FERTILISER USE IN THE MANAGEMENT OF PINE AND EUCALYPT PLANTATIONS IN AUSTRALIA: A REVIEW OF PAST AND CURRENT PRACTICES

ELAINE M. BIRK

State Forests of New South Wales, P.O. Box 100, Beecroft, New South Wales, Australia 2119

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ABSTRACT

Soils, climate, and historical factors affecting plantation distribution, and attitudes toward nutritional management, have affected the use of fertiliser in Australian plantations, primarily exotic pines. The diverse nature of nutritional problems encountered in plantations across Australia, and the separate management agencies involved, resulted in a strong divergence of policies and practices regarding the use of fertilisers among the different States until the 1980s. At this time various common pressures, including increasing land costs, prompted reconsideration of productivity gains and returns on investments. As a result there have been several important changes in approaches to nutritional management: nutrition is now regarded as one component of total crop management; plantations are managed on a site-specific basis; management tends to be more intensive, with increased productivity per hectare; soil moisture and nutrients are managed more efficiently; and genetic improvements in nutrition and other parameters are being sought to increase performance, health, and tree form. Nevertheless, actual fertiliser practices vary considerably among regions owing to vast differences in soil and climatic conditions. Fertiliser practices in eucalypt plantations are still being developed although there is considerable information transfer from experience gained with exotic pines.

Keywords: nutrition; nitrogen; phosphorus; trace elements; site-specific management; later-age fertiliser; weed control; slash retention; fertiliser prescriptions.

INTRODUCTION

Timber production from approximately 12.5 million ha of native eucalypt forest and 900 000 ha of plantation forest currently supports 50% of Australia's wood requirements (Squire *et al.* 1991). Although research suggests that fertilisers could be used to increase the productivity of some regrowth eucalypt forests (O'Connell & Grove 1991), this practice has not yet been adopted on an operational scale. Exotic pine plantations, however, are intensively managed, and fertilisers are a major factor contributing to high growth rates. The aim of this paper is to review the status of nutritional management of plantation forests in Australia, principally the exotic pine forests; to identify factors contributing to the development of current practices; and, where possible, to indicate how they relate to nutrient supply and demand.

PLANTATION FORESTS: SPECIES, LOCATIONS, AND CLIMATE

The major plantation species in Australia are exotic pines, principally *Pinus radiata* D. Don, which represented approximately 66% of the total plantation estate in 1990 (Table 1). *Pinus pinaster* Aiton was planted on poorer sandy soils in Western Australia (WA), Victoria (VIC), and South Australia (SA) and tropical pines are the major exotic conifers in Queensland (QLD) and northern New South Wales (NSW). *Pinus taeda* L. and *P. elliottii* Engelm. were the main tropical pines planted initially, but in QLD these have been replaced by *P. caribaea* Mor. var. *hondurensis* Barr. and Golf. and more recently by the F1 hybrids of *P. caribaea* and *P. elliottii* (Simpson & Grant 1991). Hybrids between *P. caribaea* and *P. tecunumanii* P. Eguiluz and J.P. Perry are currently being assessed. Native conifers (*Araucaria* spp.) are planted in QLD and northern NSW. Eucalypts form the dominant broadleaved plantations across temperate and sub-tropical regions; *E. nitens* (Deane et Maiden) Maiden and *E. regnans* F. Mueller are suited to high elevations and relatively high rainfall areas, *E. globulus* Labil tolerates drier, frost-free conditions at low elevations, and *E. pilularis* Sm. and *E. grandis* Maiden are currently the dominant sub-tropical species. A range of species including *E. astringens* Maiden are planted in WA, particularly on soils degraded by salinisation.

TABLE 1–Plantation areas (ha) in 1991

	Public	Private	Total	Total area (%)	Public ownership (%)
Pinus radiata	443 850	236 795	680 645	66.5	65.2
Total conifers	666 472	261 934	926 406	90.5	71.7
Broadleaved	56 816	39 653	96 469	9.5	58.9
Total	721 288	301 587	1 022 875	100.0	70.5

Source: Australian Bureau of Agricultural Resources and Economics (1992)

Plantations in Australia have been established around the eastern and southern coasts and along the tablelands of the Great Dividing Range, the Darling Scarp in WA, and in Tasmania (TAS). Almost half the *P. radiata* plantations receive less than 900 mm rainfall/year and 90% receive less than 1200 mm/year, with summer, winter, and uniform patterns of distribution (Boomsma & Hunter 1990). The lower limit is around 600 mm/year. Moisture availability can severely limit growth at this extreme owing to the large moisture deficit which develops during the growing season. Volume growth can be directly related to rainfall (Whitehead 1985 cited by Boomsma & Hunter 1990) which has been shown to be the primary factor causing growth differences between *P. radiata* forests in Australia and New Zealand (Turner & Lambert 1986a). The regions with a silvicultural emphasis on water-use efficiency are south-eastern and central SA, western VIC, and WA.

The lower rainfall limit for commercially viable eucalypt plantations appears to be about 800 mm/year (Orme *et al.* 1992; Weston 1991; Stanton 1991), although this limit is extended in drier areas where plantations are established for the purpose of effluent treatment (Boardman 1991; Boomsma & Hunter 1990).

SOIL FERTILITY AND NUTRITION

Because of the absence of extensive coverings of volcanic ash or loess, other parent materials have had a major role in determining the types of soils developed in Australia, by setting limits to quartz, clay, and nutrient content, particularly phosphorus and trace elements. According to Waring (1981a) there is greater similarity between Australian soils and those of the upper coastal plain of the south-eastern USA than those in New Zealand because of the reserves of unweathered, primary minerals in New Zealand soils. In south-eastern Australia many soils formed *in situ* on exposed sediments and metamorphic rocks of the Ordovician, Silurian, and Devonian Periods (Waring 1981a); soil parent materials in this region carrying pine plantations range from highly siliceous sandstone to basic rocks rich in ferro-magnesium minerals. Deeply weathered laterites in WA and central SA carry pines although plantations are more widespread on deep, leached, coastal sands (podsols) in south-western WA and south-eastern SA. Exotic pine plantations in QLD are generally confined to the coastal lowlands (podsols and humic podsols) in the south-east and to granitic outwash soils north of the Tropic of Capricorn.

The diverse range of parent materials in south-eastern Australia has been a major factor explaining variations in plant nutrient status and plantation productivity in this region (Turvey *et al.* 1986; Turner & Holmes 1985; Knott & Ryan 1990; Turvey *et al.* 1990). Knott & Ryan (1990) showed variations in basal area of inventory plots from plantations without fertiliser on a range of parent rock types in NSW (Fig. 1). The highest basal area increments were found on granodiorite and basalt and the lowest were on quartzose sandstone and rhyolite.

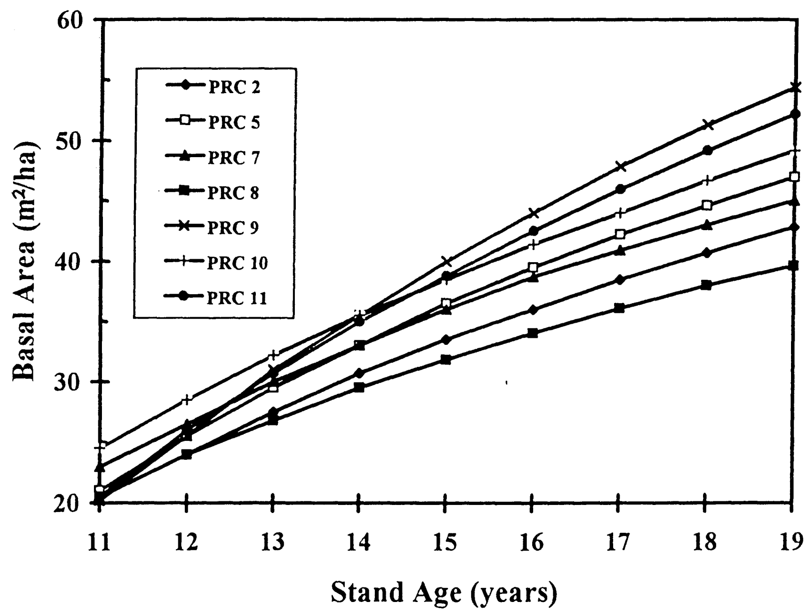

FIG. 1–Relationships between stand basal area (m^2/ha) and stand age for *Pinus radiata* grown (without fertiliser) on different parent rock types in New South Wales (from Knott & Ryan 1990, reproduced with permission). *See* Table 3 for parent rock code descriptions.

Many reviews over the past few decades have documented aspects of pine plantation nutrition and growth responses to fertiliser treatment in Australia generally (Waring 1971, 1981a,b; Woollons & Snowdon 1981; Neilsen 1982; Turner & Lambert 1986a; Boomsma & Hunter 1990) or in particular States (including Kessell & Stoate 1938; Stoate 1950; Raupach *et al.* 1969; Boardman 1974; Knott & Turner 1990; Simpson & Grant 1991). Nutritional problems in *P. radiata* and other exotic pines can be predicted if parent material is known because there is a strong influence of soil parent material on nutrient supply (Turner & Lambert 1986a). Phosphorus is the major growth-limiting element and substantial growth responses can be achieved with fertiliser treatments. Phosphorus deficiency occurs on a wide range of soils including those derived from deposited sands, sandstones, sedimentary rocks, acid volcanics, granites, metamorphics, and weathered laterites. Critical foliage concentrations are used to identify phosphorus deficiencies in established stands but they vary as a function of soil or rock type, stand age, species, and rainfall (Fig. 2) (Turner & Lambert 1986a; Lambert & Turner 1988).

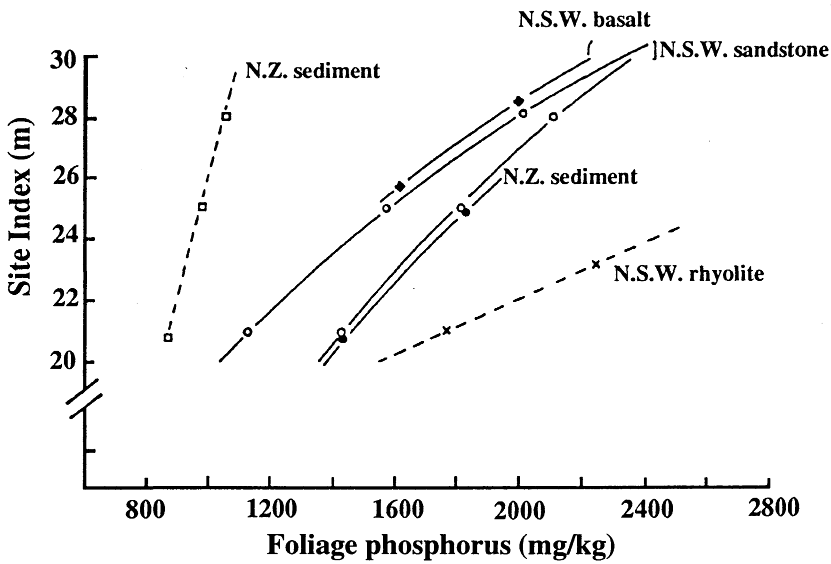

FIG. 2–Foliage phosphorus concentrations and related site index (m) for *P. radiata* (from Turner & Lambert 1986a, reproduced with permission).

Calcium deficiencies in *P. radiata* are relatively localised, occurring on acid volcanics and sandstones in association with phosphorus deficiency, and potassium deficiency occurs on coastal sands in WA, eastern VIC (Raupach & Hall 1974), and in south-east QLD (Simpson & Grant 1991). Magnesium deficiencies are not common, although low foliar magnesium levels occur in young stands on improved pasture sites (Birk 1992) where soils have been stripped of exchangeable base cations through acidification reactions.

Micro-nutrient deficiencies are common on specific soil types and failure to address these problems has frequently resulted in failed plantations. Hill & Lambert (1981) reviewed trace element deficiencies in Australian plantations. Zinc deficiency is a problem for *P. radiata* on coastal sands and it is often associated with copper and molybdenum deficiencies

(Boardman & McGuire 1990). Copper deficiency also occurs on coastal areas on deep humus podsols or poorly drained podsols. Boron deficiency can occur on soils derived from igneous rocks and is exacerbated by water stress and by weed competition. Like boron, sulphur deficiency has been found on soils derived from igneous rocks (Lambert & Turner 1977) although it can be induced by application of nitrogen fertilisers or leguminous nitrogen-fixers on former pasture sites (Turner & Lambert 1986a).

