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Review of fertiliser use in Australian forestry

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Review of fertiliser use in Australian forestry

Prepared for

Forest & Wood Products Australia

by

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

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EXECUTIVE SUMMARY

This report reviews the history and current state of knowledge of fertiliser use in softwood and hardwood plantations in Australia, surveys current fertiliser use and strategies and compares these with those in selected agricultural crops. In addition, it estimates environmental impacts in terms of emissions to both air and water from fertiliser use in forestry and agricultural systems, and it puts these in terms of Australia's greenhouse gas emissions. Opportunities for improving fertiliser efficiency and profitability are identified and knowledge gaps are summarised.

Hardwood and softwood plantations cover a total area of 1.8 million ha of Australia and produce 16.7 million m^3 wood annually worth $1.0 billion. As a result of recent expansion of the plantation estate, this volume is forecast to increase to 30 million m^3 $year^{-1}$ by 2020. Softwood plantations are owned by both public agencies and private investors and are managed primarily to produce sawlogs on a 30-35 year rotation. Hardwood plantations are owned mainly by Managed Investment Scheme investors, and are mostly managed for pulpwood on a 10-15 year rotation. Fertiliser application at, or soon after, establishment, or to mid-rotation plantations forms a key component of maintaining and enhancing stand productivity and profitability.

Research into nutrient management of plantations can be divided into the following areas:

- Initial studies in the 1930's-40's into the causes of poor growth on some sites resulted in widespread use of trace elements (zinc and copper) and phosphorus in young softwood stands.
- Identification of the problem termed "second rotation decline" in the 1960's in which replanted *Pinus radiata* stands failed to grow as fast as the previous rotation on sandy soils in southern Australia resulted in substantial research into slash management and nutrition of young stands (including weed control). During subsequent decades, this research led to changes in site preparation, weed control and nitrogen fertiliser use in young plantations.
- Large numbers of fertiliser experiments were established in the 1980's and 90's as focus switched to opportunities for improving stand growth though post-thinning fertilisation. A large range of growth response was reported, and various diagnostic techniques were tested to improve the accuracy of targeting responsive stands for fertiliser application. Typically, responses to phosphorus fertiliser were found to be long-lasting, sometimes continuing into subsequent rotations, while those to nitrogen were shorter (around 4-6 years duration). Short-term accelerations in growth that were not expected to raise overall site productivity were termed Type 1 responses, responses that resulted in long-term increases in site production potential were termed Type 2 responses. This work coincided with the concept of site-specific management in which silviculture and nutrition were tailored to maximise production (or profitability) for a given site and species. Systems based on soil-type were developed for fertiliser use in most states.
- With the establishment of large-scale eucalypt plantations during the 1990's, research was conducted into nutrient management on ex-native forest and ex-pasture sites. Similar to earlier research with softwoods, these studies demonstrated that large growth responses were possible to nitrogen and phosphorus fertiliser on some sites and that several foliar- or soil-based indices could be used to predict response. Other studies demonstrated the importance of conserving harvest slash for the supply of nutrients, and the likelihood that nitrogen supply in particular was likely to limit growth of future rotations.
- Further research into the effects of varying fertiliser rate, form, placement and timing through the rotation took place in the 2000's in order to optimise fertiliser strategies

for particular sites and management regimes in both hardwood and softwood plantations. This work was combined with further development and testing of diagnostic methods and improved economic modelling, which together led to the development of decision support systems and process-based models.

- Research into the effects of fertiliser on wood quality showed that effects of fertiliser on density or fibre strength were generally minor and short lived. Furthermore, for older stands, the net effect was to increase the log value by increasing the amount of higher value outer wood.
- Research into the effects of fertiliser on soil chemistry and nutrient leaching showed that effects were generally negligible except where large or long-term repeated doses were applied. The use of riparian buffer strips was found to be useful in minimising the risk of direct application of fertiliser, or nutrient runoff into surface water courses.

Fertiliser use in hardwood and softwood plantations for the period 2002-04 was surveyed across 8 softwood and 6 hardwood growers representing 84% of the total softwood resource and 50% of the total hardwood resource across Australia. The results of the survey are summarised as follows:

- Nitrogen and phosphorus were reported to be the most common nutrient deficiencies with all softwood growers reporting phosphorus deficiencies and 70% reporting nitrogen deficiencies while, 85% of hardwood growers reported nitrogen and phosphorus deficiencies (Figure 2). Other common nutrient deficiencies included Zn, potassium, copper, and boron.
- A total of 10,400 t nitrogen, 4,300 t phosphorus, 3,800 t sulphur, 2,500 t potassium, 120 t copper and 70 t zinc were currently applied across the total plantation estate each year (Table 9). Most fertiliser was applied to hardwood plantations including 69% of total nitrogen, 65% phosphorus, and 82% of potassium, 85% copper and 83% zinc. The total area of hardwoods fertilised was approximately triple that for softwoods for every element except boron (Figure 4).
- Rates of fertilisation with macro-nutrients in softwood plantations were almost double those for hardwood plantations on a per-unit-area fertilised basis. For example, the average rate of nitrogen application was 72 kg N ha^{-1} in softwoods compared with 48 kg N ha^{-1} in hardwoods while the average rate of phosphorus application was 42 kg P ha^{-1} for softwoods compared with 25 kg P ha^{-1} for hardwoods (Table 9). However, rates expressed on a total plantation area basis were three to four times greater in hardwood plantations compared with softwood plantations. Annual rates of fertiliser use were equivalent to 9.7 kg N ha^{-1}, 3.8 kg P ha^{-1} and 2.8 kg K ha^{-1} across the total hardwood plantation estate and 3.4 kg N ha^{-1}, 1.6 kg P ha^{-1} and 0.5 kg K ha^{-1} across the total softwood plantation estate (Figure 6).
- The most common forms of fertiliser used were NPKS blends, urea, sulphur coated urea and DAP (diammonium phosphate). Urea or sulphur coated urea made up at least 37% of nitrogen fertiliser applied to hardwood plantations and 57% of that applied to softwood plantations (Figure 9). DAP made up 24% of phosphorous fertiliser applied to hardwood plantations and 44% of phosphorous fertiliser applied to softwood plantations (Figure 10).
- The amount of fertiliser applied at different stages of the rotation varied with species and element. Around 50% of nitrogen and 35% of phosphorus was applied to mid-rotation hardwood (3-11 year old) and softwood (11-20 year old) plantations (Table 10). Most potassium fertiliser was applied at establishment for hardwood plantations (56%) and to mid-rotation softwood plantations (46%). Rates of fertiliser application (in terms of the amount applied per hectare fertilised) tended to increase through the rotation for nitrogen and phosphorus for both softwood and hardwood plantations and potassium and sulphur for softwood plantations only (Table 10).

- Major factors influencing fertiliser use included amelioration of nutritional deficiencies, maximising profit, increasing wood production, and the cost of fertiliser (Figure 13). Evening out wood flows, and land price and availability were relatively unimportant factors according to survey results. Market demand for wood and potential impacts on wood quality were considered more important in fertiliser decisions in softwood plantations than hardwood plantations.

- The method used to select sites to fertilise varied depending on the plantation age. Prior to establishment, soil analysis or description was the main method, while foliar analysis was the primary method for young hardwood and established softwood plantations. For mid-rotation or later-age hardwood stands, growth rate was the dominant method (Figure 14). On, the whole most growers were confident in the accuracy of the method used. However, while this confidence tended to increase with stand age in softwood plantations, it tended to decrease for hardwood plantations as a result of limited data (Figure 15).

- Application methods varied depending on the form of fertiliser applied and plantation age. Hand application was used at planting, while liquid fertilisers (predominantly zinc and copper) were applied using fixed wing aircraft. Solid fertilisers were applied in older stands either aerially (using fixed wing aircraft or helicopters) or from the ground using tractors or modified skidders. Application cost tended to decrease with plantation age from \$103 ha^{-1} at establishment in hardwood plantations and \$82 ha^{-1} at establishment in softwood plantations to \$13 ha^{-1} in later-age hardwood and \$40 ha^{-1} in later-age softwood stands (Table 12).

- Average estimated relative growth responses over 6 years to fertiliser application in hardwood plantations varied from 24% at establishment to 49% for mid-rotation stands (Figure 17). In comparison responses in softwood plantations varied from 13% for young stands to 30% at establishment.

- An economic model based on reported growth rates, rotation lengths, fertiliser costs and responses to fertiliser indicated that fertiliser application at establishment was unlikely to be profitable for a type 1 response (6 year duration,Table 14), but could be profitable for a type 2 response (i.e. where the response continues to the end of the rotation, Table 15)

- For both types of responses, the most profitable time to apply fertiliser was at midrotation (7 years for hardwood and 15 years for softwood plantations). However, factors not considered in the analysis including the need for fertiliser in order to obtain acceptable survival and growth on some sites, changes in unit wood value in response to fertiliser, and effects on tree form and growth of subsequent rotations will also influence the optimum timing of fertiliser application.

- Leaching losses from fertiliser application expressed on a total plantation area basis were estimated to range from 0.09-0.38 kg N ha^{-1} as nitrate and 0.007-0.022 kg ha^{-1} as phosphate for hardwood plantations and from 0.03-0.13 kg N ha^{-1} as nitrate and 0.006-0.017 kg P ha^{-1} for phosphate (Table 16). However, emissions to streams were expected to be negligible provided best management practices were adhered to including retention of forest litter after harvest and stream-side buffer strips, preventing direct application of fertiliser to waterways and avoiding overuse of nitrogen fertiliser in particular.

- Based on IPCC default values for emissions of greenhouse gasses from agricultural fertiliser use, total direct and indirect N_2O emissions were estimated to average 0.19 kg ha^{-1} for hardwood plantations and 0.07 kg ha^{-1} for softwood plantations (Table 17). These rates were equivalent to 140 t N_2O $year^{-1}$ (46,000 t CO_2-e $year^{-1}$) in hardwood plantations and 67 t N_2O $year^{-1}$ (22,000 t CO_2-e $year^{-1}$) in softwood plantations.

