation forests and how to manage these values for societies.
- Discounted cash flow is widely used to value forests and make management decisions (see Chapter 3). By its very nature, the use of commercial discount rates tends to downplay social benefits that may accrue to future generations. There is still no agreement on how to overcome this aspect of discounted cash flow.
- There is ongoing debate about whether radiata pine forest managers should aim to grow their trees for particular markets in the future or alternatively to provide industry with uniform logs that can be manufactured into products needed at a given time.

THE FUTURE OF RADIATA PINE FORESTS

After a rapid expansion from the 1960s, the growth in area of radiata pine forests has stagnated (Table 1.2). There is still some expansion in Chile, but globally this is offset by the contraction of radiata pine in New Zealand, where competition from other land uses is high. At the same time, many areas have been through several rotations successfully. The forests and industries they support are largely privately owned. The radiata pine industry is hence in a "mature" phase.

The prospect of a new era of radiata pine planting should not be discounted. There is no shortage of physically suitable land in major grower countries on which this could occur. Planting trees as carbon sinks, as well as for wood, fibre and energy, and the placing of financial values on other social services could perhaps drive this growth.

On the other hand, market uncertainty and the increasing cost of land resulting from competition from other land uses may be impediments to further planting.

It is very unlikely, however, that large-scale planting of radiata pine will occur outside the current major radiata pine-growing countries. Species–climate matching programmes suggest that suitable lands are relatively scarce in other countries.

Future radiata pine forests will change in nature in response to market and social demands and because there are strong research programmes. Concerns over ecological sustainability because of soil degradation have proved manageable. The greatest threats to radiata pine plantations seem to be from climate change, the uncertainty around invasive organisms, and other rapid changes as an expanding world population adjusts to limited resources. Market changes are also occurring with, for example, moves towards reconstituted wood with predictable properties tailored to specific uses, or to meet demands for energy-efficient "green" buildings. Market changes will therefore continue to influence the nature of radiata pine plantations.

Forest managers can look forward to further exciting developments and be confident that they are growing a species of benefit to their communities. Communities can be equally confident that radiata pine plantations and their products are renewable, environmentally friendly and energy-efficient. The future for radiata pine forests is bright.

Glossary

300 index	Stem volume mean annual volume increment for a 30-year-old stand, at 300 stems per ha and pruned to 6 m.
Adventious	Abnormal development of plant parts; used here in respect to epicormic branches from needle fascicles.
Allozyme	Variant of an enzyme coded by a different allele.
Branch index	Average diameter of the largest branch in each of the four quadrants of a standard log length.
Broad-sense hertitability	(H^2) – the proportion of the combined additive and non-additive components to total phenotypic variability.
Chipwood	Wood suitable for making chips (small pieces of wood) used to make pulp, wood composites, etc.
Clearwood	Defect-free wood produced by a tree following pruning.
Conditioning	In nurseries, those techniques used to prepare growing stock for the shock of planting in the field.
Crown thinning	Removal of dominant or co-dominant trees in order to favour the best trees in these crown classes. Also called thinning from above.
Cutting	Logging – the felling of trees. Regeneration – planting stock derived by rooting shoots or other plant parts.
Decurrent	Spreading crowns resulting from branches growing nearly as fast as the central leader.
Epistasis	Genetic dominance of one allele over others.
Fascicle	Short-shoot, which in radiata pine typically has three needles.
Gibberellin	Plant hormone that regulates growth and other developmental processes.
Internode index	Percentage of the log length comprising clear lengths greater than 0.6 m.
Internode	The clear proportion of a stem between branch whorls.
Lammas shoot	Abnormal late-season growth of leaves, leader or branches. In radiata pine, the growth of upper branches results in retarded leader syndrome.
Lignotuber	Woody storage structure close to ground level which has concealed, dormant buds. Found in many eucalypts.
Log sweep	Lack of straightness in a log. Often measured in mm per m of log length.
Low thinning	The removal of trees in lower crown classes (subdominants or suppressed trees) to favour the upper crown classes. Also called thinning from below.
Meristem	Plant tissue of rapidly dividing cells that differentiate into new tissues or organs.
Microfibril angle	The angle at which cellulose microfibrils in the S2 layer of the cell walls wind around the cell.
Micropyle	In radiata pine, a minute opening in the ovule through which the pollen tubes enter.
Multinodal	When a tree produces more than one whorl of branches per year. A commonly used term for a polycyclic tree.