Nitrogen is rarely a primary growth-limiting element in young stands but it often becomes limiting once phosphorus deficiencies are corrected, particularly on ex-native forest sites (Turner & Lambert 1986a), in later-aged stands (Turner & Knott 1991), and on second-rotation sites (Woods 1981). Concentrations of nitrogen, phosphorus, aluminium, and manganese in foliage are higher in pine plantations on improved pastures than in plantations on cleared native hardwood forest soils, and problems associated with high nitrogen availability have been observed in recent years (Carlyle *et al.* 1989; Birk 1990). High nitrogen availability can induce deficiencies of several elements: phosphorus and sulphur in *P. radiata* (Lambert 1986); boron, copper, and zinc in *P. radiata* and tropical pines (Hill & Lambert 1981); and copper in *P. radiata* (Turvey 1984) and *E. nitens* (Turnbull *et al.* 1994).

HISTORICAL PATTERN OF PLANTATION ESTABLISHMENT

Of the wide range of exotic pines tested for afforestation purposes in southern Australia around the turn of the century, *P. radiata* and *P. pinaster* showed the most promise across a range of sites. There was a mistaken idea that the demands of *P. radiata* ("Monterey Pine") could be readily satisfied by the poorest of soils and, given the priority allocation of good lands to agriculture, pine plantations were restricted to land considered unsuitable for agricultural production, particularly along the coastal plains (Kessell & Stoate 1938). Selection of planting sites had little to do with soil qualities (J.Turner, State Forests of NSW, pers. comm.): in SA, uneconomic agricultural land was released for reforestation; in NSW, timbered sites of low commercial value were converted to plantation to concentrate plantings in large blocks to attract industry; and in TAS, cheap land was cleared to plant trees to overcome unemployment during the depression.

The demand for timber increased in the later 1960s and 1970s after the first Softwood Forestry Agreement with the Commonwealth Government (1966 to 1971) which resulted in an upsurge in plantation establishment. This forced expansion on to a wider range of site types including higher-quality soil supporting native eucalypt forests in the south-eastern states. Conversion of native forest to pine continued for a number of years although it attracted considerable public attention. By the late 1970s and through the 1980s the clearing of native forest (SA) or of publicly-owned forest (VIC) for conifers was banned and other State agencies changed their policies accordingly (Fergurson 1991).

Prior to 1970, the largest planting areas were in SA and VIC, predominantly on deep, unconsolidated, coastal sands. Since 1970, the highest rate of new plantings has been in NSW, largely on fine-textured soils. Turner & Lambert (1991) summarised the area of pine plantations according to soil parent material and recent changes in the distribution of plantations (Table 2). The major parent rock types represented across all plantations include shale, siltstone, and mudstone soils (argillaceous rocks). Characteristics of the soil parent materials associated with each rock class are summarised in Table 3. Since the late 1970s,

TABLE 2–Estimate of the area of Australian plantations on various soil parent materials classified according to Parent Rock Code (from Turner & Lambert 1991)

Parent Rock Code*		1970		1990	
		(ha)	(%)	(ha)	(%)
02		7 105	1.6	18 475	1.9
022	shallow	77 220	18.2	158 425	15.9
	deep	61 635	14.5	104 845	10.6
03		5 735	1.4	20 635	2.1
04					
05		147 920	34.9	352 565	35.5
06		940	0.2	1 800	0.2
07					
08		10 345	2.4	30 210	3.0
09		47 550	11.2	145 670	14.7
10					
11		65 485	15.5	161 355	16.2
12					
Total		423 935		993 965	

* *see* Table 3 for explanation and descriptions of Parent Rock Codes

large areas of plantations in south-eastern Australia have been established on agricultural land "improved" with fertilisers (especially phosphorus and nitrogen) and introduced legumes, and degraded through erosion, compaction, acidification, and salinisation.

The area of second-rotation plantings has increased substantially over the last decade but in several parts of the country there is little or no expansion of the plantation estate. All plantings in SA are now second or subsequent rotations. Second-rotation plantings exceed first-rotation establishment in NSW, VIC, and TAS and were expected to by 1993 in QLD (Table 4).

INITIAL APPROACHES TO THE NUTRITIONAL MANAGEMENT OF EXOTIC PINE PLANTATIONS

The widespread development of pine plantations on poor soils pre-empted the need for fertilisers, but pines were introduced with a philosophy that climate set the limits to growth. Based on Northern Hemisphere experiences, considerable effort was expended on matching species to specific site types and vigorous debate continued through several decades about the importance of soil factors. In SA and WA, *P. pinaster* was planted on soils where *P. radiata* was unsatisfactory or failed. Most foresters supported the view that water limitations were controlling growth, and stressed the importance of moisture-holding capacity, soil depth, and root penetration into sub-soil. There was little support for the idea that nutrients limited growth until a few innovative foresters found that fertilisers corrected growth disorders previously thought to be pathological problems. Notably, superphosphate overcame needle fusion on several soils (Ludbrook 1937; Young 1940; Kessel & Stoate 1938) and zinc sulphate sprays overcame rosetting and tip dieback on coastal sands (Kessell & Stoate 1938). These developments generated an alternative school of thought contending that there may be insufficient quantities of essential elements in some soils for good growth (Kessell & Stoate 1938). By about 1950, remedial and establishment fertiliser applications

TABLE 3–Classification of rock types according to dominant soil-forming properties

Code	Parent Rock Class	Soil forming potential dominated by:	Examples of rock type in each class: Consolidated	Unconsolidated
00	Unspecified	Parent rock unknown		
01	Carbonaceous	Carbon compounds	Coal, carbonaceous shale	Peat
02	Quartzose	Quartz of secondary silica	Quartzite, chert, jasper, silcrete, quartzose sandstone/conglomerate	Quartz sand
03	Sesquioxide	Iron and aluminium minerals or oxides	Ferruginous sandstone/ shale/sand, massive laterite/bauxite	
04	Calcareous	Secondary calcium (and some magnesium) compounds, mainly carbonates	Marble, limestone, dolomite, calcrete, highly calcareuos shale	Marl, shelly sands
05	Argillaceous	Clay and/or silt particles	Slate, shale, siltstone, mudstone, peltic tuff, greywacke	Clay mantles
06	Micaceous-chloritic	Micas and/or chlorites	Phyllites, schist	
07	Feldspathic-quartzose A	Medium- to coarse-grained feldspar and quartz	Granite, pegmatite, granitic gneiss, feldspathic sandstone	Granitic saprolite
08	Feldspathic-quartzose B	Fine- to med.-grained feldspar and quartz	Rhyolite, ignimbrite, felsite, rhyolitic tuff	Tephra, pumice, rhyolitic ash
09	Feldspathic-micaceous	Medium- to coarse-grained feldspar and mica	Granodiorite, quartz diorite, monzonite, diorite	
10	Feldspathic	Fine- to med.-grained alkali feldspar	Trachyte, comendite, syenite	
11	Ferro-magnesium	Dark silicate minerals, especially amphibole, pyroxine and olivene	Spillite, basalt, dolerite, andesite, gabber, grindstone	
12	Magnesium-silicate	Ultra-basic magnesium silicates	Serpentenite, periodite, talc	

Sources: Turner *et al.* (1990); Ryan & Knott (1991)

TABLE 4–Area (ha) of plantations established in 1992

	Exotic conifers		Eucalypts	Total
	Second rotation	First rotation		
NSW	1394	1348	101	2843
VIC	1114	743	325	2182
TAS	1548	464	7390	9402
WA	872	1942	4565	7379
SA	1723	0	24	1747
QLD	642	1808	0	2450

Source: 1991–92 or 1992–93 Annual Reports from each State agency were routine for *P. pinaster* and *P. elliottii*, and to some extent for *P. radiata*, because in the poorest soils they would not grow at all without superphosphate.

General attitudes toward use of fertilisers have changed from the days when they were considered a "luxury" to their present use as a basic management tool. The areas treated increased substantially through the 1970s and particularly in the 1980s (Boomsma & Hunter 1990; Knott & Turner 1990). Fertiliser treatments are integrated with other silvicultural practices to increase utilisation of native soil supplies and recycle nutrients in harvest residues (Squire *et al.* 1991; Hopmans *et al.* 1993) in order to sustain or increase productivity and to maintain stand health. Attention has also been given to improving pine growth and form by selection and breeding, particularly in SA (Boardman 1988) and QLD (Simpson & Grant 1991; Simpson & Osborne 1993).

Minimal attention was given to site preparation beyond hand digging prior to planting, and burning the logging debris left after eucalypts were cleared. Improved growth in cultivated fire breaks was observed in WA in the 1930s and survival and growth after the first summer were increased after ploughing (Kessell & Stoate 1938). Ploughing with disc ploughs to eradicate scrub, and other practices such as bedding and mounding, were widespread by the 1950s. The winged ripper, developed in New Zealand, is now more commonly used for cultivation (Johnston 1982). Chemical sprays including atrazine were subsequently developed for weed control and introduced relatively early in SA and QLD, but residual herbicides were not considered a practical option until the late 1970s (Flinn *et al.* 1979a; Boomsma 1982).

STATE TRENDS IN FERTILISER USE UP TO THE 1980s

Being independent management agencies, each State evolved different management policies and practices to deal with its regional plantation problems. The extent of these differences is evident from a comparison of developments in several regions. I have summarised past practices in south-eastern SA, NSW, and south-eastern QLD based on information from publications on fertiliser use (Boardman 1988; Simpson & Grant 1991; Simpson 1991; Knott & Turner 1990), forest management manuals (Woods and Forests 1987), and unpublished materials (R.Boardman, SA Dept of Primary Industries, pers. comm.; Turner pers. comm.) to show the divergent attitudes, policies, and practices during the first few decades of plantation management. Of necessity these are brief summaries and leave much unsaid about the overall development of silvicultural practices in these regions.

Exotic Pines in South-eastern South Australia

Routine fertilisers other than zinc sprays were not used in SA prior to the mid-1950s when superphosphate was applied to *P. radiata* and *P. pinaster* on sites of marginal fertility. Research trials indicated that large areas of coastal sands in south-eastern SA were responsive to application of phosphorus fertiliser as a function of site quality (a function of native phosphorus supplies) and soil moisture. Dry sites did not respond to phosphorus owing to moisture limitations, and the response on wet sites was enhanced by cultivation because of its control of competing vegetation (Boardman 1974). With low organic matter content and low phosphorus-fixation capacities, phosphorus retention was a problem and further applications were required after 2 and 4 years' growth (Boardman pers. comm.).

Growth rates were related to foliage concentrations (Raupach *et al.* 1969) and foliar analysis became an important tool for predicting the need for fertiliser in established stands. Parallel improvements occurred during this period in weed control technology, resulting in a combination of manual and periodic chemical (residual) control measures.

Plantation establishment on native forest sites considered marginal for *Pinus* ceased by the 1970s which brought an end to the planting of *P. pinaster*. All new plantations were established on ex-agricultural land and limited to *P. radiata*. The diversity of soil types increased but the energy costs involved were reduced as establishment fertilisers other than trace elements were not applied in previously treated areas. Second-rotation establishment increased during this period and, after productivity declines were identified on soils with low nutrient reserves where harvest residues were burned as part of the subsequent site preparation (Keeves 1966), there was an intensification of both research and management input into improving second-rotation practices. This culminated with Woods' (1976) Maximum Growth Sequence (MGS) aimed at sustaining growth after clearfelling. The MGS involved repeated nitrogen, phosphorus, and trace element treatments in which nitrogen was the key element (300 kg/ha) applied with at least six other nutrients in conjunction with chemical weed control. Application rates increased progressively to match perceived increases in nutrient demand over the first 4 years of a new plantation. The MGS transformed plantations into stands of "outstanding uniformity, health and great vigour" (Boardman 1988) and became the routine practice for a period of about 3 years (1976–79) while additional research was carried out to identify stand requirements on a site-specific basis (Boardman pers. comm.). The programme was justified economically at that time in that minimum acceptable growth rates (Site Quality IV; Lewis *et al.* 1976) could be achieved and maintained (Woods 1981), but fertiliser costs were scrutinised and alternative strategies involving intensive silviculture, particularly weed control, were investigated (Cellier *et al.* 1985).

Several studies showed that it was critical to eliminate weed competition, particularly for soil moisture, and that the role of nitrogen fertiliser was less significant during the first year after establishment than was previously thought (Squire 1977; Cellier & Stephens 1980a,b; Cellier *et al.* 1985; Nambiar & Cellier 1985; Woods *et al.* 1992). Added nitrogen had a small direct effect on total production, but without nitrogen second-rotation productivity was lower than in comparable first-rotation stands owing to differences in the mineralisation rates of soil organic matter (Theodorou & Bowen 1983). With suitable combinations of silvicultural inputs, the productivities of second and first rotations were found to be equal. Strip weed control with slash was as effective as total weed control in the absence of slash (Squire *et al.* 1991). Smethurst & Nambiar (1989, 1990a,b) examined interactions between weed control and slash retention and showed that mineralisation of organic matter from harvest residues provided more nitrogen than was required by the young pines for at least 3 years after planting.