Trends in fertiliser use, prices and application rates and emissions for different agricultural zones and crops were compared with those in forestry. This assessment showed the following:

- Australian fertiliser consumption has increased substantially over the past twenty years. Nitrogen use tripled between 1986-87 and 2004-05, potassium use more than doubled and phosphorus use increased by 40% (Figure 22). Fertiliser use in forestry represents just 1% of the nitrogen and 0.9% of phosphorus and 1.4% of potassium applied across Australia each year.

- Between 1984-85 and 2004-05 fertiliser prices increased at annual rates ranging from 1.6-1.7% for urea and DAP to 3.0-3.3% for single super phosphate and ammonium sulphate (Figure 23). However, between March 2007 and May 2008 fertiliser prices increased sharply with the retail price of urea increasing 30% and the retail price of DAP doubling over the period.

- Estimated annual rates of fertiliser use in agricultural systems varied from 0 kg N ha^{-1} $year^{-1}$ and <10 kg P ha^{-1} $year^{-1}$ for extensive grazing, to 150-300 kg N $ha^{-1}$and 50-100 kg P ha^{-1} for fruit and vegetable crops (Table 18). Compared with estimated average annual fertiliser rates across a range of agricultural crops and pastures, average rates of fertiliser use in plantation forestry were among the lowest on a total area basis with rates lower only for pasture and oilseed/legume crops (Table 19).

- Greenhouse gas (GHG) emissions from agricultural soils (51,000 t N_2O $year^{-1}$ or 15.8 Mt CO_2-e $year^{-1}$) comprise 64% of total N_2O emissions and 2.7% of total GHG emissions for Australia and have been growing at a rate of 10% per annum. Based on the amounts of fertiliser applied and DCC emission factors, the total estimated emission of N_2O from fertiliser use in agriculture plus forestry is around 9,700 t $year^{-1}$ (Table 20).

- Based on the very conservative IPCC default values for emissions, forestry may contribute around 2% to total N_2O emissions from fertiliser use. The most greenhouse intensive crops in terms of emissions from fertiliser were sugarcane (4.4 kg N_2O ha^{-1} $year^{-1}$) and horticultural crops (5.5 kg N_2O ha^{-1} $year^{-1}$), while the least greenhouse intensive were pasture (0.02 kg N_2O ha^{-1} $year^{-1}$), oilseed/legumes (0.05 kg N_2O ha^{-1} $year^{-1}$) and non-irrigated cereals (0.20 kg N_2O ha^{-1} $year^{-1}$). In comparison, estimated emissions from fertiliser use in forestry plantations were 0.12 kg N_2O ha^{-1} $year^{-1}$.

- Leaching of nutrients is a serious problem across most catchments in Australia. According to the National Land and Water Resources Audit, excess nutrients are a major water quality issue in 61% of Australia's water catchment basins. Agricultural systems with high rates of leaching of nitrogen include dairy (3-34 kg N ha^{-1} $year^{-1}$), sugarcane (2.9 kg N ha^{-1} $year^{-1}$) and horticultural crops (eg. 80-140 kg N ha^{-1} $year^{-1}$ for bananas). These figures are at least an order of magnitude greater those for hardwood or softwood plantations. The overall contribution of fertiliser use in forest plantations to nutrient leaching across Australian catchments was estimated to be just 0.2% for N and 0.1% for P.

Areas for further research identified include: improved prediction and modelling of fertiliser responses, assessment of nutrient requirements of mid-rotation and second rotation hardwood plantations, improved economic modelling of the effects of alternative fertiliser strategies, and application of remote sensing for broadscale assessment of nutritional requirements of individual stands across the plantation estate. In addition, quantification of N_2O emissions from fertiliser application in plantation forest will be important for greenhouse gas accounting for forestry. Improved estimates of losses of fertiliser through leaching and runoff across a broader range of soils climates and stand ages will allow a better understanding of the effect of plantations compared with other land-uses on water quality.

This study provides detailed, information on current fertiliser use across Australia's hardwood and softwood plantations. Current fertiliser strategies have developed from a long period of research into nutrition of softwood and, more recently, hardwood plantations, subject to specific nutrient constraints and requirements depending on differences in soil, climate, genetics and management systems. Both the amount and rate of fertiliser use in forestry plantations are far lower than those for most agricultural systems. Thus, the impact on greenhouse gas emissions and water quality of plantation fertiliser use appears to be very low. Further improvements in both the efficiency and economics of fertiliser use in forestry are expected in the future with continued research into this critical aspect of sustainable forest management.

1. GLOSSARY OF TERMS

The following abbreviations for chemicals or fertiliser forms are used throughout the report:

Element Symbols

B boron

C carbon

CO_2 carbon dioxide

Ca calcium

Cu copper

K potassium

KCl potassium chloride

K_2SO_4 potassium sulphate

N nitrogen

N_2O di-nitrogen oxide

NO_3^- nitrate

NH_4^+ ammonium

NH_3 ammonia

P phosphorus

S sulphur

Mg magnesium

Mn manganese

Mo molybdenum

Zn zinc

Fertiliser forms

AS ammonium sulphate, sulphate of ammonia

DAP di-ammonium phosphate

KCl potassium chloride, muriate of potash

MAP mono-ammonium phosphate

Super super phosphate

SCU sulphur coated urea

TS triple super phosphate

Other terms

CO_2–e carbon dioxide equivalents (global warming impact of all emissions to air expressed as the equivalent amount of carbon dioxide)

GHG greenhouse gas

IRR internal rate of return

P probability that treatment effects are equal.

SD standard deviation

Species common names

Acacia dealbata	silver wattle
Acacia mangium	acacia mangium
Araucaria cunninghamii	hoop pine
Corymbia maculate	spotted gum
Eucalyptus dunnii	Dunns white gum
Eucalyptus globulus	Tasmanian bluegum
Eucalyptus grandis	flooded gum
Eucalyptus nitens	shining gum
Eucalyptus regnans	mountain ash
Pinus caribaea	Caribbean pine
Pinus elliottii	slash pine
Pinus pinaster	maritime pine
Pinus radiata	Monterey pine or radiata pine
Pinus taeda	loblolly pine

2. INTRODUCTION

Fertilisers are widely used in plantations across Australia to ameliorate nutrient deficiencies and boost stand growth. Fertiliser management now forms a crucial component of most plantation management systems and plays a key role in allowing plantation forestry to be a profitable enterprise. Research into fertiliser use spans almost the entire period of plantation establishment in this country and has resulted in the development and refinement of fertiliser strategies that match the requirements of different sites and species and the varied objectives of plantation owners. However, (i) changes in the species and sites planted, (ii) variations in the cost of land, materials, and their relativity, (iii) a shift from 1st to subsequent rotations, and (iv) increasing focus on the impact of fertilisers on water quality and greenhouse gas emissions mean that forest managers and researchers continually face new challenges in trying to optimise plantation nutrient management to meet varied and often-conflicting objectives.

A number of studies have reviewed fertiliser use in softwood and hardwood plantations across Australia over the years (eg. Birk, 1994; Smethurst *et al.*, 2004; Turner, 1983; Turner *et al.*, 2001). Others have quantified growth and other responses to fertiliser and evaluated the economics of fertiliser usage (Knott *et al.*, 1996; eg. Knott *et al.*, 1996; Smethurst *et al.*, 2001; Snowdon & Waring, 1990). More recently, a number of studies have attempted to explain the soil and plant processes involved in fertiliser response and the impacts on nutrients in soil or water (eg. Carlyle, 1995; Fife & Nambiar, 1999; Forsyth *et al.*, 2006; Snowdon, 1995). Much of this work has focussed on fertiliser usage in softwood plantations. However, a growing number of studies have or are investigating nutrient management across the rapidly growing area of hardwood plantations.

With increased competition for land and resources between forest plantations and traditional agricultural systems, there is a growing need to properly quantify the impacts of different land uses on the environment. Much of the current focus is on the impact on water yield. However, attention is turning to the impacts on water quality and greenhouse gas emissions. These are both critical issues as a large proportion of Australia's rivers and aquifers now carry significant nutrient loads as a result of nutrient runoff from agricultural systems, and a significant proportion of Australia's greenhouse gas emissions (~2%) are from agricultural soils (DCC, 2008a; National Land and Water Resources Audit, 2002). While plantation forestry is generally considered to have a relatively minor negative impact on water quality compared with agriculture, there is little Australian data on which to base these claims.

This report (i) reviews the current state of knowledge of fertiliser management in hardwood and softwood plantations in Australia, (ii) provides up to date information on fertiliser usage, and (iii) compares fertiliser use in and emissions from forestry with those from selected agricultural systems. It brings together past studies into plantation nutrient management across Australia to show how the focus of fertiliser strategies and research has changed over time. Data on current fertiliser usage in hardwood and softwood plantations was obtained by means of a commercial-in-confidence survey of forest owners. Information provided included the rate and type of fertiliser applied, timing of fertiliser applications in the rotation, methods used to select which stands to fertilise, and the expected growth responses. Risks of emissions to air and water contamination from fertiliser were assessed from relevant literature. Fertiliser usage and emissions were compared with those from a range of agricultural systems and put these into the context of total consumption and emissions from fertiliser across Australia. Finally, opportunities for improving the efficiency and economics of fertiliser use and knowledge gaps for further research are identified.

3. FOREST INDUSTRY OVERVIEW

As of 2005, forest plantations covered a total of 1.7 million ha across Australia. This included 0.7 million ha of hardwood and 1.0 million ha of softwood plantations (ABARE, 2008), Table 1. Total wood removals from hardwood plantations in 2006-07 were 4 million m^3 compared with 14.5 million m^3 from softwood plantations (ABARE, 2008). Hardwood plantations are mostly managed for pulpwood production (with pulpwood comprising 95% of total hardwood production) and rotation lengths are typically around 10-12 years. In contrast, softwood plantations are managed for sawlog production (with sawlogs comprising 65% of total softwood production) and have rotation lengths of around 30-40 years.

