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.

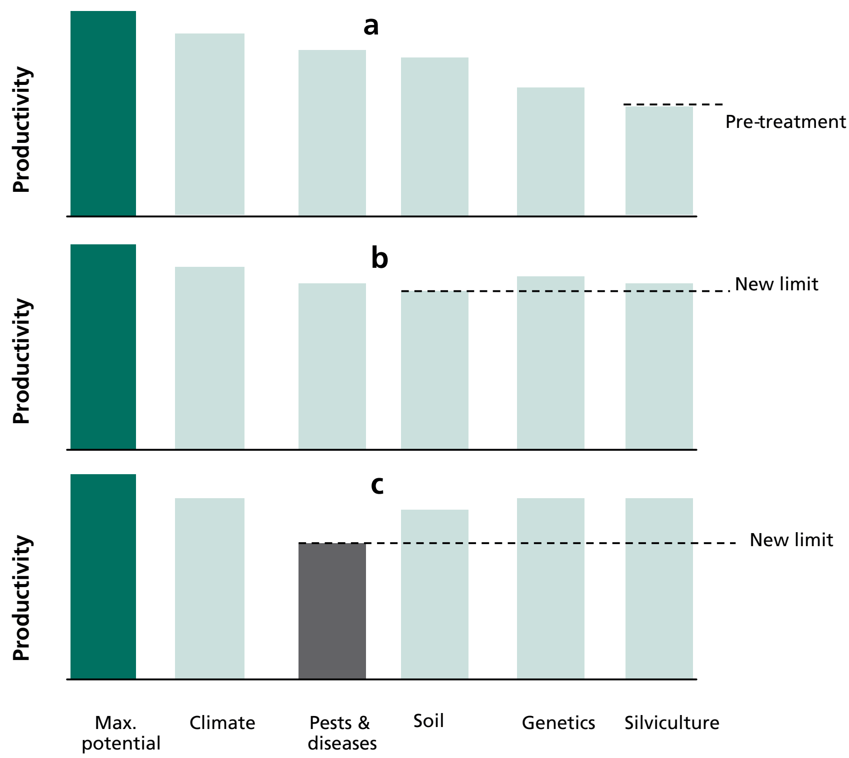
As discussed in Chapter 5, productivity is ecologically defined as the net biomass production per unit area per unit time. Leaf area index and volume growth, which are closely related to biomass production, are often used as productivity indicators. However, for this discussion, net MAI (m^3 per ha per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

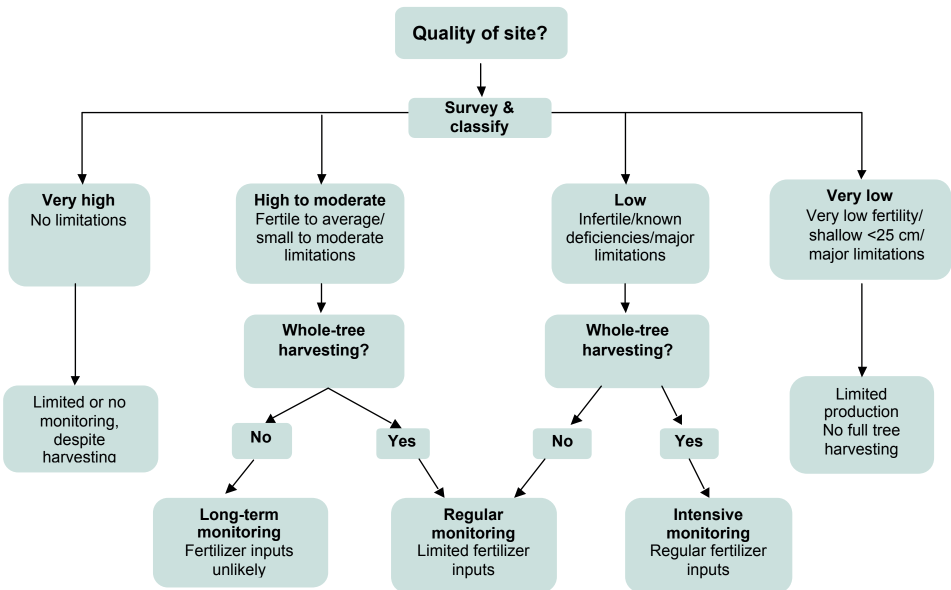
The importance of defining management objectives (principle 1 above) is stressed in earlier chapters. This is also critical for nutrient management because it influences decisions on growing and harvesting methods and their intensity. This principle thus helps define likely nutrient risks. Principle 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.