Related studies on similar soils in VIC showed the importance of undecomposed litter and harvest residues as a surface mulch maintaining more favourable soil moisture than in slash burned soils (Squire *et al.* 1979). Harvest residues were also found to contain a substantial proportion of the site nutrient reserves on these coastal sands (Flinn *et al.* 1979b). The mulching effect of logging residues improved early growth of *P. radiata* compared with burned sites (Squire *et al.* 1979, 1985; Squire 1983; Farrell 1984) largely due to the conservation of soil moisture and increased availability of nitrogen. Hopmans *et al.* (1993) found that higher growth rates could be sustained for at least 15 years where logging residues were retained rather than cleared or burned.

The MGS procedure was revised to ensure that small-sized harvest residues were retained, and to place weed control at a higher priority than establishment fertilisers. Early growth rates are now closely monitored and fertilisers are applied or re-applied if measurements indicate that growth is below the minimum acceptable for SA (fertiliser treatments in SA are no longer based on foliar analysis). The same principles are followed in both the south-east (mostly coastal sands) and in the central region where the landscape is more complex and includes both high and low phosphorus-fixing, fine-textured soils. The rates of application, the fertilisers used, and the frequency of treatment vary according to the soil phosphorus-fixing capacity and current growth rates (Woods and Forests 1987) and are discussed in more detail later in this review.

Exotic Pines in South-eastern Queensland

In south-eastern QLD, the early plantations of *P. taeda* and later *P. elliottii* were established on better-drained sites on the coastal lowlands. As these soils are coarse textured and of low nutrient status, application of phosphorus fertilisers was essential for stand growth and economic viability (Simpson & Grant 1991). In the 1940s, total soil phosphorus was used to determine the species to be planted and the need for phosphorus fertilisers, but the system developed limitations once the plantation expanded across a broader range of soil types. Applications of 50 kg P/ha, as Nauru rock phosphate, prior to and 3 years after planting became routine in the 1950s (Simpson & Grant 1991). There were unsuccessful attempts to relate site index to total soil phosphorus to determine site-specific application rates (Pegg 1967). As site preparation techniques and soil cultivation techniques improved, plantings of exotic pines, mainly *P. elliottii*, were extended in the 1970s to less fertile soils with poorer drainage. Rock phosphate was replaced with more soluble fertilisers; initially ordinary superphosphate (OSP) was applied by air, but it was later replaced by triple superphosphate (TSP) and then by mono-ammonium phosphate (MAP) which is now preferred because nitrogen encourages early growth and can be applied at little extra cost. This required manual application of fertiliser or tractor-mounted equipment which applied fertiliser to individual trees or as a band along the planting row. *Pinus caribaea* and, more recently, the hybrid between *P. caribaea* and *P. elliottii*, replaced *P. elliottii* in the 1980s and plantings were extended on to land formerly under agricultural production.

Research focused on identifying limiting elements and their interactions across the range of sites and for the range of species and taxa being planted (Simpson & Osborne 1993). Different phosphorus response curves were identified for wet and dry sites and for sedimentary and granitic soils, with the result that standard fertiliser trials were introduced on a site-specific basis to identify nutrient requirements and fertiliser prescriptions (Simpson & Grant 1991).

Foliage nutrient concentrations were monitored in routine stands to diagnose responsiveness to phosphorus fertiliser in established plantations and to calibrate nutrient data from trials (Bevege & Richards 1972) as the initial dressings were not considered adequate for a full rotation. Standard re-application trials established on a soils basis resulted in routine treatments of 40 kg P/ha as MAP in aerial applications to established *P. elliottii* plantations older than about 12 years of age. All of the *P. elliottii* plantations were re-treated by 1992 (Simpson & Grant 1991).

Exotic Pines in New South Wales

Early plantings of *P. radiata* in NSW extended from the coast to the tablelands on soils derived from a range of rock types including sandstones, shales, acid volcanics, conglomerates, and granites, most of which are nutritionally poor. In keeping with approaches in other States, there were attempts to match species to sites, and failures were attributed to poor climate and selection of "inappropriate country". After Ludbrook (1937) demonstrated that phosphorus alleviated "needle fusion", limited areas with visual phosphorus-deficiency symptoms received a single, low-cost, phosphate treatment. However, the view that climate rather than soil fertility set the limits on growth (Henry 1963 cited by Knott & Turner 1990) meant that phosphorus fertilisers were not widely used for several decades—longer than in other States—despite research trials demonstrating phosphorus limitations in climatically suitable regions. By the early 1970s, only limited areas of 10-year-old plantations were receiving broadcast applications of superphosphate at rates up to 100 kg P/ha.

Brockwell & Ludbrook (1962), Gentle *et al.* (1965), and later Turner (1982) carried out trials which demonstrated that there were sustained responses to early broadcast applications of superphosphate. Gentle *et al.* (1986) reported that responses lasted at least two rotations on the phosphorus-fixing sandstone soils south of Sydney. Site quality increased owing to higher organic matter levels, and total nitrogen and calcium contents (Turner & Lambert 1986b). With high soil phosphorus-fixation capacities, soils research focused on the chemistry of soil reactions (Gentle & Humphreys 1968) in relation to different rock types and on quantifying growth responses to alternative forms of phosphate fertiliser (G.Windsor, Forestry Commission, unpubl. data 1972–77; Humphreys 1964).

Establishment fertiliser application commenced in a limited way in plantations on soils derived from sandstone south of Sydney in the early 1960s using a "spot" or "band" of lime-super at 240 kg P/ha. In the 1970s OSP replaced lime-super because of changes in fertiliser availability. Application rates varied from 500 to 1000 kg OSP/ha, applied broadcast at planting (Gentle *et al.* 1965). Subsequent studies by Waring (1981b) confirmed the importance of fertiliser application at establishment. He found that the merchantable volume of stands treated with phosphate at planting was 235% greater than untreated stands after 8 years; the volume of stands treated at 4 years was only 118% greater than the untreated stands. Larger volumes were achieved with phosphorus and nitrogen; however, the total weed control measures required were not routinely practised at this time.

Foliage analysis confirmed that additional phosphorus applications would be required within a few years after planting. Application of superphosphate at 75 kg P/ha after 5 years (Lambert & Turner 1986) became the standard practice. Nevertheless, the cumulative area being treated during the 1970s was relatively small and limited to areas south and west of Sydney. Total areas treated with fertiliser annually in NSW between 1955 and 1989 are indicated in Fig. 3. It was not until the 1980s that broad-scale fertiliser treatment of NSW plantations occurred across all regions, including the southern and northern Tablelands. The surge in fertiliser use at this time coincided with the development of high analysis fertilisers;

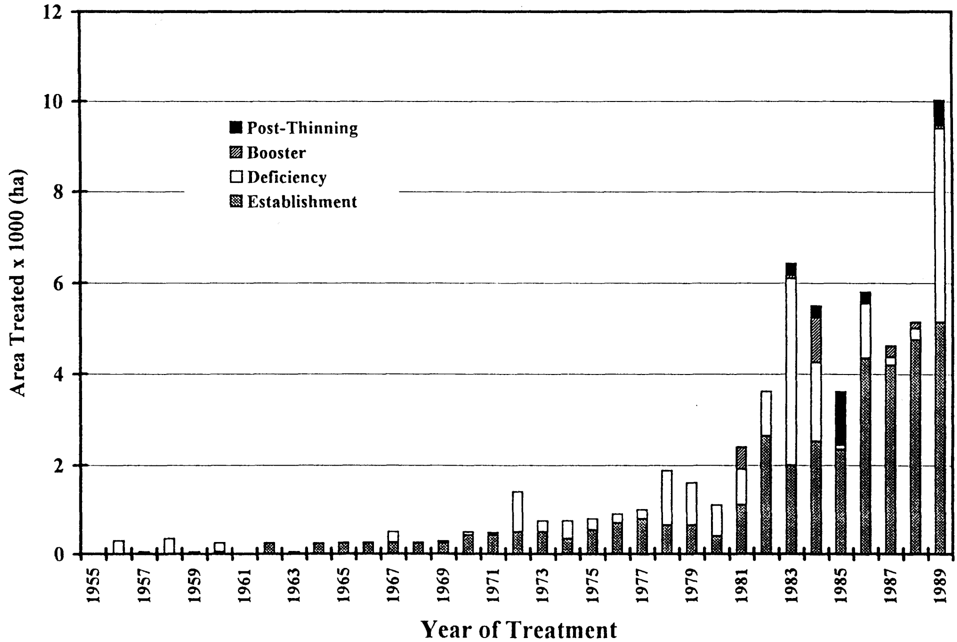

FIG. 3–Areas of *Pinus* plantation in New South Wales treated with fertiliser between 1955 and 1989 (from Knott & Turner 1990, reproduced with permission). Fertilisers applied at plantation establishment in the treatment of nutrient deficiencies, e.g., boron in young stands, as "booster" treatments to increase growth rates in young stands not showing deficiency symptoms, and as post-thinning treatments.

"Starter 12" (22.8% P, 11% N) replaced superphosphate at establishment and the method of application reverted to an individual-tree basis at rates of 90 to 150 g/tree. Second-rotation plantings had the highest priority for treatment and ex-pasture first-rotation sites the lowest priority.

Routine foliage analysis (crop logging) across the State's plantations formed a basis for developing relationships between geology and nutrition (Gentle & Humphreys 1968; Lambert & Turner 1988). Lambert & Turner (1977) identified relationships between geology and boron and sulphur deficiency, and the potential for nitrogen to induce sulphur deficiency (Kelly & Lambert 1972; Lambert 1986). Operational treatment of boron deficiencies commenced in the late 1980s with attention concentrated on large areas of ex-pasture plantations on low-boron parent materials. Low-solubility products including colemanite (calcium borate) and ulexite (calcium-sodium borate) were used in preference to borax (sodium borate) which is readily leached.

USE OF NITROGEN FERTILISERS AT ESTABLISHMENT

Nitrogen is rarely the primary growth-limiting element for newly established *P. radiata* plantations. Nitrogen fertilisers were applied at planting to first-rotation stands in SA, WA, and TAS, and second rotations in SA, mostly on an experimental basis, but not in NSW (Humphreys 1977) or VIC (Flinn *et al.* 1979a, 1982). But routine applications of nitrogen were limited prior to the 1970s, and ceased in SA until the benefits could be demonstrated (Woods 1981). The results were often conflicting and there were inconsistent responses in trials (Nambiar & Cellier 1985) and operations (including growth depressions). Nitrogen caused root damage and at some sites nitrogen induced trace element deficiencies (Woods 1976).

There was nevertheless an accumulating body of research data showing that once phosphorus deficiency was alleviated, *P. radiata* stands responded to additions of nitrogen (Waring 1971, 1981a,b)—providing competition from weeds was controlled. Higher rates of nitrogen are required in the absence of weed control, but if too much nitrogen is applied relative to phosphorus, growth rates are depressed at all stages of a rotation (Crane 1981). Most sites show strong nitrogen × phosphorus interactions, but the ratio of nitrogen to phosphorus is critical because soil type affects phosphorus-fixation capacity and hence the actual availability of phosphorus relative to nitrogen. Optimum fertiliser N:P ratios have been found to vary from 11:2 on sands to between 1:1 and 2:1 on moderately fertile soils in NSW, VIC, and TAS (Crane 1981). Nitrogen also interacts with several other elements to affect growth: if sulphur levels are inadequate there are no additional growth responses to nitrogen over that due to phosphorus alone (Turner 1981); excess nitrogen may induce copper deficiency (Turvey 1984; Simpson & Grant 1991), zinc deficiency (McGrath & Robson 1984), boron deficiency (NSW and VIC; Lambert & Turner 1977), and sulphur deficiency (Lambert 1986).

Legumes were introduced to supply nitrogen for *P. radiata* on deep weathered laterites in WA, and were tried on coastal sands in SA but competition for water use proved to be a problem with perennial lupins. Early maturing, annual lupins may be a suitable alternative (Nambiar & Nethercott 1987), except perhaps on low rainfall sites (P.Hopmans, Dept Conserv. & Natural Resources, VIC, pers. comm.).