Softwood plantations have been established in all states (NPI 2006). The rate of expansion of softwood plantations is fairly low with a 4% increase in total planted area over the past five years (ABARE, 2008). *Pinus radiata* is the predominant species planted across southern Australia, while *P. carribea* and *P. elliottii* and their hybrid are grown in Queensland. Smaller areas of *P. pinaster* in Western Australia, and *Araucaria* spp. (particularly hoop pine) in Queensland, are also grown. Of the total area of softwood plantations, about 75% are *P. radiata,* 20% are other introduced conifers and 5% are *Araucaria* spp.

In contrast to softwood plantations, the area under hardwood plantations has been expanding rapidly over the past 10 years with a 40% increase in total planted area over the past 5 years (ABARE, 2008). Thus, most have not had their first commercial harvest. In southern Australia, the main species is *Eucalyptus globulus*, with *E. nitens* also planted in higher elevation areas of Victoria, Tasmania and NSW. In northern NSW and Queensland several other species are planted including *E. grandis* and *E. dunnii*.

In regions which have achieved a critical mass of plantation resource, there is an integrated industry that value-adds to plantation products. These regions include the Green Triangle in south-east South Australia and western Victoria, the Murray Valley in north-east Victoria, and the south-west slopes of New South Wales. The forest industry in each of these regions includes the forest estate, various organisations involved in establishing, managing, harvesting and transporting logs and woodchips, and downstream processing facilities including sawmills, veneer mills, particleboard and fibreboard mills, pulp and paper mills and various associated service industries.

Table 1: Australian plantation estate by State/Territory in 2005.

State/Territory	Hardwoods (ha)	Softwoods (ha)	Other categories (ha)	Total (ha)
Australian Capital Territory	0	9,500	0	9,500
New South Wales	55,196	273,606	2,821	331,623
Northern Territory	14,090	2,239	0	16,329
Queensland	37,496	186,033	2,108	225,637
South Australia	42,341	124,163	457	166,962
Tasmania	155,500	71,600	100	227,200
Victoria	164,724	218,412	1,463	384,599
Western Australia	270,813	104,480	2,305	377,598
Australia	740,161	990,034	9,255	1,739,450

Source: Parsons *et al.* (2006).

3.1 Forest ownership

Plantations are owned and managed by both private and public companies. The majority of softwood plantations (71%) are publicly owned or managed, while the majority of hardwood plantations (95%) are privately owned (Table 2). Government agencies in Queensland, WA, NSW, SA and Tasmania manage 42% of the total hardwood and softwood plantation estate. The largest private growers include HVP (169,000 ha softwoods), ITC (140,000 ha hardwoods), great southern plantations (110,000 ha hardwoods), Gunns Ltd. (110,000 ha hardwoods and 35,000 ha of softwoods in its subsidiary Auspine Ltd.) and Timbercorp (80,000 ha hardwoods).

Table 2: Ownership of hardwood and softwood plantations in Australia.

Owner	Type	Area (ha)	(%)		Source
Softwood					
Forests NSW	Public	250,113	14.4		Parsons et al (2007)
Forestry Plantations Queensland	Public	193,407	11.1		Parsons et al (2007)
HVP Ltd	Private	169,000	9.7		Jenkin and Tompkins (2006)
Forest Products Commission	Public	106,172	6.1		Parsons et al (2007)
ForestrySA	Public	87,000	5.0		Parsons et al (2007)
Forestry Tasmania	Public	52,855	3.0		Foresry Tasmania (2005)
Auspine Ltd	Private	35,181	2.0		Jenkin and Tompkins (2006)
Willmott Forests Ltd	Private	30,000	1.7		Jenkin and Tompkins (2006)
Green Triangle Forest Products	Private	25,000	1.4		A. Moore Pers. Comm (2007)
Norske Skog	Private	20,000	1.1		J. Bruce (2007)
Environment ACT	Public	9,500	0.5		Parsons et al (2006)
AKD Softwoods	Private	4,000	0.2		Jenkin and Tompkins (2006)
Other	Private	5,874	0.3		Parsons et al (2007)
	Unknown	1,933	0.1		
Total	Public	699,047	40.2	70.6	
	Private	289,055	16.6	29.2	
	Total	**990,034**	**56.9**	**100.0**	Parsons et al (2007)
Hardwood					
ITC Ltd	Private	140,000	8.0		Jenkin and Tompkins (2006)
Great Southern Plantations Ltd	Private	110,000	6.3		Jenkin and Tompkins (2006)
Gunns Ltd	Private	110,000	6.3		Jenkin and Tompkins (2006)
Timbercorp Ltd	Private	80,000	4.6		Jenkin and Tompkins (2006)
WA Plantation Resources Ltd	Private	33,000	1.9		Jenkin and Tompkins (2006)
Forestry Tasmania	Public	32,634	1.9		Foresry Tasmania (2005)
Forest Enterprises Australia Ltd	Private	32,000	1.8		Jenkin and Tompkins (2006)
Albany Plantation Company	Private	23,000	1.3		Jenkin and Tompkins (2006)
Forestry Plantations Queensland	Public	10,000	0.6		Bubb, FPQ Pers. Comm. (2008)
Other	Private	167,595	9.6		Parsons et al (2007)
	Unknown	1,933	0.1		
Total	Public	42,634	2.5	5.8	
	Private	695,595	40.0	94.0	
	Total	**740,161**	**42.6**	**100.0**	Parsons et al (2007)

3.2 Wood production

The average total volume of logs harvested from plantations in 2001-07 was 16.7 million cubic metres, with 85% (14.1 million m^3) from softwood plantations and 15% (2.3 million m^3) from hardwood plantations (ABARE, 2008, Table 5). However, production from hardwood plantations has been increasing rapidly as a larger proportion of the estate reaches harvestable age with the total contribution increasing from 8% (1.1 million m^3) in 2001-02 to 22% (4.0 million m^3) by 2006-07. The volume harvested from softwood plantations has been relatively stable over recent years increasing by just 1.2 million m^3 or 9% between 2001-02 and 2006-07 when a total 14.2 million m^3 were harvested.

Softwood plantations are mainly grown for sawlog production with saw and veneer logs comprising 63% of removals. Pulplogs for paper or wood-based panel products make up 34% with the remainder consisting mainly of posts that are treated and used for fencing or trellises. In contrast, hardwood plantations are normally grown on short rotations for export woodchips, with pulplogs for paper production comprising 92% of total removals. However, a small proportion of hardwood plantations (mainly in Tasmania) are also managed for sawlog production.

Total harvestable volume from softwood plantations is expected to increase by just 7% to 15.6 million m^3 $year^{-1}$ by 2010-14 (Parsons *et al.*, 2007, Figure 1). In contrast, total harvestable volume from hardwood plantations is expected to increase by 250% to 14.1 million m^3 $year^{-1}$ over the same period (Parsons *et al.*, 2007). By 2020, the total wood production from plantations is predicted to reach 30 million m^3 with over half this amount being supplied by hardwood plantations.

The average gross value of annual production from plantations for the period 2001-07 was $1.0 billion (ABARE, 2008, Table 4); the value of the associated forest products sector is considerably higher. This value of wood harvested comprised $173 million (18%) from hardwood plantations and $812 million (82%) from softwood plantations. Between 2001-02 and 2006-07, the value of wood production from softwood plantations increased by 25% while that from hardwood plantations increased by 470%.

Table 3: Volume of wood production from different log categories in Australia. Source: ABARE (2008).

Forest and log type	Annual Total						Avg 2001-07	
	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07	Avg.	Std. Dev.
	m3 '000	m3 '000	m3 '000	m3 '000	m3 '000	m3 '000	m3 '000	m3 '000
Hardwood								
Saw and veneer logs	67	153	177	273	208	158	173	68
Pulpwood								
For wood based panel	43	-	34	9	-	-	14	19
For paper and paperboard	998	1,435	1,599	2,640	3,554	3,866	2,349	1,188
Other	4	6	9	14	17	15	11	5
Total	1,112	1,594	1,819	2,936	3,779	4,038	2,546	1,216
Softwood								
Saw and veneer logs	8,244	8,557	9,143	9,121	9,384	9,477	8,988	485
Pulpwood								
For wood based panel	1,473	1,584	1,418	1,318	1,418	1,154	1,394	146
For paper and paperboard	3,223	3,392	3,684	3,410	3,162	3,439	3,385	184
Other	415	377	343	347	415	472	395	49
Total	13,355	13,910	14,588	14,196	14,379	14,542	14,162	467
Total								
Saw and veneer logs	8,311	8,710	9,320	9,394	9,592	9,635	9,160	532
Pulpwood								
For wood based panel	1,516	1,584	1,452	1,327	1,418	1,154	1,409	152
For paper and paperboard	4,221	4,827	5,283	6,050	6,716	7,305	5,734	1,170
Other	419	383	352	361	432	487	406	51
Total	14,467	15,504	16,407	17,132	18,158	18,581	16,708	1,572