Narrow sense heritability	(h^2) – the proportion of the additive to total variance
Ortet	The original plant from which vegetatively propagated plants are derived.
Outbred	Genetic material produced through the mating of unrelated individuals (outcrossing).
Outrow	A row of trees removed during thinning to provide easier access for harvesting equipment.
Ovule	The part of an ovary that develops into a seed.
Parenchyma	Thin-walled, live ground tissues in plants having various functions and found in different organs: e.g. the pith or rays in stem wood.
Phenotype	The observed description of characters or traits.
Plantlet	Tiny vegetative plant that needs to be on-grown to form planting stock.
Polycyclic	Multiple growth cycles of shoots. See also multinodal.
Procambium	A meristematic tissue in plants that provides the primary tissues of the vascular system.
Provenance	The original geographic source of seed.
Ramicorn	A large, high-angled branch.
Seedling	A young plant derived from seed.
Selection index	Numeral value that represents multiple traits and often weighted by their economic importance.
Selection thinning	Removal of trees in the upper crown classes to favour trees in the lower crown classes. Also called dominant thinning.
Serotinous	Pertaining to cones that remain on the tree without opening.
Shelterbelt	A single row or multiple rows of trees or shrubs that alter wind flow and microclimate in the sheltered zone. Timberbelts emphasise an economic product from the trees. See also windbreak.
Shelterwood	A regeneration method in which most trees are harvested but some are retained to provide a suitable microclimate and seed for natural regeneration. The remaining mature trees are later removed.
Silvopastoral	An agroforestry system consisting of trees, pastures and animals.
Site index	A species-specific measure of actual or potential forest productivity. For radiata pine plantations, it is usually the top height at age 20 years.
Slabwood	Wood from the outer portion of logs, often used for other purposes such as chipwood or energy.
Somatic embryogenesis	A process by which ordinary plant tissue is grown into differentiated somatic (diploid) embryos.
Stool beds	An area, usually in a nursery, where plants are grown to obtain cuttings for vegetative propagation.
Stratification	The practice of exposing seed to cold, moist treatments to overcome dormancy and promote even germination.
Strobilus	The cone of a conifer.
Tracheid	Longitudinal wood element predominant in softwoods.
Trait	A characteristic of an organism.
Undercutting	In nurseries growing bare-rooted stock, the practice of cutting the tap root in the nursery bed.
Uninodal	When a tree produces only one 'whorl' of branches per year.

Windbreak	Any barrier (natural, such as trees, or artificial, such as fences or walls) that provide protection against the wind. See also shelterbelt.
Wrenching	In nurseries growing bare-rooted stock, the practice of disturbing tree roots to stimulate the development of a fibrous root system.

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FAO FORESTRY PAPER

Sustainable management of *Pinus radiata* plantations

Pinus radiata (radiata pine) is a versatile, fast-growing, medium-density softwood, suitable for a wide range of end-uses. Its silviculture is highly developed, and is built on a firm foundation of over a century of research, observation and practice. Radiata pine is often considered a model for growers of other plantation species. This book explores current knowledge of, and experience with radiata pine forest plantation management and examines its long-term sustainability.

Radiata pine management needs to integrate the biological aspects of tree-growing, with socio-economics, management objectives, practical considerations and other constraints and opportunities. Although stands of radiata pine may appear to be simple, they are actually quite complex ecosystems because they contain large, long-lived trees that change dramatically over time and interact in changing ways with the environment and with other organisms.

The focus of this book is on the principles and practices of growing radiata pine sustainably. It also looks ahead to emerging challenges facing radiata pine plantation management, such as the effects of climate change, new diseases and other threats, and meeting changing product needs and societal demands.

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