The complex and largely unpredictable nitrogen response limited its routine use in establishment fertiliser programmes in most regions prior to the 1980s. It was introduced with the advent of high-analysis fertilisers, which reduced fertiliser application costs, and with increased understanding of factors affecting growth responses. Mono-ammonium phosphate (MAP, "Starter 12"), DAP, ammonium nitrate ("Starter 15"), and double and triple superphosphate were the principal fertilisers used in place of superphosphate. Specific fertiliser mixes including trace elements were also developed in some regions and are still important in WA (Agras), VIC, and SA (Forest Mix 4, Forest Special Mix). As broadcast methods were not suitable for applying nitrogen fertilisers to newly planted stands there was a general shift to spot, banded, or slit treatments, which required mechanisation to reduce labour costs. Improvements are still being sought in this area.

Nitrogen in Ex-agricultural Sites

Problems associated with excess nitrogen in young stands were initially relatively localised; they occurred where excess nitrogen fertiliser was applied or where plantations were located on high-quality soils derived from basalt (Lambert & Turner 1977). Excess nitrogen causes severe tree form problems in plantations on fertile ex-agricultural land, particularly in NSW and north-eastern VIC (Carlyle *et al.* 1989; Birk 1990). Ex-pastures were initially treated with high-analysis NP fertilisers at planting but this practice has largely ceased: in QLD superphosphate is applied according to the intensity and duration of previous pasture fertiliser applications (Simpson & Grant 1991); no NP fertilisers are used on improved/fertile ex-pasture sites in WA (J.McGrath, C&LM, WA, pers. comm.), VIC (Hopmans pers. comm.), or south-east SA unless previous growth rates are inadequate (Woods and Forests 1987); most new plantings in NSW in 1993 were not treated with nitrogen or phosphorus and increased attention was given to weed control (M.Pettit, State Forests of NSW, pers. comm.). Recent trials indicate either no response or a negative response to nitrogen on improved pastures (McGrath pers. comm.; Hopmans, pers. comm.; P.Ryan, CSIRO Div. Forestry, Canberra, pers. comm.) but significant growth responses have been obtained with phosphorus on some unimproved pastures (Cellier *et al.* 1985) and with nitrogen plus phosphorus on some soil types (Ryan pers. comm.).

NUTRITIONAL MANAGEMENT AND FERTILISER USE IN THE 1990s

We entered the 1990s with a more diverse plantation resource, identified markets for plantation products, increased demands for high-quality logs and wood products, increasing land costs (the shift to ex-agricultural land brought an end to "free land"), and the need to improve productivity of the existing plantation land base. The various pressures prompted reconsideration of productivity gains and returns on investments (Turner & Lambert 1991).

These issues focused attention on the role of silvicultural practices in increasing productivity and resulted in a general convergence of practices and policies across all plantation regions. Four common themes emerged in relation to nutritional management and fertiliser use:

(1) Site-specific management throughout a rotation with supporting databases and GIS systems to facilitate information transfer and decision making;
(2) Genetic improvements in tree form, wood quality, nutritional characteristics, and disease resistance to increase plantation performance;
(3) More efficient use of and conservation of resources including water, organic matter (harvest residues), fertilisers;
(4) More intensive management practices including soil cultivation (deep ripping), mounding, and weed control combined with fertilisers to increase production per hectare.

The concept of site- or soil-specific management has been adopted throughout the country for pine plantations and more recently for eucalypt plantations. As each site presents specific resource limitations, the management aim is to select the appropriate species, taxa, provenances, or families for a site, to ameliorate site factors which restrict growth, and thereby achieve levels of productivity per hectare which are closer to the site's biotic potential (Boardman & Simpson 1981). The emphasis in breeding programmes is on volume growth, tree form, wood quality, and resistance to disease and pests (Nambiar & Booth 1991), but there may be some opportunity for improving nutritional characteristics through breeding or for selecting genetic material which can perform well on sites with specific nutrient problems (Simpson & Osborne 1993). The strong genetic control over stem deformation in *P. radiata* on ex-pasture sites (Bail & Pederick 1989) indicates that some families can tolerate the unusually high levels of mineral nitrogen in these soils. Cuttings of nitrogen-tolerant families also produce stems of superior form to seedlings on ex-pasture sites. Hybridisation programmes in QLD have greatly increased the range of genetic material available for plantations on the coastal lowlands in south-east QLD and the superiority of the F1 hybrid between *P. elliottii* and *P. caribaea* has been demonstrated across a wide range of sites and in response to fertiliser treatment (Simpson & Osborne 1993). Foliar nutrient concentrations vary among these taxa on the same sites and suggest that the hybrid and *P. caribaea* may be suited to high nitrogen–low copper sites, and *P. caribaea* may better tolerate sites low in both phosphorus and potassium (Simpson & Osborne 1993).

The development of a Pine Soil Technical Classification (STC) specifically for *P. radiata* plantations (Turvey 1987) has increased the opportunity for selecting the appropriate silviculture and suitable fertiliser regimes on a compartment basis in operational forestry. This classification enables management areas to be stratified into uniform units and provides a basis for extrapolating research results within and between forests and agencies (Turner *et al.* 1990). The STC classifies parent rock types by soil-forming properties which are related to *P. radiata* productivity through their relationships with nutrient supply, moisture supply, the development or restriction of roots, and resilience to mechanical load or pressure. The properties used are all observable in the field and include parent rock, texture profile, depth to and nature of the impeding layer, texture and condition of the uppermost 10 cm, character of the surficial horizons as determined from the occurrence of a paler sub-surface zone or exposed subsoil, and condition and colour of the subsoil (Turner *et al.* 1990). Turvey *et al.* (1990) showed that parent rock alone explained 31% of the variance in merchantable volume of 11-year-old untreated *P. radiata* from sites in NSW, VIC, and SA and most properties were individually related to wood production. The classes of parent rock identified (Table 2) are organised such that they set upper limits on the total amount of clay, primary quartz, and many plant nutrients that can be released through mineral weathering (Turner *et al.* 1990). It is not surprising, therefore, that the parent rock classes are strongly discriminated on the basis of soil chemistry, especially total-phosphorus and exchangeable bases (Ryan & Knott 1991), which also explains foliar nutrient status across different rock types (Knott & Ryan 1990). Plantations can be grouped according to properties in the classification which are related, for example, to potential deficiencies in macro- and micro-nutrients, disease and tree deformation, erosion, or trafficability problems related to soil physical properties. Appropriate fertiliser regimes can be allocated to specific management units from the results of field trials on comparable sites.

Plantations in many regions of Australia are now stratified on a soils basis (nutrient and moisture considerations) and land may be classified prior to purchase to determine it suitability and appropriate management regimes. All NSW pine plantations have been classified by parent rock type (and previous land use) and information on parent rock type, nutrition, and growth is incorporated into a relational database (Knott & Ryan 1990) for access by forest managers. In TAS, soils mapping is being carried out to prepare a database and will include other soil factors (organic matter and nutrient contents) in addition to growth data (W.Neilsen, Tasmanian Forestry Commission, pers. comm.). In order to refine fertiliser prescriptions, fertiliser trials were initiated in NSW and QLD during the 1980s using standard fertiliser designs across a broad range of site types more typical of those being planted at the time. Sections of a plantation requiring specific fertiliser or other treatments can be readily identified once the resource is appropriately stratified.

Conservation of harvest residues during site preparation between successive rotations is becoming increasingly important but current practices vary considerably between states owing to differences in the intensity of clearfelling operations, technologies available to handle harvest materials, soil types, and concerns regarding moisture stress, nutrients, and soil loss. Except in SA, large-scale replanting operations have commenced only over the last decade.

The major developments in inter-rotational management in Australia were discussed in the section on management practices on the coastal sands in south-eastern SA. There is much less known about impacts on fine-textured soils but, compared with sandy soils, the proportional loss of nutrients through log removal and burning is relatively low (<5%) (Hall 1984; Birk 1993). Nevertheless, in a trial on sedimentary soils in NSW, Hall (1985) found taller trees and higher foliar nitrogen and phosphorus concentrations in plots with slash retention than in raked and burned plots. Foliage concentrations (phosphorus, nitrogen, boron) on burned sites are lower in second-rotation plantations than on first-rotation sites (Knott & Ryan 1990). Ryan (pers. comm.) found significant early growth responses to NP fertilisers supplied at planting on slash burned sites in NSW, and inventory data from second-rotation plantations indicate that the productivity of chopper-rolled sites in southern NSW is higher than on burned sites (R.Orman, State Forests of NSW, pers. comm.). These trends suggest that even on fine-textured soils nutrient availability and/or nutrient uptake is reduced through slash burning, and further investigations are warranted.

Smaller-sized harvest residues are currently retained after harvest in most regions where mulching is a practical option. In addition to moisture and nutrient conservation, slash reduces soil erosion and in TAS it is retained to reduce the regeneration of *P. radiata* from seed. Slope angle and intensity of wood utilisation affect the decision to retain harvest residues as chopper-rolling is not suitable on steep slopes and gravity-rolling systems are not generally utilised at this time. Large slash loads inhibit the efficient operation of cultivation equipment and so chopper-rolling is more practical where wood utilisation is high (hence lower amounts of harvest residue). Low residue logging at clearfelling is now routine practice in SA.

In first and subsequent rotations, substantial gains in productivity are being achieved by reducing the level of environmental resistance to growth, including soil physical constraints and nutrient limitations, through intensive site preparation and weed control in conjunction with fertiliser and nutrient conservation measures. On poor quality sites, intensive treatments are necessary to supply sufficient resources to achieve significant productivity gains. On better quality sites, the main effect of intensive interactive treatments is a reduction in competitive effects rather than the alleviation of nutrient deficiency (Turner 1984). It is now common for fertiliser funds to be directed to higher-quality sites with nutrient limitations than to low-quality sites. Some management agencies have reduced, delayed, or eliminated fertilisers at planting, while reducing weed competition and cultivating to enhance root penetration (Hopmans pers. comm.; McGrath pers. comm.; Woods and Forests 1987). Fertilisers are therefore being used more conservatively and applied where they are expected to be most effective. The aim is to time fertiliser application to match periods of high demand and to direct limited fertiliser resources to sites where their use will provide the best economic return.

CURRENT FERTILISER PRACTICES

Knott & Turner (1990) stated that the major reasons for fertiliser treatments in Australian plantations in the current decade are to:

(1) Assist in successful plantation establishment;

(2) Correct recognised deficiencies which result in economically significant mortality, disease, or losses in growth potential;

(3) (a) Increase the rate of wood production in young, actively growing stands where no deficiency symptoms are obvious but where nutrient levels are potentially limiting growth;

(b) Maximise the economic benefit of increased wood production after stand release by thinning.

Treatments are carried out during several stages of stand development, with an emphasis on the period prior to canopy closure when nutrient requirements are met primarily from soil reserves. Most fertiliser applications to correct nutrient deficiencies are carried out within a few years of planting, but treatments in older stands have been required in many areas to compensate for the lack of fertiliser at establishment in the 1970s. Post-thinning application is becoming increasingly important in the 1990s and the areas being treated appear set to increase as the economic benefits are more clearly demonstrated.

A soil's nutrient-supplying capacity and its nutrient-retention characteristics appear to be major factors (within economic constraints) affecting the frequency of fertiliser treatment and the elements applied. The main strategies being practised in Australia after plantation establishment are summarised below, followed by details of the types of fertilisers applied.

(1) *Fertiliser at establishment (within 2 months of planting) followed by repeated "booster" treatments prior to crown closure; subsequent re-application is delayed until after thinning*. This strategy is carried out on coastal sands with low nutrient-retention capacities in SA and WA, and on fine-textured soils with high phosphorus-fixing capacities in SA. However, if weed control is not adequate in SA, then no establishment fertilisers are applied (Woods and Forests 1987) and a second attempt to establish the plantation is undertaken. Subsequently, fertiliser is applied annually for the first 4 years if required. If minimum acceptable growth rates are not achieved in SA plantations at 30 months post-planting, the stands are treated at 38 months and possibly at 50 months (Woods and Forests 1987) as specified in the MGS fertiliser regime. In WA, fertiliser is applied at 2-yearly intervals for 6 years, but may continue for up to 25 years on some sites. Drought-prone sites in WA are an exception as they may not receive fertiliser until after thinning. Establishment treatments are usually carried out in spring within a few weeks of planting, to take advantage of good growing conditions and to avoid loss through leaching. Application has to be completed within a few weeks in summer drought areas or the benefits will be lost owing to induced water stress.