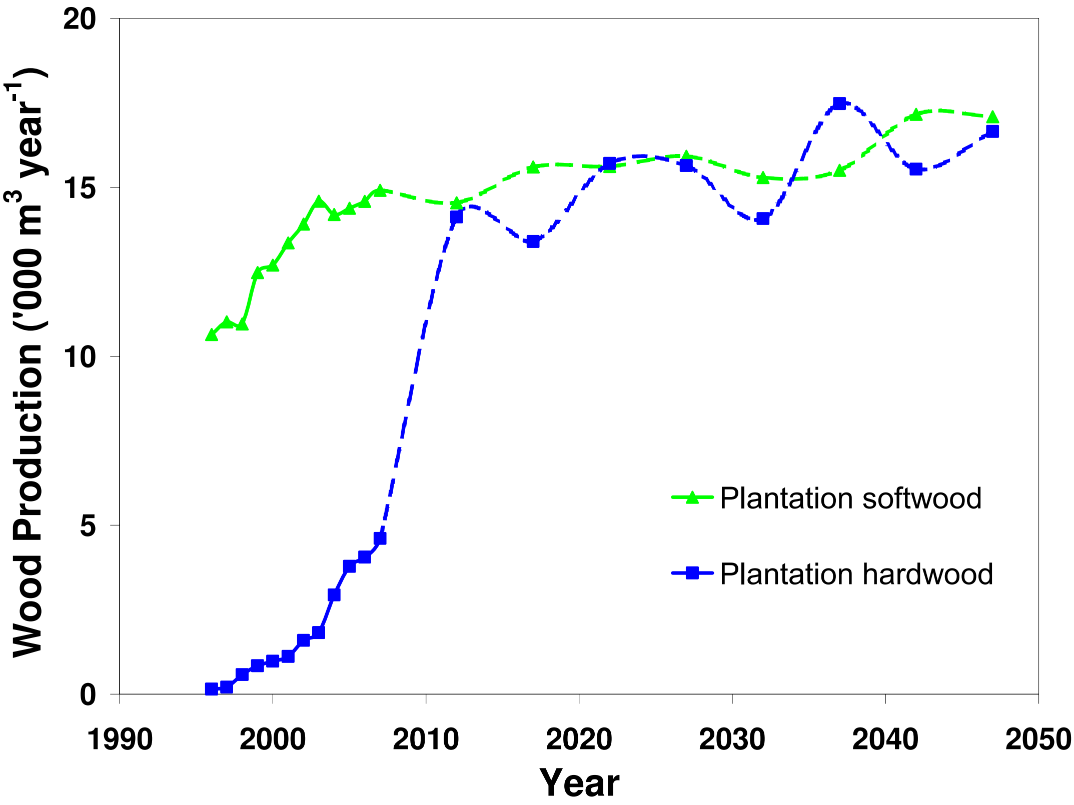

Figure 1: Historic (solid lines) and forecast (dashed lines) wood production from Australian softwood and hardwood plantations (ABARE 2008, Parsons *et al.* 2007).

Table 4: Value of wood production from softwood and hardwood plantations in Australia.

Plantation Type	Annual Total						Avg 2001-07	
	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07	Avg.	Std. Dev.
	$m	$m	$m	$m	$m	$m	$m	$m
Hardwood	58	81	102	172	237	272	173	83
Softwood	680	754	816	820	825	847	812	35
Total	738	835	918	992	1062	1119	985	113

Source: ABARE (2008).

4. RESEARCH INTO FERTILISER USAGE IN PLANTATION FORESTRY

4.1 Softwood plantations

4.1.1 Early research

The use of fertiliser to correct nutrient deficiencies and increase productivity has been widespread in Australian forest plantations since the mid-1960's (Attiwill, 1982). The approaches taken have varied with region due to differences in soil, climate, species requirements, and different attitudes and objectives of the management agencies. Birk (1994) and Turner *et al.* (1999) have reviewed research into fertiliser use in plantations across Australia from the 1920's to the late 1990's. The following summarises these reviews together with other relevant studies.

Prior to 1970, most plantations were established on poorer soils including deep unconsolidated sands in Victoria and South Australia (Birk 1991). Although, initially it was thought that moisture limitations controlled growth, research in the 1930's soon demonstrated that fertilisers corrected disorders previously thought be pathological including needle fusion (corrected by phosphorus) and tip dieback on coastal sands (corrected by zinc, Birk, 1994). Thus, by 1950, remedial and establishment fertiliser applications were routine for *P. pinaster* in WA, *P. elliottii* in south-east Queensland and *P. radiata* in South Australia and Victoria growing on the poorest soils (Simpson & Grant, 1991; Stoate, 1950).

Despite research showing the critical nature of soils and nutrition, there was a lengthy period when the concept of a "small quantity, quick fix" fertiliser application was common place (Turner *et al.*, 1999). In the 1960's, this focus changed as a result of intensive research into nutrient (especially nitrogen and phosphorus) deficiencies, availability and responses to fertiliser in plantations (Gentle & Humphreys, 1967; Humphries & Bourgeron, 2003; Waring, 1963). This work led to the adoption of ameliorative type fertiliser strategies. Subsequent economic analysis by Cromer and Dargavale (1977) showed that intensive treatment with fertiliser and weed control was a better investment of capital than planting additional land. Establishment and mid-rotation fertiliser use aimed at maximising financial gain soon became important, leading to research into relationships between soils, climate, and nutrient interactions (Turner *et al.*, 1999).

4.1.1.1 South east Queensland

In SE Queensland, application of phosphorus was found to be essential for growth and economic viability of the main pine species (*P. elliottii*) planted on the coarse-textured, coastal soils (Simpson and Grant 1991). In the 1950's, applications of 50 kg P ha^{-1} equivalent of rock phosphate prior to, and 3 years after, planting, became routine. A review of fertiliser requirements of softwood plantations in SE Queensland in the 1960's confirmed that phosphorus was the major limiting factor and that, once this deficiency was corrected; smaller responses could be obtained to nitrogen fertiliser. With the advent of high analysis fertilisers and expansion of plantations on to less fertile soils in the 1970's, fertiliser usage switched to triple super phosphate. In the 1980's, prescriptions were introduced for nitrogen fertiliser on podsolic soils on southern and poorly drained central and northern sites in Queensland (Simpson and Grant 1991). Since 1987, mono-ammonium phosphate (MAP) has become the major form of phosphorus used.

In the 1980's, *Pinus caribaea* and later, the hybrid between *P. elliottii* and *P. caribae*a, were planted in preference to *P. elliottii* in SE Queensland due to superior growth, form and wood properties and the expansion of plantation forestry onto higher fertility ex-agricultural land. Fertiliser research then focussed on identifying key limiting nutrients and their interactions with site and species (Simpson and Osborne 1993). Response to phosphorus varied with soil type and moisture availability, and fertiliser experiments were introduced on a site-specific basis to identify nutrient requirements and tailor fertiliser prescriptions for individual sites and taxa (Simpson & Osborne, 1993; Xu *et al*., 1995b; Xu *et al*., 1995c). In addition, Simpson and Grant (1991) reported that substantial responses to potassium could be achieved on podsols once phosphorus deficiency had been corrected. Thus, potassium fertiliser prescriptions of 50-100 kg ha^{-1} for stands on these soils were recommended.

4.1.1.2 Western Australia

Initial research in WA focussed on the identification and remediation of a variety of growth disorders of *P. radiata* and *P. pinaster* that were being widely planted on the relatively infertile sandy soils of the Gnangara mound and similar regions. This work showed that application of zinc sulphate and super phosphate at, and just after, establishment corrected most nutritional disorders (Stoate, 1950). Subsequent research focussed on responses to nitrogen, phosphorus, potassium and zinc, on the sandy soil of the Swan coastal plain, modes and timing of fertiliser application in relation to nutrient immobilisation, leaching and root development, rate of response, and nutrient cycling through litterfall and decomposition (Hopkins, 1960). Work by McGrath and Robson (1984) confirmed earlier findings on the importance of foliar application of zinc after planting and demonstrated the need to balance the supply of nitrogen, phosphorus and zinc to avoid inducing nutrient deficiencies (McGrath, 1978).

4.1.1.3 Green Triangle

In the Green Triangle region of south-west SA and south-east Victoria, zinc application to stands aged 3 years was regularly used as a standard establishment practice in the 1940's to prevent tip dieback and leader multiplication (Stoate, 1950). Around the same time, application of phosphorus fertiliser as superphosphate at establishment and 15 years for plantations with symptoms of nutrient deficiency was shown to be economic (Boomsma, 1949). Subsequent field trials showing increases in stand productivity with phosphorus fertiliser application across specific soil types, productivity classes, moisture regimes and stand ages resulted in an increase in phosphorus fertiliser usage between the 1950's and 70's (Boardman, 1974). In the 1960's, studies investigated other nutrient limitations and Raupach *et al.* (1969) showed that productivity of older stands was related to foliar concentrations of both nitrogen and phosphorus, and thus recommended the use of foliar analysis as a diagnostic tool for predicting nitrogen and phosphorus limitations.

4.1.1.4 NSW

In NSW, despite efforts of Ludbrook (1942) showing the critical nature of soils and nutrition, widespread usage of phosphorus fertiliser was slower to gain acceptance due to a prevailing view that climate rather than nutrients limited growth. In the 1960's intensive research commenced on nutrients (especially phosphorus and calcium), the use of soil or foliar analysis for assessing deficiencies, and the magnitude and duration of response to fertiliser on poorer sites (Humphreys, 1964; Turner *et al*., 1999). As a result of these studies, recommendations were made for applying super phosphate and limestone or gypsum to stands where soil analysis indicated deficiencies. A series of studies in NSW demonstrated that large responses to phosphorus fertiliser could be sustained for long periods resulting in improved growth rates of trees even in subsequent rotations (Gentle *et al*., 1965).

Application of phosphorus fertiliser at establishment commenced in a limited way in plantations on sandstone soils to the South of Sydney in the early 1960's using lime super, and later ordinary super phosphate in the 1970's (Knott & Turner, 1990). Repeat applications at 5 years of 75 kg P ha^{-1} became standard practice in the 1970's, but the total area fertilised during this period remained relatively small (Knott & Turner, 1990; Turner & Lambert, 1986). It was not until the 1980's, with the advent of high analysis fertilisers that broad-scale use of nitrogen and phosphorus fertilisers became standard practice across all regions, with the area fertilised increasing from 1000 ha $year^{-1}$ in 1980 to more than 6000 ha $year^{-1}$ in 1983 (Birk, 1994; Knott & Turner, 1990).

Relationships between soil and foliar nutrients, parent material, nutritional deficiencies and response to phosphorus continued to be investigated by researchers (Lambert & Turner, 1988; Turner, 1982; Turner & Lambert, 1986). This work resulted in sites potentially responsive to phosphorus treatments being identified on the basis of soil type. Similar relationships between geology and boron or sulphur deficiencies were also identified (Lambert & Ryan, 1990; Turner *et al.*, 1977).