(2) *Fertiliser at establishment (within 2 months of planting) followed by a single "booster" treatment within a few (3 to 5) years, usually prior to crown closure; subsequent application is delayed until after thinning*. This regime is generally carried out in first-rotation *P. radiata* on moderately fertile but phosphorus-limited soils in NSW, TAS, and VIC. In NSW, VIC, and QLD, the decision to apply fertiliser is based on foliar analysis, and in SA "booster" fertiliser is applied only if growth rates fail to reach prescribed minima for height and basal area in the middle of the third and fourth years post-planting. Fertiliser is applied 8 months after measurement if growth is below acceptable levels (Woods and Forests 1987). Established stands of *P. caribaea* on coastal sands in QLD also require supplements of potassium within a few years of establishment (Simpson & Grant 1991).

(3) *No fertiliser at establishment: initial treatment is delayed for several (3+) years and subsequent application is delayed until after thinning.* This regime has been adopted for *P. radiata* and tropical pines on relatively fertile, ex-pasture sites where there is sufficient residual fertiliser from previous pastoral activities to achieve the required early growth rates (Simpson & Grant 1991). Application is also delayed on moderately fertile, second-rotation sites in SA if productivity in the first rotation reached the minimum acceptable level (SQ III or better; Lewis *et al.* 1976).

(4) *No fertiliser prior to thinning.* This approach is planned for *P. radiata* in WA on fertile ex-pasture sites (WA Dept of C&LM unpubl. data) and it applies to some stands on better quality sites in SA, providing minimum acceptable growth rates are maintained (Woods and Forests 1987).

Establishment Fertilisers, "Booster" Fertilisers, and Deficiency Treatments

Phosphorus, nitrogen, and occasionally potassium are the principal macro-elements applied at establishment and in "booster" treatments in first-rotation pine plantations. Application rates and types of fertilisers being used at planting for *P. radiata*, *P. pinaster* (WA), *P. caribaea*, and the F1 hybrid (QLD) are listed in Table 5. Rates of phosphorus

TABLE 5–Rates of phosphorus, nitrogen, and potassium fertilisers applied at or after planting in exotic pine plantations. Alternative prescriptions in each State are selected according to site type.

	P (g/tree)	N (g/tree)	K g/tree)	Preferred fertiliser	Ref.
Pinus radiata					
NSW	20–34	11–16	0	"Starter 12" (MAP Special)	1
	25–35	0	0	Single, or triple-superphosphate	1
VIC	20	0	0	Superphosphate + TE*	2
SA: southeast	6	42	0	Forest Mix 4	3
SA: central	4	0	0	Superphosphate + TE	3
WA	13	16	0	Agras with TE	4
	11	0	0	Superphosphate + TE	4
TAS: public	11	25	(30)†	EZ Lightening Pasture Fert. or EZ Orchard Mix (ammnium sulphate +superphosphate (+ KCl))†	5
TAS: private	17	10	0	DAP/sulphate of ammonia 10:17:0	6
P. pinaster					
WA	5.5	0	0	Superphosphate	7
P. caribaea x P. hondurensis					
QLD	50–60‡	30–35‡	(50)†‡	MAP‡ (+ KCl)	8

* TE = Trace elements

† KCl applied on potassium-deficient soils only

‡ Applied in a band along the planting row (1000 stems/ha) at 50–60 kg P /ha, 30–35 kg N/ha; 50 kg K/ka and 5 kg Cu/ha area; also applied to podsols.

[1] Knott &Turner (1990)
[2] Hopmans (pers. comm.)
[3] Woods and Forests (1987)
[4] WA Dept of C&LM, Forestry Management Guide (unpubl. data)
[5] Neilsen (1990)
[6] R. Heathcote (formerly Aust. Paper Mills, Tas.) (pers. comm.)
[7] Simpson & Grant (1991)

applied to *P. radiata* range from 4 to 35 g/tree; the rate of nitrogen is often determined by the form of phosphorus applied and ranges from 0 to 42 g/tree. Commonly used fertilisers include superphosphate, high-analysis NP fertilisers including DAP and MAP, and complete fertilisers such as the Forest Starter Mix (FSM) used in SA. FSM is used to alleviate the risk of inadequate supplies of cations and sulphur (Boardman 1988; Woods and Forests 1987). The same suite of fertilisers is used for "booster" treatments which are broadcast at rates ranging from 26 to 96 kg P/ha and 0 to 60 kg N/ha (Table 6). Soils known to be potassium deficient are treated with potassium chloride in conjunction with other fertilisers at and after plantation establishment (Tables 5 and 6).

Site types with known deficiencies of trace elements are routinely treated at establishment and with "booster" treatments. Trace element mixes including zinc, copper, and molybdenum are applied with phosphorus and nitrogen in SA and WA (Tables 5 and 6). Extra treatments required in some sites in WA are usually applied as a spray since the movement of zinc through the soil profile is quite restricted (Brennan & McGrath 1988). *Pinus caribaea* plantations on coastal sands in QLD are treated with 5 kg Cu/ha at planting.

Boron is the main trace element applied to plantations on fine-textured soils in south-eastern Australia. If treated at establishment, each tree receives 35 g ulexite (or colemanite) which is equivalent to 4.9 g B/tree. After about 2–3 years, ulexite is applied broadcast at 5–8 kg B/ha in NSW and 10.5 kg B/ha in VIC. Foliage analysis is usually carried out to identify stands with marginal boron concentrations.

Second-rotation pine plantations are treated at establishment in NSW, TAS, SA, and QLD and prescriptions are the same as for first-rotation plantings on the respective soil types. Standard fertiliser trials established in NSW in the 1980s included second-rotation sites which had been windrowed and burned prior to cultivation. Although windrowing is no longer the desired practice, Ryan (pers. comm.) found significant growth responses to combinations of nitrogen and phosphorus and the optimum rates varied according to parent rock type. On granodiorite, the optimum combination was 70 g P + 50 g N/tree, whereas on trachyte, 70 g P + 25 g N/tree produced the best response. These rates are considerably higher than the rates currently being applied (34 g P + 16.5 g N in 150 g "Starter 12") based on first-rotation prescriptions for NSW, and suggest a potential for productivity improvement.

With an increasing proportion of the plantation estates in most States approaching maturity, there will be an increase in the proportion of second-rotation sites which have a history of fertiliser treatment. Residual effects of first-rotation superphosphate on second-rotation growth have been detected in NSW (Gentle *et al.* 1986) and QLD (Simpson & Grant 1991). The area of plantation treated after thinning, possibly only a few years before final harvest, is increasing; it may become economically desirable to delay fertiliser application to the subsequent rotation on these sites until the effect of first-rotation fertiliser is assessed, at least on some soil types. There is considerable scope for research to refine fertiliser practices in second-rotation plantations in most regions.

Later Age and Post-thinning Fertiliser Treatment

After crown closure there is a decrease in the demand from soil reserves and an increase in internal nutrient redistribution. There are reports of growth responses in unthinned pine plantations on a reasonably wide range of soils including coastal sands and lateritic podsols

TABLE 6–"Booster" fertiliser treatments for *Pinus radiata* plantations

Region	Site type	Treatment age (years)	P (kg/ha)	N (kg/ha)	K (kg/ha)	Fertiliser	Ref.
NSW	Not specified*	3–6	68	0	0	Superphosphate†	1
		3–6	68	33	0	MAP Special	
VIC	Not specified*	5	64			Superphosphate†	2
TAS	Not specified	5	96	NA	(48)‡	50:50 Super- and rock-phosphate (+ KCl)	3
WA central§	Lateritic podsols	2, 4, 6	26	30	0	Agras + TE	4
	Coastal sands	1	21	0	0	Superphosphate + TE	
		2, 4, 6	26	30	0	Agras + TE	4
WA south coast§	Bush & poor pasture	2, 4, 6,	26	30	0	Agras + TE	
	Bush & pasture (cont'd)	10, 18, 20	52	60	0	Agras + TE	4
	Good pasture	10, 19, 25	52	60	0	Agras + TE	4
SA south-east	if CEG > III/IV	3, 4	0	0	0	none	5
	if CEG < III/IV	3, 4	14 (g/tree)	26 (g/tree)	0	Forest Starter Mix	5
SA central	Prev.rotation SQ ≤VI on	1	26 (g/tree)	23 (g/tree)	0	DAP 18:20:0	5
	sands with high P-fixation ¶	2	53 (g/tree)	48 (g/tree)	0	DAP 18:20:0	5
	CEG < SQ III/IV	3, 4	50 (g/tree)	45 (g/tree)	0	DAP 18:20:0	5

SQ = Site Quality (*see* Lewis *et al.* 1976)
CEG = Current Equivalent Growth
NA = Responses to nitrogen have been demonstrated but the economics of routine treatments have not yet been assessed

* Decision to apply fertiliser based on foliage analysis, fertiliser availability, and costs
† Superphosphate assumed to be 9.1% P
‡ Applied on potassium-deficient soils only
§ Examples of prescriptions being used in these regions
¶ Example for one site type in this region

[1] Knott & Turner (1990)
[2] Flinn *et al.* (1982)
[3] Neilsen (pers. comm.)
[4] WA Dept of C&LM, Forest Management Guide (unpubl. data)
[5] Woods and Forests (1987)

in WA (McGrath pers. comm.), coastal sands in SA (Fife *et al.* 1993) and QLD (Simpson & Grant 1991), granites and siltstone-derived soils in NSW (Turner *et al.* 1992), and metamorphosed sediments in TAS (Neilsen 1982; Neilsen *et al.* 1992). Some remedial fertiliser treatments are carried out after crown closure in plantations which did not receive the normal "booster" treatments and where growth responses to later-age treatments had been demonstrated, e.g., *P. elliottii* in QLD. But remedial treatment is not a widespread practice now that fertiliser application at establishment and early re-application have become routine.

Post-thinning fertiliser treatment is important because it provides managers with an option for carrying out heavier than normal thinning to meet immediate demands for additional timber, given that the additional volume can be recovered by a growth response after fertiliser application (Turner & Knott 1991). Managers can also use this strategy to prepare for anticipated future shortfalls in log availability, and the production of larger, high-quality logs is an additional economic benefit (Crane 1982; Turner & Lambert 1987; Turner *et al.* 1992). However, the high cost of fertilisers combined with variable growth responses (Turner *et al.* 1992; Turner & Knott 1991) are limiting the rate at which post-thinning fertiliser treatment is becoming routine in some States. Post-thinning fertiliser treatments considered optimal for a range of *P. radiata* plantations are listed in Table 7. Nitrogen is consistently required at higher rates than phosphorus at this stage of the rotation and routine application rates range from 30 to 250 kg N/ha and 26 to 104 kg P/ha; N:P ratios vary between 1:1 and 6:1 (Table 7). Based on experimental trials on a range of soil types in NSW, Turner & Knott (1991) found that optimum rates of nitrogen applied after first thinning range from 200 to 400 kg/ha (Table 7).

Turner & Knott (1991) and Turner *et al.* (1992) found that the absolute biological responses to post-thinning fertiliser, the potential economic responses, and the optimum rates of nitrogen and phosphorus applied varied according to site type. Increased growth responses to fertiliser were sustained for 4 to 5 years, and were not different from the control

TABLE 7–Rates of nitrogen and phosphorus fertiliser applied post-thinning to *Pinus radiata*.

Region	Site type	N (kg/ha)	P (kg/ha)	N:P ratio	Ref.
VIC*	Not specified	250	50	5:1	1
SA south-east*	Not specified	166	26	6:1	2
SA central*	Not specified	74	41	1.8:1	2
WA* †	Deep coastal sands	30	26	1.2:1	3
	Lateritic podsols	60	52	1:1	3
	'Hills' ex-bush	120	104	1:1	3
NSW‡	Shale (Bondi S.F)	400	75	5:1	4
	Shale (Carabost S.F.)	200	225	0.8:1	4
	Granodiorite (Green Hills S.F.)	200	225	0.8:1	4
	Quartzose-sandst. (Penrose S.F.)	200	75	2.6:1	4

* Operational prescriptions
† Selection from the range of prescriptions being used
‡ Optimum rates from post-first thinning fertiliser trials

[1] Hopmans (pers. comm.)
[2] Woods and Forests (1987)
[3] WA Dept of C&LM, Forest Management Guide (unpubl. data)
[4] Turner & Knott (1991).

after 7 years had elapsed (Turner *et al.* 1992). This period represents the usual interval between thinnings. The decline in responsiveness appeared to be due to a decrease in nitrogen availability rather than a loss of phosphorus.

An economic evaluation of these trials (Turner & Knott 1991) showed that the spatially complex regions such as the central tablelands in NSW need to be stratified according to site and stand factors critical to the biological response (parent rock type, age, and thinning history) to select the most appropriate NP treatment on a compartment basis. Broad-scale application of a standard NP fertiliser after thinning may not be appropriate; if some sites have low or negative growth, responses on some sites could result in financial losses.