4.1.1.5 Victoria

In Victoria there was extensive research into nutrient deficiencies and responses in both *P. radiata* and eucalypt plantations established in Central Gippsland. Early work by Hall and Raupach (1963) demonstrated the presence of potassium deficiency and its alleviation with application of potassium chloride in young pines in eastern Victoria. Analysis of changes in foliar nutrient concentrations over time indicated that both potassium and phosphorus tended to be efficiently recycled within the crown. Cromer *et al.* (1985a; 1985b) studied the effects of fertiliser on growth, form, foliar nutrient concentrations and partitioning of biomass and nutrients in 10 year old *P. radiata*. Application of phosphorus fertiliser (67 kg P ha^{-1}) resulted in an 85% increase in growth, but there was no response to nitrogen or potassium. Phosphorus fertiliser also influenced the dynamics of changes foliar phosphorus concentrations over time, but did not affect wood density or partitioning of biomass between stem and crown.

4.1.1.6 Tasmania

In Tasmania, Neilsen studied the nutrition of P. radiata stands looking at the relationship between a land unit classification for pine plantations and nutrient deficiencies (1977) and later studying interactive effects of nitrogen and phosphorus fertiliser on growth and nutrient uptake (Neilsen *et al.*, 1984). This work showed the critical need to use balanced nitrogen and phosphorus fertiliser mixes. Application of urea or superphosphate alone resulted in extreme N: P ratios and poor growth. Similar negative effects of urea fertiliser applied in the absence of phosphorus were reported by Snowdon and Waring (1985) for pines fertilised at planting in the ACT.

4.1.2 Second rotation decline

In the 1960's, Keeves (1966) noted that growth of second rotation radiata pine stands in the Green Triangle region was well below that of the growth of the original first rotation stands. This finding led to the initiation of considerable research into what became known as the "2nd rotation decline" problem (eg. Cellier *et al.*, 1985; Sands & Zed, 1979; Waring, 1968). Subsequent trials resulted in the development of the what was termed the "maximum growth sequence" (Woods, 1976; Woods, 1990). This prescription included intensive weed control and repeated applications of a complete fertiliser mix that included large amounts of nitrogen, phosphorus, potassium and trace elements.

However, subsequent research demonstrated that nitrogen fertiliser was less important than previously thought during first 3 years after establishment (Nambiar & Cellier, 1985). It also showed that retention of organic matter and harvest slash increased early growth by providing favourable moisture and temperature conditions on the predominantly sandy soils (Flinn *et al.*, 1979; Smethurst & Nambiar, 1990; Squire *et al.*, 1979). Smethurst and Nambiar (1990) demonstrated that the slash contained significant amounts of nitrogen and that slash and litter retention increased rates of nitrogen mineralisation with total nitrogen mineralised over 4 years 30% greater compared with where they were removed. Removal of slash and litter had little effect on early tree growth and that heavy applications of N resulted in only a 10% increase in stem diameter over the first three years (Smethurst *et al.*, 1990). However, decreasing rates of nitrogen mineralisation over time were asynchronous with increasing demand for nitrogen by the young trees, indicating that slash retention or nitrogen fertiliser application could be beneficial in subsequent years. As a result of this research, application of nitrogen at establishment was temporarily halted and the practice of broadcast burning of harvest slash was phased out and replaced with heaping and burning of larger woody material and chopper rolling the finer debris (Woods, 1990). Hopmans (1993) demonstrated that this site preparation method could increase growth rates for at least 15 years after establishment.

Although second rotation decline was normally associated with radiata pine on the sandy soils of the Green Triangle, similar problems were recorded on infertile sites in WA (Hopkins, 1971). There, poor growth of second rotation sites was attributed to deficiencies of nitrogen and phosphorus with the application of 45 kg P ha^{-1} as superphosphate and 115-290 kg N ha^{-1} as urea was recommended (Hopkins, 1971). This led to numerous studies, in the late 1970's and 1980's, of the effect of different rates and forms of nitrogen and phosphorus application at planting, single vs. multiple applications, and interactions between application rate and soil type, and between nitrogen, phosphorus and zinc (McGrath, 1978; McGrath & McArthur, 1990; McGrath & Robson, 1984; Moore, 1982). In Victoria, Turvey and Cameron (1986), and Cromer and Dargavel (1977) showed that mound-ploughing, good weed control, and adequate fertilisation resulted in good growth of the second rotation.

Research into the effects of slash management on growth of tropical pines (*P. elliottii var. elliottii x P. caribaea var. hondurensis*) was undertaken in SE Queensland by Simpson *et al.* (2000). This work showed that significant proportions of total above-ground nitrogen prior to harvest were contained in residues (12% of total nitrogen and 5% of total phosphorus) or exported in logs (8% of nitrogen and 3% of phosphorus). Retention of litter and harvest residues increased above-ground biomass production of the next rotation with the differences largely attributed to increased foliar nitrogen and moisture availability in slash retention treatments.

On the fine-textured soils in NSW, despite research indicating that growth and foliar nitrogen and phosphorus contents were increased by slash retention compared with litter raking and residue burning (Hall, 1985) and that foliar nitrogen and phosphorus concentrations were reduced on burnt second rotation sites (Birk, 1994), broadcast burning remained the predominant site preparation method, at least up to the mid 2000's. Although, burning of forest debris in the Green Triangle has now virtually ceased, it is still standard practice on some sites in other parts of Australia where site conditions or lack of a market for pulpwood restricts options for removal of larger woody material. However, this situation is now changing and is gradually being replaced with harvest residue retention in most regions (K. Bubb, FPQ; D. Watts, FNSW; and S. Ward, FPC 2008, Pers. Comm.).

4.1.3 Post-thinning fertiliser application

After initial problems related to the nutrient management of younger pines had been generally solved, attention shifted to the potential to increase growth of older stands, especially after thinning (Attiwill, 1982). In order for the stand canopy to recover after tree removal, rates of nutrient uptake and recycling by retained trees must be increased. If soil nutrient availability is too low, then the rate of crown recovery will be slower, increasing the risk of "thinning shock" where the stand productivity is significantly reduced. Where this increased demand for nutrients exceeds the rate of supply from soil, fertiliser can reduce the time taken for growth to recover. Alternatively, post-thinning fertiliser application may allow thinning intensity to be increased without affecting stand productivity (Birk, 1994). This strategy can be used to prepare for anticipated shortfalls in wood supply or to improve the economics of wood production by increasing both revenue early in the rotation and the proportion of larger, high value logs at final harvest.

As a result of early work by researchers including Raupach *et al.* (1969) and Woollons and Will (1975), post-thinning fertiliser experiments were initiated in the late 1970's to 1990's to determine the potential responsiveness of thinned stands to nitrogen and phosphorus fertiliser and to optimise rates, combinations and timing of fertiliser applications (eg. Crane, 1981; 1982; Waring, 1980). Snowdon (1995) summarised results from a number of these studies in a review of fertiliser experiments across southern Australia (Table 5).

Table 5: Volume responses to nitrogen and phosphorus fertilizer applied after thinning from other studies across Australia showing age at time of fertilizer application and years for which growth response was measured. Rates of nitrogen application ranged from 150 to 300 kg N ha-1, while rates of phosphorus application ranged from 125 to 250 kg P ha-1. Data is adapted from Snowdon (1995).

Location	Age	Years	Volume Gth Control $m^3\ ha^{-1}\ y^{-1}$	Cumulative Response N $m^3\ ha^{-1}$	Cumulative Response P $m^3\ ha^{-1}$	Cumulative Response N+P $m^3\ ha^{-1}$	Relative Response N %	Relative Response P %	Relative Response N+P %	Reference
Belangalo	9	5	17.6	-	3	5	-	3	5	Waring 1980
Belangalo	16	4	17.9	-	-	2	-	-	2	Crane 1981
Buccleuch	16	4	29.0	4	-1	8	4	-1	7	Snowdon et al 1995
Buccleuch	15	2	29.0	9	5	17	15	9	29	Snowdon et al 1995
Buccleuch	26	2	25.5	-5	3	12	-10	5	23	Snowdon et al 1995
Bondi	14	6	22.3	4	-	11	3	-	8	Turner and Knott 1991
Carabost	17	6	22.6	-3	-	4	-3	-	3	Turner and Knott 1991
Carabost	24	6	-	-1	-	8	-	-	-	Turner and Knott 1991
Green Hills	14	6	18.4	5	-	8	4	-	7	Turner and Knott 1991
Gurnang	14	4	18.5	6	2	8	9	3	11	Turner and Lambert 1987
Kowen	25	4	12.8	-	-	5	-	-	10	Crane 1981
Lidsdale	17	6	15.2	-	-	2	-	-	3	Turner and Knott 1991
Mount Gan	20	3	21.0	15	-	-	23	-	-	Woods (Crane 1982)
Mount Gan	20	3	21.0	15	-	-	23	-	-	Woods (Crane 1982)
Mount Gan	21	2.5	15.0	-	-	13	-	-	34	Woods (Crane 1982)
Mount Gan	24	3.5	11.5	-	-	15	-	-	38	Woods (Crane 1982)
Nundle	14	6	19.7	-3	-	4	-3	-	3	Turner and Knott 1991
Penrose	17	6	17.3	4	-	5	4	-	5	Turner and Knott 1991
Sunny Corı	16	6	24.7	-2	-	8	-1	-	5	Turner and Knott 1991
Sunny Corı	30	6	27.0	2	-	10	1	-	6	Turner and Knott 1991
Tower Hill	16	12	8.5	14	-	-	14	-	-	Turner and Knott 1991
Uriarra	23	4	19.0	-	-	7	-		9	Crane 1981
Vulcan	24	6	18.7	1	-	6	1	-	5	Turner and Knott 1991
Max			29.0	15	5	17	23	9	38	
Min			8.5	-5	-1	2	-10	-1	2	
Avg			19.6	4	2	8	6	4	11	

These data indicate that responses to nitrogen ranged from -5 to 15 $m^3\ ha^{-1}$ (-10 to 23% greater than the growth of controls), responses to phosphorus varied from -1 to 5 $m^3\ ha^{-1}$ (-1 to 9% greater than controls), while responses to N+P fertiliser ranged from 2 to 50 $m^3\ ha^{-1}$ (2 to 41% greater than controls). Thus, while some sites are highly responsive to fertiliser, others may give low or even negative responses to fertiliser after thinning. This variability in response combined with high costs of fertiliser have limited the use of post-thinning fertiliser in some parts of Australia (Birk, 1994). Much research has therefore focussed on trying to develop diagnostic tools or fertiliser prescriptions that help target potentially responsive sites (see section 4.4).

In the mid-1990's, Turner *et al.* (1996) analysed data from a range of post-thinning fertiliser trials across NSW and demonstrated that productivity gains of up to 30% were achievable by carefully selecting responsive stands. They showed that responsiveness to nitrogen and phosphorus fertiliser could be discriminated on the basis of parent rock type. This work led to the development of fertiliser prescriptions based largely on parent rock code, which now forms the basis of fertiliser application and other silvicultural programs across softwood plantations in NSW.

Birk (1994) listed rates of nitrogen and phosphorus fertiliser applied to post-thinning radiata pine in different parts of Australia in the early 1990's. Rates for nitrogen ranged from 30 kg N ha^{-1} across deep coastal sands of WA to 250 kg N ha^{-1} for stands in Victoria, while rates for phosphorus ranged from 26 kg P ha^{-1} for stands on sandy soils in WA and in south-east SA to 52 kg P ha^{-1} for stands on lateritic soils in WA. In SA and WA, fertiliser application was delayed for at least one year after thinning to reduce the risk of damage from bending and wind-throw (resulting from the development of a heavy crown) as well as minimising the development of a wide ring of low density wood.

In Queensland, most research focussed on the nutrient requirements, especially phosphorus, of younger stands (Simpson & Osborne, 1993; eg. Xu *et al.*, 1995a). Softwood plantations in Queensland are typically only thinned once per rotation, thus there is only limited opportunity for post-thinning fertiliser application. However, an analysis of growth response to phosphorus fertiliser applied to older slash pine (*P. elliottii*) stands aged 14-22 years indicated that wood yield at the end of the rotation could be increased by 6-14% giving an internal rate of return of between 9 and 14% (Simpson & Grant, 1991). In contrast, there was no evidence of a response to refertilising in hybrid pine (*P. carribea var. hondurensis*) stands. As a result of this work, 25% of the slash pine estate was fertilised with 40 kg P ha^{-1} by 1987. However, there was no evidence of a response to nitrogen, even after repeated applications, although this may have been a result of limited capacity for canopy development as a result of high stocking levels at the research trial site (Simpson & Grant, 1991).

In WA, large growth responses have been reported to nitrogen and phosphorus fertiliser applied after second or third thinning in radiata pine stands on infertile sandy soils on the Swan Coastal Plain. McGrath (2003b) reported a 50% increase in basal area increment 6 years after 175 kg N ha^{-1} plus 76 kg P ha^{-1} were applied after second thinning and a similar response to 400 kg N ha^{-1} and 200 kg P ha^{-1} applied after third thinning. Similar responses to nitrogen alone indicated that nitrogen was the primary limiting nutrient. The authors suggested that repeated applications as frequent as every 3-4 years could be necessary to optimise growth on deep sandy soils.

In the early 1990's pre-thinning fertiliser application was also considered for plantations on sandy soils in the Green Triangle. The theory being that at least some of the fertiliser adsorbed by the unthinned stands would be recycled in organic forms in the thinning residues (Carlyle, 1995). However, subsequent fertiliser experiments across a range of sites in the region that included pre-thinning fertiliser application showed no benefit of this treatment compared with post-thinning fertiliser application (May and Carlyle, unpublished data). These experiments demonstrated that ranges of relative growth responses to nitrogen (200 kg ha^{-1} as urea) were 4-17% (average 9%), to phosphorus (80 kg ha^{-1}) -1-14% (average 2%) while responses to nitrogen plus phosphorus fertiliser were 5-27% (average 14%, May *et al.*, 2009). In 2002, a series of nitrogen and phosphorus rate experiments were established. These indicated that the response to nitrogen was maximised at 200 kg N ha^{-1} while response to phosphorus was maximised at 80 kg P ha^{-1}. However, the studies also indicated there was significant variation in response to different forms of nitrogen, with urea typically giving a poorer response compared with ammonium-based fertilisers. Results from this research have contributed to an increase in post-thinning fertiliser (especially N) application across the region.

4.1.4 Site specific management

The term "site specific management" is used to describe the optimization of major components involved in plantation output for a specific product (Turner *et al.*, 1999). First applied to plantations in the 1980's, this concept involves, tailoring the management regime and genetic material for a given set of site characteristics and production goals and thus achieving levels of productivity that might be closer to the sites "biotic potential" (Boardman & Simpson, 1981). By the early 1990's, the concept of site specific management had been almost universally adopted across Australia's softwood plantations (Birk, 1994). There was a strong emphasis on tree breeding to improve genetic characteristics including growth, form, wood quality, and resistance to pests and disease, as well as studying the interaction between genotype and nutrition (eg. Bail & Pederick, 1989; Fife & Nambiar, 1995; Simpson & Osborne, 1993).

The development of the Soil Technical Classification provided the opportunity for forest managers to adapt stand management and nutrition to specific sites based on soil information (Turner *et al.*, 1990). This system was based a range of soil properties observable in the field including parent rock type, texture profile, depth and type of impeding layer, texture, condition and weathering of surface soil and texture and colour of the subsoil. Turvey (1990) showed that this classification system (excluding subsoil texture and colour) explained 75% of variation in wood volume while parent rock type alone explained 31% of variation across 181 *P. radiata* stands from NSW, Victoria, SA and Tasmania. Parent rock was classified to set the upper limits on percent sand and clay and the release of soil nutrients through weathering, Thus, this classification was strongly related to available phosphorus, total nitrogen and cation exchange capacity (Turvey *et al.*, 1986). In Gippsland, Victoria, Turvey and Smethurst (1994) showed that soil types based on observable soil profile criteria reflected differences in nutrient status and could be used as classes to manage both soil fertility and wood production.

As a result of this work, stands in many regions were stratified on a soils basis to select appropriate management regimes, especially fertiliser application. All NSW pine plantations were classified using parent rock material as the primary indicator and pervious land use as a secondary indicator (Birk, 1994; Turner *et al.*, 1999). The same was done for pine plantations in Tasmania (J. Bruce, CSIRO, Pers. Comm.).

Turner *et al.* (2001) classified 685,000 ha (70%) of Australia's radiata pine plantations according to parent rock code and rainfall. This provided a system for extrapolating research results and developing site specific management systems. Most stands were located on consolidated shales (17%), or rhyolites (10%) or unconsolidated sands (14%) in the 700-1000 mm rainfall range. However, analysis of the distribution of fertiliser experiments across this classification system indicated that while some soils (those derived from shales, sandstone, granite or granodiorite) were well represented, others (including the unconsolidated sands) were inadequately covered to be confident about their results. Across this classification system, average increases in growth for optimum fertiliser treatments ranged from 25.5 m^3 ha^{-1} for sandstone soils to 44.6 m^3 ha^{-1} for shales. This analysis showed that, application of research results from one site to another required validation before it can be undertaken with any confidence. For example, with increasing average rainfall, absolute response to optimum fertiliser treatments (200 kg N ha^{-1} with or without phosphorus) tended to increase on some soil types (especially shales) but not others. There was a strong relationship (R^2 = 0.75) between relative response to these treatments and initial foliar nitrogen, with average response decreasing from 45% to 15% as foliar nitrogen increased from 0.8 to 1.8%. Thus, the authors concluded that foliar analysis assisted with verifying the fertiliser response, while site information (parent rock code and rainfall) was useful for identifying the type (nitrogen, phosphorus or nitrogen plus phosphorus) and quantity of fertiliser required and for estimating the absolute level of response.

While parent rock code can be useful for indicating the general range of growth rates response to fertiliser, it is a very coarse instrument and does not differentiate between sites with soils derived from the same parent material. For example, most of the soils in the Green Triangle region fit into the same parent rock code (unconsolidated sands). However, studies have shown that growth rates can vary considerably across this region (15-35 m^3 ha^{-1} $year^{-1}$ for stands aged 22 - 35 years) while six year responses to nitrogen plus phosphorus fertiliser can vary from 5 to 27% (May *et al.,* 2009).

4.2 Hardwood plantations

The large scale establishment of hardwood plantations across Australia has been a relatively recent phenomenon. Thus, research into and understanding of nutrient management of these plantations is still at an early stage compared with that in pines. Furthermore these plantations were primarily planted as short rotation (8-12 year) pulpwood plantations on relatively fertile ex-pasture land. Thus the nutrient demands on sites and optimum timing and rates of fertiliser application are likely to be very different to those for the longer rotation softwood plantations. The following summarises the development of the hardwood plantation industry and research into nutrient management over the past 20 years.

Initially, eucalypt plantations were established largely on ex-native forest land in Tasmania and northern NSW and some ex-pasture land in Victoria and WA (Birk, 1994). During the 1990's and early 2000's there was rapid expansion of eucalypt plantations, with 370,000 ha planted between 1990 and 2000 and 307,000 ha planted between 2001-05 compared with a total of just 61,000 ha planted prior to 1990 (Parsons *et al.* 2007). Large scale plantings by MIS (Managed Investment Schemes) were initially established in south west WA and Tasmania in the early 1990's, with bluegum (*E. globulus*) primarily planted in WA and a mixture of bluegum and shining gum (*E. nitens*) planted in Tasmania. In the mid-1990's, plantings extended into Green Triangle, Central Victoria, north coast of NSW, and later into south-east Queensland. *Eucalyptus globulus* now comprises around 60% of total plantings, and *E. nitens* 20%. In northern NSW and Queensland, subtropical species including *E. dunnii*, *E. grandis*, *Corymbia maculata*, and *E. pilularis* are planted, while *Acacia mangium* is being planted on Melville Island in the NT. Although most plantations are being grown for pulpwood, a proportion of those in Tasmania and the North Coast of NSW are grown for longer rotations (20-25 years) for production of sawn timber.