Fertiliser application after thinning is being delayed in WA and SA until at least one full growing season has elapsed. The delay minimises the development of a wide ring of low-density (early) wood and the development of a heavy crown which could cause damage from bending and windthrow (Woods and Forests 1987; WA Dept of C&LM unpubl. data). Recent studies in SA suggest that it may be beneficial to apply nitrogen a year before thinning on sandy soils since nitrogen absorbed by the unthinned stands can be recycled in organic forms in thinning residues (C.Carlyle, CSIRO Div. Forestry, Mt Gambier, pers. comm.). This strategy is likely to be adopted for second and later thinnings in SA, and on high-quality sites at first thinning if they are thinned on time or have had a pre-commercial thinning (Boardman pers. comm.)

NUTRITIONAL MANAGEMENT OF EUCALYPT PLANTATIONS

Given abundant natural eucalypt forests, which are managed on a sustained growth basis, there has been little incentive for the timber industry to make the large investments required to establish, manage, and protect eucalypt plantations. However, eucalypt plantations are attracting considerable public support in the belief that they are environmentally sound and can replace native eucalypt forests as our source of hardwood timber for sawlogs and pulpwood (Stanton 1992).

There are approximately 100 000 ha of eucalypt plantation in Australia in both public and private ownership (Fig. 4) established over the past 30 years with substantial and increasing involvement of the private sector. The total area increased from 1.6% to 8.3% of the total plantation estate between 1970 and 1990 (Turner & Lambert 1991) and annual plantings (>12 000 ha) are now double the area of new exotic pine plantings (Table 4). The major planting activity is in TAS (>7000 ha in 1993) and WA (>4000 ha in 1993).

New plantations are being established on cleared land; this includes some steep sites which previously carried eucalypt forest (private ownership) in TAS and ex-agricultural land or otherwise degraded land elsewhere. Early plantations in WA were established to reduce problems of stream salinity (Ritson *et al.* 1991) whereas plantations on the north coast of NSW were established after harvesting and burning to ensure successful regeneration of eucalypts ahead of the aggressive weed regrowth, or to increase productivity by changing species (Stanton 1992). These areas have been managed more like the surrounding regrowth forests rather than as intensively managed plantations.

The management of recent plantings has been intensive, capitalising on lessons learned from exotic pines. The emphasis on site-specific management extends to the selection of suitable land, appropriate species or provenances, and silvicultural techniques to increase

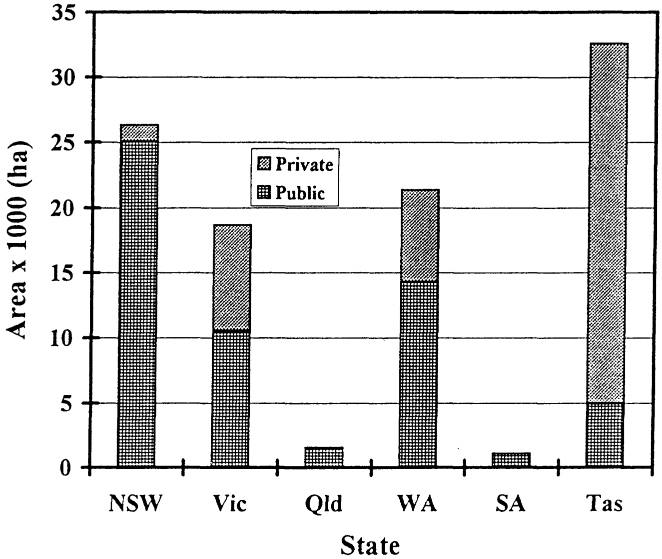

FIG. 4–Areas of eucalypt plantation in Australia by ownership and State at 31 March 1991 (from Stanton 1992, reproduced with permission).

early growth rates. A land capability system, including climate and soils data, has been developed for site selection in TAS (Laffan 1993, 1994) and land evaluation surveys are being carried out in WA (R.Harper, WA Dept of C&LM, pers. comm.) and NSW (Stanton 1991). Walsh (1991) reported correlations between early growth rates and both soil and climatic indices in TAS. Moisture availability will probably limit growth on sites with less than 800 mm rainfall and fertiliser additions are not likely to be justified in these areas (Weston 1991), particularly if the soils are not at least moderately fertile (Orme *et al.* 1992).

Land converted to eucalypt plantations is cultivated, ripped, and often mounded to increase root penetration, but achieving adequate pre-planting weed control is of major concern as eucalypts are more susceptible to chemical treatments and weed competition than exotic pines. There were early plantation failures and depressed growth rates after fertiliser application in plantations established where weeds were not controlled. Fertiliser tablets (NP or NPK) have been widely used, generally to provide a nutrient source to enable trees to "get away" quickly rather than to overcome nutrient deficiencies. It is unlikely that the rates applied are either biologically or economically optimal (Ritson *et al.* 1991; C.Weston, School of Forestry, Creswick, pers. comm.), given the dramatic increases in early growth rates demonstrated for both temperate (Cromer & Williams 1982) and sub-tropical species (Birk & Turner 1992; Cromer *et al.* 1993a). Fertiliser rates applied in *E. grandis* super-culture trials (Birk & Turner 1992; Cromer *et al.* 1993a,b) demonstrate the limitations of the native soils' nutrient supplies, even in moderately fertile sites, but they exceeded optimum biological and economic rates of application.

Growth responses to nitrogen and phosphorus fertilisers in eucalypt plantations vary with soil fertility and species requirements. There has been a limited response to nitrogen on more fertile soils in the Latrobe Valley of VIC (Weston pers. comm.) and the same is expected on ex-pasture sites. On farmland sites in WA, *E. globulus* and *E. sideroxylon* (A.Cunn.) ex

Woolls respond to phosphorus alone whereas *E. microcarpa* Maiden does not respond to either nitrogen or phosphorus at planting (Ritson *et al.* 1991). The rates of nitrogen and phosphorus being applied in WA (McGrath pers. comm.) and in State-owned plantations in TAS (Neilsen 1990) are the same as for pine plantations. However, one private company in TAS which has been establishing plantations for several years applies nitrogen and phosphorus (plus potassium) to *E. regnans*, *E. globulus*, and *E. nitens* on ex-native forest sites at double the rate applied to *P. radiata*, and the trees are treated again after 12 months (P.Naughton, Forest Resources, TAS, pers. comm.). Many new fertiliser trials have been established in temperate and sub-tropical locations to develop appropriate establishment fertiliser prescriptions for a range of eucalypt species on specific site types.

High and rapid rates of nutrient accumulation in eucalypt plantations suggest that the optimum fertiliser rates may be higher than the current prescriptions for pine plantations. In a summary of nutrient accumulation data per tonne of dry weight, Birk & Turner (1992) showed that phosphorus and calcium accumulation by eucalypt plantations exceeds that of native eucalypt forests. In eucalypt plantations, phosphorus accumulation is greater than for pine on the poor to moderately fertile soils in Australia (Fig. 5), but not greater than for *P. radiata* stands in New Zealand, and plantation eucalypts accumulate substantially more calcium than pines. Similar amounts of nitrogen are accumulated per unit biomass by both pines and eucalypts (Birk unpubl. data).

In plantations where crown closure is achieved rapidly (less than 4 years; Beadle & Mummery 1990; Cromer *et al.* 1993a), particularly in fast-growing eucalypts, there will be a limited opportunity to monitor plant nutrient status and apply remedial fertilisers. Cromer *et al.* (1993b) applied fertiliser to *E. grandis* at rates calculated to parallel the expected pattern of nutrient accumulation; the results showed a close relationship for the first 2 years but uptake subsequently declined despite continued fertiliser application. The decline was rapid compared with pine plantations and reflected the rapid rate of crown closure. Our potential to use foliage analysis to monitor nutrition in routine eucalypt operations is also limited by inadequate baseline nutrition data (Judd *et al.* 1991).

There is a concern that improving the nutrient status of eucalypt plantations with high rates of fertiliser will increase susceptibility to insect defoliation or disease (Adams & Atkinson 1991; Stone 1993). Some trials have been completely defoliated or lost through fungal attacks (Cromer *et al.* 1991). Provenance selection and tree breeding are being addressed to improve the productive potential of eucalypt plantations although initial emphasis is on characteristics of form and yield, and insect and disease resistance (Nambiar & Booth 1991), rather than on nutrient or water use.

POTENTIAL FOR IMPROVING FERTILISER PRACTICES

Empirical fertiliser trials have been and may continue to be the major research tool used to determine optimum fertiliser prescriptions in plantations. With more intensive management, however, there is a "need to develop a more comprehensive understanding of the timing of peak demands and changes in requirements, nutrient interactions, changes in nutrient availability and effects of climate" (Turner & Lambert 1986a). It is therefore important to complement empirical trials with process studies aimed at explaining the nature of responses observed. There have been notable examples where soil processes controlling nutrient

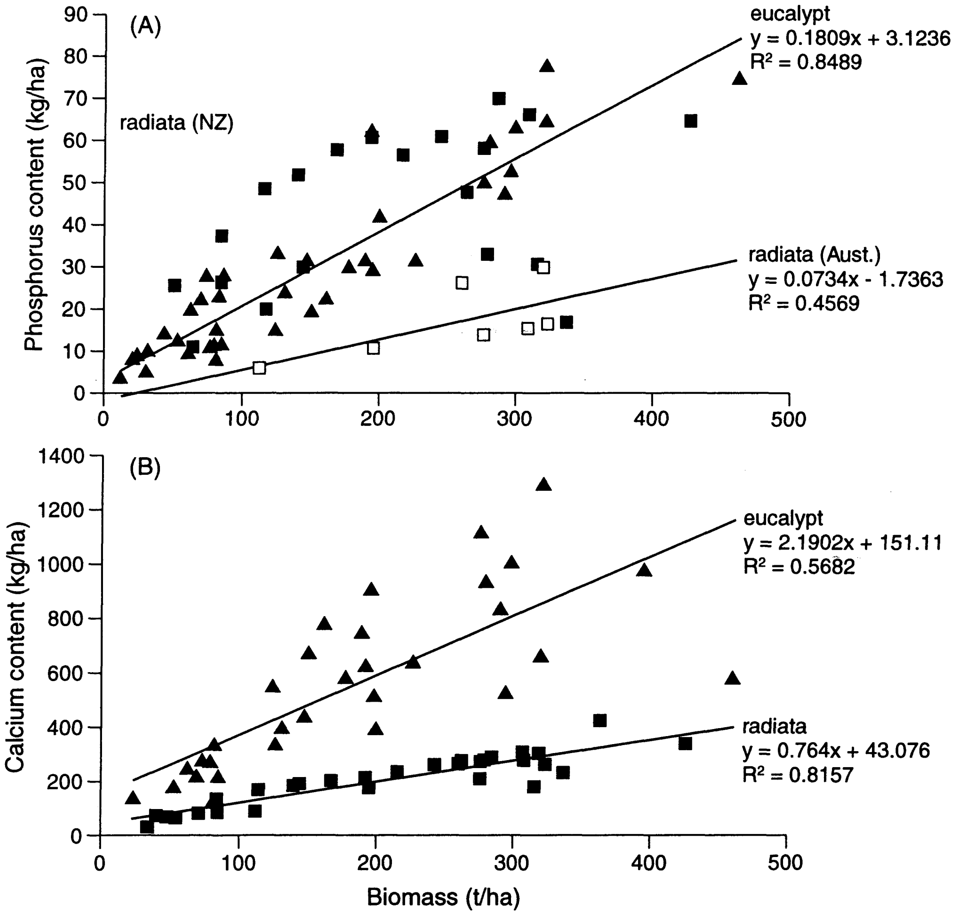

FIG. 5–Phosphorus (A) and calcium (B) accumulation (kg/ha) per unit of stand dry weight in *Pinus radiata* plantations (squares) and eucalypt plantations (triangles) (after Birk & Turner 1992, reproduced with permission). In (A) ■ = New Zealand and □ = Australian pine plantations. In (B) ■ = New Zealand and Australian pine plantations.

supply have been examined, including the work on phosphorus fixation (Gentle & Humphreys 1968; Truman *et al.* 1983; Truman & Humphreys 1985), boron retention (Ryan 1989; Lambert & Ryan 1990), zinc movement (Brennan & McGrath 1988), and nitrogen availability (Smethurst & Nambiar 1989, 1990a,b). For elements with strong reactions in soils with moderate to strong nutrient retention capacities (e.g., phosphorus in fine-textured soils) there is a need to focus on interactions between fertilisers and geochemical properties of the soil, whereas interactions between fertilisers and organic materials are of more concern in soils with low nutrient retention (coastal sands).