Except for in Tasmania, the vast majority of eucalypt plantations over the past 10-15 years have been established on ex-pasture land. This land is typically far more fertile than the ex-native forest and degraded agricultural land where most 1st rotation pine plantations have been established. Mendham *et al.* (2002) showed that C: N and C: P ratios soils under eucalypt plantations aged 7-10 years in south west WA were substantially lower than those in adjacent native forest and were similar to those in adjacent pasture, indicating that the residual effects fertiliser applied to the pasture prior to conversion to plantation persisted throughout the 1st rotation. Thus, high rates of nitrogen mineralisation on ex-pasture sites has reduced the need for nitrogen fertiliser in 1st rotation plantations (Aggangan *et al.*, 1998; Moroni *et al.*, 2002). However, strong evidence of decreasing rates of nitrogen mineralisation over time from ex-pasture soils under eucalypt plantations indicates that fertiliser requirements for subsequent rotations may be substantially greater (O'Connell *et al.*, 2003).

Initially, nitrogen fertiliser application to 1st rotation hardwood plantations resulted in reduced growth or even stand failure where it was not accompanied by weed control (Birk & Turner, 1992). Fertiliser tablets (containing nitrogen, phosphorus and with or without potassium) were widely used in order to promote rapid early growth allowing the young trees to outcompete weeds. However, there was evidence that the amounts used exceeded optimum biological or economic rates of application (Ritson *et al.*, 1991).

On ex-forest sites in Tasmania and Gippsland, fertiliser experiments demonstrated that large growth responses were possible on both fertile and infertile sites (Bennett *et al.*, 1997; Cromer *et al.*, 2002; Cromer *et al.*, 2002; Judd *et al.*, 1996). However, even after high rates of fertiliser application, productivity on very infertile sites was considered unlikely to be economically viable. Results from Bennett *et al.* (1997) supported earlier findings that phosphorus in particular was important for early growth. Responses to nitrogen and phosphorus fertiliser in Gippsland varied with soil texture, water availability and potassium limitation (Bennett *et al.*, 1997). Based on the results from these experiments the authors recommended optimum rates of 50-100 kg ha for nitrogen and phosphorus (1:1 ratio) at 9 months, with staggered additions of 100 kg N ha^{-1} and 50 kg P ha^{-1} throughout the period up to canopy closure. In contrast Cromer *et al.* (2002) recommended application of at least 300 kg N ha^{-1} at age 2-3 on "wet" ex-forest sites with relatively fertile soils.

Birk (1994) suggested that opportunities for remedial fertiliser application in eucalypt plantations were limited due to rapid crown development and lack of baseline nutritional data making it difficult to monitor plant nutrient status. Concerns have also been raised that improving nutrient status with high rates of fertiliser application would increase susceptibility to insect attack (Stone, 1993). In a longer rotation mountain ash (*E. regnans*) sawlog plantation on an ex-native forest site in Tasmania, annual applications of nitrogen fertiliser (100 kg N ha^{-1}) for 13 years (from ages 5 to 19) doubled volume growth (Ringrose & Neilsen, 2005a). However, these frequent repeated applications resulted in a significant reduction in soil pH and exchangeable magnesium concentrations. Mitchell and Smethurst (2004) reported similar changes in soil pH and exchangeable cations across a range of softwood and hardwood fertiliser experiments after high cumulative rates of fertiliser were applied (> 600 kg N ha^{-1} and 250 kg P ha^{-1}). Thus, too much fertiliser risks increased acidification of topsoil and reduction in base cations as well as increased risk of insect attack.

Smethurst (2004) reviewed nitrogen management in eucalypt plantations in Tasmania. Studies in the 1990's indicated that rates of soil nitrogen mineralisation varied widely across Tasmanian plantation soils and ranged from highly deficient to super-abundant in terms of the uptake requirements of high productivity eucalypt plantations just prior to canopy closure (~200 kg N ha^{-1} $year^{-1}$). The authors suggested that, for low nitrogen sites, an average of 30-40 kg ha^{-1} $year^{-1}$ could be expected to be required over a 15-25 year rotation. However, care needed to be exercised to avoid nitrogen saturation. Results from fertiliser experiments showed that cumulative nitrogen applications of at least 500 kg N ha^{-1} between planting and 3 years were needed to maximise growth at many sites, but that individual applications should not exceed 200 kg ha^{-1}.

4.3 Processes involved in fertiliser response

4.3.1 Role of nutrition in stand development

Much of the research into fertiliser response has focused on measuring responses of particular species at a particular site or set of sites to different types or rates of fertiliser. While this is useful for estimating the range of responses that might be expected for a given set of inputs across a particular set of experimental conditions, this approach is often of limited value for in terms extrapolating responses outside these conditions, identifying potentially responsive sites and optimizing the combination, timing or rate of application (Sheriff, 1996). To answer these questions we must understand how and why a stand responds to fertiliser, and the processes governing this response.

The biology of forest growth experiment established near Canberra in the ACT was the first large-scale Australian study of the many processes involved in stand nutrition and response to fertiliser. In this experiment, nitrogen and phosphorus fertiliser were applied with or without irrigation to 10 year old trees and the effects on the nutrient fluxes and foliage development and water stress, litterfall, stand structure and stem growth studied over the following 4 years (Benson *et al.*, 1992). The results showed the linkages between nutrient cycling and uptake (Raison *et al.*, 1992a), foliage production (Raison *et al.*, 1992b) and stem and branch growth (Snowdon & Benson, 1992) and highlighted the critical nature of interactions between water and nitrogen on foliar efficiency (Thompson & Wheeler, 1992), tree growth and response to fertiliser (Crane & Banks, 1992). This work resulted in the production of the BIOMASS growth model (McMurtrie & Landsberg, 1992) and was important in the development of current process-based growth models such as CenW (Kirschbaum, 1999), 3PG (Landsberg and Waring) and Cabala (Battaglia *et al.*, 2004).

This type of research has provided a better understanding of the way that trees grow and interact with their environment and the roles of fertiliser addition and nutrient cycling in this process. Goncalves *et al.* (2004) described this process in their review of the effects of silvicultural treatments on productivity and wood quality of eucalypt plantations. A plant allocates photosynthates (fixed carbon) to whichever components are critical for meeting its needs. For example, to access adequate nutrients and moisture, seedlings allocate most of their available resources to root production during the first few moths after planting. Once these needs are met, photosythates are then redirected to shoot and leaf development to maximize light capture and carbon fixation. This balance between allocation to roots and shoot growth changes continually as the crop develops. Provided nutrient and water supply is adequate, photosynthetic activity is maximized and the canopy and root system develop quickly which, in turn, produces even greater demands for nutrients and water. Peak rates of nutrient uptake normally occur a year or two prior to peak leaf area at canopy closure. Following canopy closure, litterfall increases and internal and external cycling of nutrients supplies most of the stand's needs reducing tree dependence on nutrient supply from soil reserves. Thus, nutrient deficiencies and fertiliser responses tend to be more common prior to rather than following peak leaf area.

However, reduction in canopy through thinning or insect defoliation effectively resets the nutritional stage of the stand to that before canopy closure. In order to regrow the canopy, demand for nutrients increases. Thus, responses to fertiliser applied after thinning are common (Crane, 1981; McGrath *et al.*, 2003b; Snowdon & Waring, 1990; Snowdon & Waring, 1995; Turner *et al.*, 1996). In stands where the potential uptake of nutrients from trees exceeds the rate of supply from the soil, the increased availability of nutrients from fertiliser increases the rate of recovery of the canopy, allowing the growth of the stand to return to prethinning levels more quickly.

In the absence of thinning, foliage mass tends to decline within a few years of reaching its peak as a result of increased rates of litterfall. This decline is the major cause of age related declines in growth rates (Ryan *et al.*, 1997). The reasons for the decline leaf area and mass are not fully understood but may include a) loss of branches due to abrasion, b) increased hydraulic resistance reducing rates of photosynthesis, c) maturational changes or d) reduced nutrient supply as a result of increased immobilization in litter. A fifth category, not properly addressed in any studies, could be the preferential loss of foliage in the lower crown as a result of increased self shading following crown closure. However, it is likely that in the longer term nutritional limitations are a major factor in age-related declines in growth.

Miller (1981) suggested that the growth of a stand could be broken into three distinct phases: stage 1, where the developing crowns require large amounts of all nutrients, little of which is returned through litterfall; stage 2, where the only continued immobilization of nutrients by the trees is in the woody components and nutrient cycling within both the tree and the ecosystem as a whole becomes the dominant process; and stage 3, where immobilization of nutrients within the continually deepening humous layer may exceed the rate of input. In this last phase, this process can lead to late rotation nitrogen deficiency on sites with low nutrient capital (eg. Turner *et al.*, 1977). Thus, Miller (1981) theorized that it is in this stage that a response to nitrogen could be expected.

4.3.2 Nutrition, foliage development and age related decline in growth

Nitrogen is essential for foliage growth and chlorophyll production. Carlyle (1998) reasoned that the potential growth response after thinning was related to the rate of canopy expansion, which in turn depended heavily on nitrogen supply. Thus, post-thinning leaf area development and subsequent stem growth were highly correlated with post-thinning nitrogen uptake across fertilised and unfertilised treatments in a fertiliser x thinning experiment in an 11-year-old stand. Detailed measurements of soil nitrogen mineralisation and uptake, leaf area and water stress of trees indicated that both leaf area and growth on thinned plots were closely related to nitrogen uptake. However, in unthinned plots, where water stress was greater, growth per unit nitrogen uptake or leaf area was lower and the relationship between the two variables was weaker. Thus, the response to fertiliser in the thinned stand was greater than in the unthinned stand as a result of reduced water stress.