Current fertiliser regimes aim to recognise, and are geared to coincide with, major periods of nutrient demand. Fertiliser treatments are more cost effective if applied during periods when nutrient demand exceeds the availability of native soil supplies, at rates which minimise the potential for loss of excess nutrients. Timing of fertiliser applications is critical in this regard, as are the type of fertiliser used, method of application, and the soil's capacity to retain nutrients. The timing of fertiliser treatment is more critical for elements with weak soil reactions (e.g., boron, nitrogen) since they are more susceptible to loss from the system by leaching and ionic exchange processes.

While these studies can be expected to improve the efficiency of nutrient and fertiliser use in plantations, other constraints will limit the operational use of fertilisers. Decisions to carry out treatments are based on economic considerations and trade-offs between various management objectives competing for limited funds. There are additional pressures to reduce costs by carrying out uniform treatments to reduce labour costs associated with fertiliser application. Inevitably, nutritional management practices will continue to evolve in response to changes in management objectives, changes in fertiliser technology, and increased understanding of nutritional requirements and soil processes.

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REFERENCES

ADAMS, M.A.; ATKINSON, P.I. 1991: Nitrogen supply and insect herbivory in eucalypts: the role of nitrogen assimilation and transport processes. Pp.239–41 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

AUSTRALIAN BUREAU OF AGRICULTURAL RESOURCES AND ECONOMICS 1992: "Australian Forest Resources 1990 and 1991". Commonwealth of Australia.

BAIL, I.R.; PEDERICK, L.A. 1989: Stem deformity in *Pinus radiata* on highly fertile sites: expression and genetic variation. *Australian Forestry 52*: 309–20.

BEADLE, C.L.; MUMMERY, D.C. 1990: Stand growth and development of leaf area index in young plantations of *Eucalyptus nitens* at 2 × 2 m spacings. Pp.254–9 *in* James, R.N.; Tarlton, G.L. (Ed.) "New Approaches to Spacing and Thinning in Plantation Forestry", Proceedings of IUFRO Symposium, 10–14 April 1989, Rotorua, New Zealand. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No.151.*

BEVEGE, D.I.; RICHARDS, B.N. 1972: Principles and practices of foliar analysis as a basis for crop logging in pine plantations. II. Determinations of critical phosphorus levels. *Plant and Soil 37*: 159–70.

BIRK, E.M. 1990: Poor tree form of *Pinus radiata* D. Don on former pasture sites in New South Wales. *Australian Forestry 53*: 104–12.

——1992: Nitrogen availability in radiata pine plantations on previously improved and unimproved pastures. *Plant and Soil 143*: 115–25.

———1993: Biomass and nutrient distribution in radiata pine in relation to previous land use. II. Nutrient accumulation, distribution and removal. *Australian Forestry 56:* 148–56.

BIRK E.M.; TURNER J. 1992: Response of flooded gum (*E. grandis*) to intensive cultural treatments: Biomass and nutrient content of eucalypt plantations and native forests. *Forest Ecology and Management 47:* 1–28.

BOARDMAN, R. 1974: Pine stand improvement in the south-eastern region of South Australia. *Woods and Forest Department South Australia, Bulletin No.21.*

———1988: Living on the edge—The development of silviculture in South Australian plantations. *Australian Forestry 51*: 135–56.

———1991: Impacts on planted trees and soils of re-using effluents and waste waters in Australian environments—A review. Pp.87–106 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

BOARDMAN, R.; McGUIRE, D.O. 1990: The role of zinc in forestry. II. Zinc deficiency and forest management: Effect on yield and silviculture of *Pinus radiata* plantations in South Australia. *Forest Ecology and Management 210*: 207–18.

BOARDMAN, R; SIMPSON, J.A. 1981: Fertilisation to optimise productivity. Pp.303–17 *in* Proceedings of Australian Forest Nutrition Workshop "Productivity in Perpetuity", 1–14 August 1981, Canberra. Australian Forestry Council.

BOOMSMA, D. B. 1982: Herbicide usage in the establishment of coniferous plantations in Australia and New Zealand. Pp.59–72 *in* "Establishment of Coniferous Plantations", 20–23 September 1982, Mount Gambier. Woods and Forests Department, S.A.

BOOMSMA, D. B.; HUNTER, I.R. 1990: Effects of water, nutrients and their interactions on tree growth and plantation forest management practices in Australasia: A review. *Forest Ecology and Management 30*: 455–76.

BRENNAN, R.F.; McGRATH, J.F. 1988: The vertical movement of zinc on sandy soils in southern Western Australia. *Australian Journal of Soil Research 26*: 211–6.

BROCKWELL, J.; LUDBROOK, W.A. 1962: The response to phosphate of *Pinus* grown on infertile soils in New South Wales. *CSIRO Division of Plant Industry, Division Report No.22.*

CARLYLE, J.C.; TURVEY, N.D.; HOPMANS, P.; DOWNES, G.M. 1989: Stem deformation in *Pinus radiata* associated with previous land use. *Canadian Journal of Forest Research 19*: 96–105.

CELLIER, K.M.; STEPHENS, C.G. 1980a: Effect of fertiliser and weed control on the early growth of *Pinus radiata* D. Don in southern Australia. *Australian Forest Research 10*: 141–53.

———1980b: Effect of weed control and fertiliser placement on the establishment and early growth of *Pinus radiata* in southern Australia. *Australian Forest Research 10*: 361–9.

CELLIER, K.M.; BOARDMAN, R.; BOOMSMA, D.B.; ZED, P.G. 1985: Response of *Pinus radiata* D. Don to various silvicultural treatments on adjacent first and second rotation sites near Tantanoola, South Australia. I. Establishment and growth up to age 7 years. *Australian Forest Research 15*: 431–47.

CRANE, W.J.B. 1981: Nitrogen fertilisation and *Pinus radiat*a. Pp.327–39 *in* "Managing Nitrogen Economies of Natural and Man Made Forest Ecosystems", 5–9 October 1980, Mandurah, W.A. CSIRO Division of Land Resources Management:

———1982: Fertiliser treatment of *Pinus radiata* at establishment and at thinning—An evaluation of its potential in Australia. *New Zealand Journal of Forestry Science 12*: 293–307.

CROMER, R.N.; WILLIAMS, E.R. 1982: Biomass and nutrient accumulation in a planted *E. globulus* (Labill.) fertiliser trial. *Australian Journal of Botany 30*: 265–78.

CROMER, R.N.; CAMERON, D.M.; RANCE, S.J.; RYAN, P.A.; BROWN, M. 1993a: Response to nutrients in *Eucalyptus grandis*. 1. Biomass accumulation. *Forest Ecology and Management 62*: 211–30.

———1993b: Response to nutrients in *Eucalyptus grandis*. 2. Nutrient accumulation. *Forest Ecology and Management 62*: 231–43.

CROMER, R.N.; RYAN, P.A.; BOOTH, T.H.; CAMERON, D.M.; RANCE, S.J. 1991: Limitations to productivity of *Eucalyptus grandis* plantations in sub-tropical Australia. Pp.133–46 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

FARRELL, P.W. 1984: Radiata pine residue management and its implications for site productivity on sandy soils. *Australian Forestry 47*: 95–102.

FERGURSON, I.S. 1991: Plantation development in Australia: past, present and perhaps. Pp.7–14 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

FIFE, D.N.; NAMBIAR, E.K.S.; EVANS, R. 1993: Effects of nitrogen on growth and properties of stem wood of *Pinus radiata* families. *CSIRO User Series No.8*. 17 p.

FLINN, D.W.; JAMES, J.M.; HOPMANS, P. 1982: Aspects of phosphorus cycling in radiata pine on a strongly phosphorus-adsorbing soil. *Australian Forest Research 12*: 19–35.

FLINN, D.W.; HOPMANS, P.; FARRELL, P.W.; JAMES, J.M. 1979: Nutrient loss from the burning of *Pinus radiata* logging residue. *Australian Forest Research 9*: 17–23.

FLINN, D.W.; HOPMANS, P.; MOLLER, I.; TREGONNING, K. 1979: Response of radiata pine to fertilisers containing N and P applied at planting. *Australian Forestry 42*: 125–31.

GENTLE, S.W.; HUMPHREYS, F.R. 1968: Experience with phosphatic fertilisers in man-made forests of *Pinus radiata* in New South Wales. *In* Proceedings of Ninth Commonwealth Forestry Conference, India, 1967. Forestry Commission NSW.

GENTLE, S.W.; HUMPHREYS, F.R.; LAMBERT, M.J. 1965: An examination of a *Pinus radiata* phosphate fertilizer trial fifteen years after treatment. *Forest Science 11*: 315–24.

———1986: Continuing response of *Pinus radiata* to phosphatic fertilisers over two rotations. *Forest Science 32*: 822–9.

HALL, M. 1984: Establishment of radiata pine on a high altitude second rotation site. I. Effect of site preparation on early survival and growth. *Australian Forestry 47*: 194-98.

———1985: Establishment of radiata pine on a high altitude second rotation site. II. Effect of site preparation on nutrient capital. *Australian Forestry 48*: 79–83.

HILL, J.H.; LAMBERT, M.J. 1981: Physiology and management of micronutrients in forest trees in Australasia. Pp.93–103 *in* Proceedings Australian Forest Nutrition Workshop "Productivity in Perpetuity", 10–14 August 1981, Canberra, Australia. CSIRO.

HOPMANS, P.; FLINN, D.W.; GEARY, P.W.; TOMKINS, I.B. 1993: Sustained growth response of *Pinus radiata* on podsolised sands to site management practices. *Australian Forestry 56*: 27–33.

HUMPHREYS, F.R. 1964: The nutrient status of pine plantations in central New South Wales. *Appita 18*: 111–21.

———1977: Establishment fertiliser practice in NSW. Pp.123–4 *in* Ballard, R. (Comp.) "Use of Fertilisers in New Zealand Forestry". *New Zealand Forest Service, FRI Symposium No.19*.

JOHNSTON, T. 1982: Cultivation. Pp.25–9 *in* "Establishment of Coniferous Plantations", 20–23 September 1982, Mount Gambier. Woods and Forests Department, S.A.

JUDD, T.S.; ATTIWILL, P.M.; ADAMS, M.A. 1991: Foliar diagnosis of plantations of *Eucalyptus globulus* and *E. nitens* in south-eastern Australia. P.162 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

KEEVES, A. 1966: Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the south-east of South Australia. *Australian Forestry 30*: 51–63.

KELLY, J.; LAMBERT, M.J. 1972: The relationship between sulphur and nitrogen in the foliage of *Pinus radiata. Plant and Soil 37*: 395–407.

KESSELL, S.L.; STOATE, T.N. 1938: Pine nutrition. A account of investigations and experiments in connection with the growth of exotic conifers in Western Australian plantations. *W.A. Forestry Department Bulletin No.50*. 45 p.

KNOTT, J.; RYAN, P. 1990: Development and practical application of a soils database for the *Pinus* plantations of the Bathurst Region. *Forestry Commission of NSW, Research Paper No.11*. 85 p.

KNOTT, J.; TURNER, J. 1990: Fertiliser usage in Forestry Commission of N.S.W. 1955-1989. *Forestry Commission of NSW, Technical Paper No.51*. 95 p.

LAFFAN, M.D. 1993: Site productivity and land suitability for eucalypt and radiata pine plantations in Tasmanian State Forest: A framework for classification and assessment of land resources. *Forestry Commission, Tasmania, Soil Technical Report No.3*.

———1994: A methodology for assessing and classifying site productivity and land suitability for eucalypt plantations in Tasmania. *Tasforests 6*: 61–7.

LAMBERT, M.J. 1986: Sulphur and nitrogen nutrition of *Pinus radiata* at Nundle State Forest, New South Wales, Australia. *Canadian Journal of Forest Research 16*: 1055–62.

LAMBERT, M.J.; RYAN, P.J. 1990: Boron nutrition of *Pinus radiata* in relation to soil development and management. *Forest Ecology and Management 30*: 45–54.

LAMBERT, M.J.; TURNER, J. 1977: Dieback in high site quality *Pinus radiata* stands—The role of sulphur and boron deficiencies. *New Zealand Journal of Forestry Science 7*: 333–48.

———1986: Post-establishment phosphatic fertiliser treatments in a New South Wales *Pinus radiata* plantation. *Fertilizer Research 10*: 263–8.

———1988: Interpretation of nutrient concentrations in *Pinus radiata* at Belanglo State Forest. *Plant and Soil 108*: 237–44.

LEWIS, N.B.; KEEVES, A.; LEECH, J.W. 1976: Yield regulation in South Australian *Pinus radiata* plantations. *Woods and Forests Department South Australia, Bulletin No.23*.

LUDBROOK, W.V. 1937: Needle fusion of species of *Pinus* in Southern New South Wales. Progress report, 1933–36. *Coun. Science Industry Australia, Pamphlet No.72*.

McGRATH, J.F.; ROBSON, A.D. 1984: Effect of nitrogen and phosphorus supply on the response of seedlings of *Pinus radiata* D. Don to applied zinc. *Australian Forest Research 14*: 163–73.

NAMBIAR, E.K.S.; BOOTH, T.H. 1991: Environmental constraints on the productivity of eucalypts and pine: opportunities for site management and breeding. Pp.215–31 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

NAMBIAR, E.K.S.; CELLIER, K.M. 1985: Nitrogen fertiliser in establishing *Pinus radiata* plantations on sandy soils: an evaluation of their use. *Australian Forestry 48*: 242–51.

NAMBIAR, E.K.S.; NETHERCOTT, K.H. 1987: Nutrient and water availability to and growth of young radiata pine plantations intercropped with lupins. *New Forests 1*: 117–34.

NEILSEN, W.A. 1982: Use of fertilisers in establishing and growing coniferous plantations in Australia. Pp.79–92 *in* "Establishment of Coniferous Plantations", 20–23 September 1982, Mount Gambier. Woods and Forests Department, S.A.

———1990: "Plantation Handbook". Tasmanian Forestry Commission. 270 p.

NEILSEN, W.A.; PATCZEK, W.; LYNCH, T.; PYRKE, R. 1992: Growth responses of *Pinus radiata* to multiple applications of nitrogen fertiliser and evaluation of the quantity of added nitrogen remaining in the forest system. *Plant and Soil 144*: 207–17.

O'CONNELL, A.M.; GROVE, T.S. 1991: Factors contributing to the nutritional resilience or vulnerability of jarrah and karri forests in Western Australia. Pp.180–97 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

ORME, K.; ORR, S.; GERRAND, A.; TODD, G. 1992: Potential of low fertility sites for plantations in north-eastern Tasmania. *Tasforests 2*: 69–75.

PEGG, R.E. 1967: Relation of slash pine site index to soil, vegetation and climate in south-east Queensland. *Queensland Forest Department Research Note No.19*. 53 p.

RAUPACH, M.; HALL, M.J. 1974: Foliar levels of potassium in relation to potassium deficiency symptoms in radiata pine. *Australian Forestry 36*: 204–13.

RAUPACH, M.; BOARDMAN, R.; CLARKE, A.R.P. 1969: Growth rates of *Pinus radiata* D. Don in relation to foliar levels of nitrogen and phosphorus in the south-east of South Australia. *CSIRO, Soil Publication No.26*. 28 p.

RITSON, P.; PETTIT, N.E.; MCGRATH, J F. 1991: Fertilising eucalypts at plantation establishment on farmland in south-west Western Australia. *Australian Forestry 54*: 139–47.

RYAN, P.J. 1989: Boron retention within a catena of rhyolitic soils and its effect on radiata pine growth and nutrition. *Australian Journal of Soil Research 27*: 135–48.

RYAN, P J.; KNOTT, J.H. 1991: Use of the Technical Soil Classification in NSW Softwood Plantations. Pp.39–51 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

SIMPSON, J.A. 1991: Changing land resource, taxa preference and fertiliser use in exotic pine plantations in south east Queensland. Pp.31–2 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

SIMPSON, J.A.; GRANT, M.J. 1991: Exotic pine fertiliser practice and its development in Queensland. *Queensland Forest Service Technical Paper No.49*. 17 p.

SIMPSON, J.; OSBORNE, D.O. 1993: Relative fertiliser requirements and foliar nutrient levels of young slash pine, Honduras Caribbean pine and the hybrid in Queensland. *Commonwealth Forestry Review 72*: 105–13.

SMETHURST, P.J.; NAMBIAR, E.K.S. 1989: Role of weeds in the management of nitrogen in a young *Pinus radiata* plantation. *New Forests 3*: 203–24.

———1990a: Distribution of carbon and nutrients and fluxes of mineral nitrogen after clearfelling a *Pinus radiata* plantation. *Canadian Journal of Forest Research 20*: 1490–7.

———1990b: Effects of slash and litter management on fluxes of nitrogen and tree growth in a young *Pinus radiata* plantation. *Canadian Journal of Forest Research 20*: 1498–507.

SQUIRE, R.O. 1977: Interactive effects of grass competition, fertilising and cultivation on the early growth of *Pinus radiata* D. Don. *Australian Forest Research 7*: 247–52.

———1983: Review of second rotation silviculture of *Pinus radiata* plantations in southern Australia: establishment practice and expectations. *Australian Forestry 46*: 83–90.

SQUIRE, R.O.; FLINN, D.W.; CAMPBELL, R.G. 1991: Silvicultural research for sustained wood production and biosphere conservation in the pine regions and native forests of south-eastern Australia. *Australian Forestry 54*: 120–33.

SQUIRE, R.O.; FLINN, D.W.; FARRELL, P.W. 1979: Productivity of first and second rotation stands of radiata pine on sandy soils. 1. Site factors affecting early growth. *Australian Forestry 42*: 236–42.

SQUIRE, R.O.; FARRELL, P.W.; FLINN, D.W.; AEBERLI, B.C. 1985: Productivity of first and second rotation stands of pine on sandy soils. II. Height and volume growth at five years. *Australian Forestry 48*: 127–37.

STANTON, R. 1991: Land evaluation for *Eucalyptus* plantation purposes in south-eastern New South Wales. P.167 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

———1992: *Eucalyptus* plantations in New South Wales. *Forestry Commission of NSW Research Paper No.15*. 29 p.

STOATE, T. N. 1950: Nutrition of the pine. *Forest and Timber Bureau Bulletin No.30*.

STONE, C. 1993: Fertiliser and insecticide effects on tree growth and psyllid infestation of young *Eucalyptus grandis* and *E. dunnii* plantations in northern New South Wales. *Australian Forestry 56*: 257–63.

THEODOROU, C.; BOWEN, G.D. 1983: Nitrogen transformations in first- and second-rotation *Pinus radiata* forest soil. *Australian Forest Research 13*: 103–12.

TRUMAN, R.A.; HUMPHREYS, F.R. 1985: Prediction of phosphorus levels in the foliage of *Pinus radiata* in five forests in New South Wales by parameters derived from soil analysis. *Australian Forest Research 15*: 17–26.

TRUMAN, R.; HUMPHREYS, F.R.; LAMBERT, M.J. 1983: Prediction of site index for *Pinus radiata* at Mullions Range State Forest, New South Wales. *Australian Forestry 13*: 207–15.

TURNBULL, C.R.A.; BEADLE, C.L.; WEST, P.W.; CROMER, R.N. 1994: Copper deficiency a probable cause of stem deformity in fertilised *Eucalyptus nitens. Canadian Journal of Forest Research 24*: 321–36.

TURNER, J. 1981: Interactions of nitrogen with other nutrients in coniferous stands. Pp.311–26 *in* "Managing Nitrogen Economies of Natural and Man Made Forest Ecosystems", 5–9 October 1980, Mandurah, W.A. CSIRO.

———1982: Long-term super-phosphate trial in regeneration of *Pinus radiata* at Belanglo State Forest, N.S.W. *Australian Forest Research 12*: 1–9.

———1984: Potential productivity gains in Australian east coast *Pinus radiata* plantations. Pp.947–56 *in* Proceedings of IUFRO Symposium on "Site and Productivity of Fast Growing Plantations", Pretoria, South Africa.

TURNER, J.; HOLMES, G.I. 1985: Site classification of *Pinus radiata* plantations in the Lithgow District, New South Wales, Australia. *Forest Ecology and Management 12*: 53–63.

TURNER, J.; KNOTT, J. 1991: Prescribing fertilisers in New South Wales plantation forestry. Pp.265–71 *in* "Forest Fertilisation: Nutrition and Growth of Western Forests". College of Forest Resources, University of Washington, Seattle.

TURNER, J.; LAMBERT, M.J. 1986a: Nutrition and nutritional relationships of *Pinus radiata. Annual Review of Ecology and Systematics 17*: 325–50.

———1986b: Fate of applied nutrients in a long-term superphosphate trial in *Pinus radiata. Plant and Soil 93*: 373–82.

———1987: Nutritional management of *Pinus radiata* at Gurnang State Forest, New South Wales. *Fertilizer Research 13*: 127–37.

———1991: Changed perspectives on soil processes associated with the changed land base of plantation forestry in Australia. Pp.15–28 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

TURNER, J.; LAMBERT, M.J.; BOWMAN, V.; KNOTT, J. 1992: Two post thinning fertiliser trials in *Pinus radiata* in New South Wales, Australia. *Fertilizer Research 32*: 259–67.

TURNER, J.; THOMPSON, C.H.; TURVEY, N.D.; HOPMANS, P.; RYAN, P.J. 1990: A soil technical classification system for *Pinus radiata* (D. Don) plantations. I. Development. *Australian Journal of Soil Research 28*: 797–811.

TURVEY, N.D. 1984: Copper deficiency in *Pinus radiata* planted on a podsol in Victoria, Australia. *Plant and Soil 77*: 73–86.

———(Ed.) 1987: A technical classification for soils of *Pinus* plantations in Australia: Field manual. *School of Forestry, University of Melbourne, Bulletin No.6.*

TURVEY, N.D.; BOOTH, T.H.; RYAN, P.J. 1990: A soil technical classification system for *Pinus radiata* (D. Don) plantations. II. A basis for estimation of crop yield. *Australian Journal of Soil Research 28*: 813–24.

TURVEY, N.D.; RUDRA, A.B.; TURNER, J. 1986: Characteristics of soil and productivity of *Pinus radiata* (D. Don) in New South Wales. I. Relative importance of soil physical and chemical parameters. *Australian Journal Soil Research 24*: 95–102.

WALSH, J.P. 1991: Correlation of early growth rates of eucalypt plantations in Tasmania with environmental indices. P.67 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

WARING, H.D. 1971: *Pinus radiata* and the nitrogen-phosphorus interaction. Pp.144–60 *in* "Australian Forest-Tree Nutrition Conference", 6–17 September 1971, Canberra. Forest and Timber Bureau, Canberra.

———1981a: Forest fertilisation in Australia: Early and late. Pp.201–18 *in* Australian Forest Nutrition Workshop "Productivity in Perpetuity", 10–14 August 1981, Canberra, Australia. CSIRO, Canberra.

———1981b: Silvicultural management problems in supplying nitrogen for production forestry. Pp.83–123 *in* "Managing Nitrogen Economies of Natural and Man Made Forest Ecosystems", 5–9 October 1980, Mandurah, Western Australia. CSIRO.

WESTON, C.J. 1991: Factors limiting the growth of eucalypts across a range of sites in Gippsland, Victoria. Pp.158–9 *in* Ryan, P.J. (Ed.) Third Australian Forest Soils and Nutrition Conference "Productivity in Perspective", 7–11 October 1991, Melbourne. Forestry Commission of NSW, Sydney.

WOODS AND FORESTS 1987: "Forestry Manual. Volume 2". South Australian Woods and Forests Department, Adelaide.

WOODS, R.V. 1976: Early silviculture for upgrading productivity on marginal *Pinus radiata* sites in the south-eastern region of South Australia. *Woods and Forest Department South Australia, Bulletin No.24.* 90 p.

———1981: Management of nitrogen in the *P. radiata* plantations of the south-east of South Australia. Pp.354–67 *in* "Managing Nitrogen Economies of Natural and Man Made Forest Ecosystems", 5–9 October 1980, Mandurah, Western Australia. CSIRO.

WOODS, R.V.; NAMBIAR, E.K.S.; SMETHURST, P.J. 1992: Effect of annual weeds on water and nitrogen availability to *Pinus radiata* trees in a young plantation. *Forest Ecology and Management 48*: 145–63.

WOOLLONS, R.C.; SNOWDON, P. 1981: Theory and practice of forest fertilisation. Pp.219–30 *in* Australian Forest Nutrition Workshop "Productivity in Perpetuity", 10–14 August 1981, Canberra, Australia. CSIRO, Canberra.

YOUNG, H.E. 1940: Fusion needle disease and its relation to the nutrition of *Pinus*. *Queensland Forest Service Bulletin No.13.*