Interestingly, nutrient limitations have been implicated as a primary cause of age-related declines in productivity of pine stands. Typically, both growth and leaf area peak early in the rotation and then decline gradually over time. However, the reasons for these declines are not clear. Turvey and Smethurst (1994) showed that that the litter layer contained a large pool of nutrients and, as stands aged, concentrations in foliar nitrogen and phosphorus decreased while the amount of nitrogen and phosphorus immobilised in the litter increased. However they found no direct link between decline in foliar nitrogen or phosphorus and decreasing wood production with age.

Binkley *et al.* (1995) showed that nitrogen fertiliser application increased both needle fascicle weight and growth in older stands but not in younger stands, indicating that increasing nutrient limitation in older stands probably accounted for at least part of the decline in leaf area and growth. Subsequent work with chronosequences of maritime pine indicated that the decline in productivity with stand age was due to a decline in foliar phosphorus concentrations, indicating that phosphorus nutrition was a contributing factor (Delzon *et al.*, 2005). Recent work in south eastern Australia indicates that rates of nitrogen mineralisation decline with stand age, potentially leading to increased nitrogen deficiency. Across 10 stands aged between 15 and 28 years in the Green Triangle region of SA and Victoria there was an average 30% decline in nitrogen availability over 8 years which was only temporally reversed by thinning (May *et al.*, 2009). This decline in nitrogen mineralisation was associated with an increase in litter mass and nitrogen content indicating that rates of decomposition in older stands with closed canopies may be too low too sustain nitrogen mineralisation rates in the soil.

4.3.3 Duration of response

Studies of the long-term responses to fertiliser applied after thinning showed that the longevity and form of the response varies with site and nutrient applied. Typically, responses to nitrogen are relatively short-term, while responses to phosphorus may persist for many years (Woollons *et al.*, 1988). In WA, McGrath *et al.* (2003) showed that the response to phosphorus lasted for at least 10 years, while that to nitrogen lasted just 4 years. There was a large (50% for 176 kg N ha^{-1} plus 76 kg P ha^{-1}) but transitory response to nitrogen plus phosphorus fertiliser after second thinning and a similar response to nitrogen plus phosphorus applied after third thinning. Work on these deep sands indicated that repeated fertilisation at 9-year intervals would improve growth, with more frequent (3-4 year) applications suggested as necessary to optimise growth. Other studies where growth responses have been obtained from a single application of nitrogen have shown a peak response two to four years after application followed by a decline to previous growth rates (Ballard, 1984; Foerster, 1990). Turner *et al.* (1992) showed that the response to nitrogen plus phosphorus fertiliser tends to peak after 3 to 4 years, before falling to zero by around 7 years. At one site, the response to nitrogen alone peaked at 3 years, before falling to below zero (i.e. growth was less than the control).

Snowdon and Waring (1984) defined the different volume response patterns to silvicultural treatments as type 1 (short term increase, but no increase in the long-term) and type 2 (long-term increase) responses. Type 1 responses are characterised by a temporary increase in growth rate that reduces the time needed for a stand to reach a given stage of maturity but not increasing the plateau in wood or biomass production that is assumed to be reached in very old stands. In contrast, type 2 responses are characterised by a real and sustained increase in site productivity; although the rate of growth continues to higher for many years, it returns to the same zero value when stand growth plateaus at a higher level. Because commercial plantations do not normally reach this productivity plateau, a type 2 response is manifest as a divergence in the yield curves for treated and untreated stands.

Responses to nitrogen fertiliser typically follow the type one response pattern. In a number of studies have demonstrated that responses to phosphorus fertiliser may last across multiple rotations on some soils and thus follow the type two response pattern (Gentle *et al.*, 1986; Turner *et al.*, 2002). The reasons for the longevity of these responses include a) the original paucity of soil phosphorus on these sites and b) the high levels of retention of phosphorus on the soil. For example Gentle (1986) showed that, 34 years after initial treatment, there had been little loss of phosphorus from the treated plots. This was a result of the high adsorption capacity of the soil preventing any significant downward movement of phosphorus through the soil. Thus, foliar phosphorus concentrations can remain elevated for many years and site productivity can effectively be increased after phosphorus application. However, on other sites where phosphorus may be less limiting, the response can also follow a type 1 pattern despite persisting elevation of foliar phosphorus concentrations (eg. May *et al.,* 2009).

Type 2 responses may also be obtained as a result of repeated fertiliser applications. In Tasmania in the 1980's, long-term fertiliser experiments were established in two stands one unthinned, aged 16 years and the other, thinned, aged 20 years. Both sites were fertilised during the subsequent 12 to 13 years with annual applications of 100 kg N $year^{-1}$, with the thinned site also fertilised with two applications of phosphorus (144 kg P ha-1Neilsen *et al.*, 1992; Ringrose & Neilsen, 2005b). Growth at the unthinned site was subsequently increased by 165% and that at the thinned site was increased by 80%. The authors suggested that, as a result of the large nitrogen losses from the sites and lack of increase in organic matter, frequent applications of nitrogen fertiliser were necessary to maintain growth (Neilsen *et al.*, 1992). However, subsequent work indicated that this would be costly and could lead to substantial declines in soil pH with potentially serious long-term consequences for productivity (Ringrose & Neilsen, 2005b).

In thinned mid-rotation stands in the Green Triangle, May *et al.* (2009) found that responses to nitrogen lasted for about 6 years before declining, with growth rates of fertilised plots at many sites falling to less than those of unfertilized plots. Snowdon and Waring (1984) suggested that this was to be expected as a result of trees in fertilised plots being larger and thus reaching an increased stage of stand development sooner than unfertilized trees. Alternatively, it is likely that trees in fertilised plots reach other resource limitations (such as water, light or other nutrients) faster than those in unfertilized plots. Without, removing these limitations (eg. by thinning) there will be an erosion of the original response to fertiliser. Thus, in order to maximize the benefit of type 1 responses to fertiliser the timing of thinning regimes may need to be modified by bringing them forward in order to reduce these other limitations on growth.

4.3.4 Nutrient interactions

Interactions between different nutrients occur when the response to one nutrient is limited by deficiency in the other. This effect manifests itself in fertiliser experiments as the response to two or more nutrients applied together being greater than the sum of the individual responses to each nutrient applied separately. An interactive response can arise for two reasons, the first is when both nutrients are at growth limiting levels, preventing the trees from responding to one or the other when applied alone; the second is when the response to one nutrient induces a deficiency in the other. This latter effect can occur as a result of rapid canopy expansion as a result of nitrogen application, for example, when the requirement for other nutrients exceeds the capacity of the tree to supply them by uptake from soil or translocation from other parts of the plant (Fife & Nambiar, 1997).

The most common nutrient interaction encountered in plantations in Australia is that between nitrogen and phosphorus, which has been demonstrated in numerous studies have shown interactions between nitrogen and phosphorus in softwood plantations (eg. McGrath *et al.*, 2003a; Neilsen *et al.*, 1984; Snowdon & Waring, 1985; Turner *et al.*, 1992). Boardman (1971) stated that the response to phosphorus fertiliser appeared to be limited by nitrogen deficiency on some sites in the Green Triangle. Similarly, Snowdon and Waring (1990) demonstrated that response to nitrogen could be limited by both phosphorus and moisture availability. Thus, response to nitrogen fertiliser was greater in plots that were also fertilised with phosphorus and thinned to a lower basal area. Similar interactive treatment effects were obtained by Turner *et al.* (1992) who showed that, while there was no response to nitrogen or phosphorus applied separately at two sites, there was a significant response to the two fertilisers applied together. This study also demonstrated that increased thinning intensity combined with fertiliser application could provide forest managers with the option to meet demands for timber while maintaining volume at least equivalent to an unthinned stand.

On some sites, application of phosphorus in the absence of nitrogen, or nitrogen in the absence of phosphorus can actually cause a reduction in growth rates (May *et al.*, 2009; Snowdon & Waring, 1985). There is limited evidence that application of phosphorus fertiliser may result in a short term increase in nitrogen mineralisation (Falkiner *et al.*, 1993). However, a longer term study in the Green Triangle showed that after an initial increase in nitrogen mineralisation following application of phosphorus fertiliser, rates of mineralisation fell below those of the control (Carlyle, unpublished data). It is suggested that the initial increase may have been due to rapid mortality of the microbial population as a result of increased acidity associated with the triple super phosphate and that subsequently soil conditions and or the microflora could not support nitrogen mineralisation at pre-fertiliser levels.

Other studies have indicated that the response to nitrogen was dependent on stand phosphorus status. Turner *et al.* (1996) showed any deficiency in phosphorus needs to be corrected before there could be significant gain from nitrogen fertiliser, but that application of other nutrients (potassium, calcium, magnesium, boron, copper and zinc) did not provide any additional productivity gains. Similarly, McGrath *et al.* (2003) showed that the primary deficiency in a softwood plantation on an ex-native forest site in southern WA was phosphorus, with no response to nitrogen alone, but a significant NxP interaction when both nutrients were applied with an 86% increase in growth to the application of 270 kg N ha^{-1} plus 90 kg P ha^{-1}.

The long-term effect of phosphorus fertiliser application on subsequent responses to nitrogen was tested in a series of experiments in the Green triangle (May *et al.*, 2009). Application of phosphorus (80 kg P ha^{-1} as triple super phosphate) after 2^{nd} thinning doubled the response to nitrogen fertiliser applied at third thinning 6-7 years later. Further, there was no difference in the NxP interaction between the prior phosphorus treatments and applying nitrogen together with phosphorus at 3^{rd} thinning and no benefit of applying phosphorus at both thinnings. Thus, it was concluded that one application of phosphorus every 2^{nd} thinning was sufficient at most sites.

4.3.5 Interactions between nutrients and water

The increase in absolute response to optimal fertiliser treatments with increasing rainfall for stands growing on shale-derived soils reported by Turner *et al.* (2001) has already been mentioned. However, this analysis showed no conclusive relationship between response and rainfall for other soil types. Clear interactions between fertiliser and irrigation also have been reported for *P. radiata* in the 'Biology of Forest Growth' experiment established near Canberra (Benson *et al.*, 1992; Snowdon & Benson, 1992). Follow-up work over a 19-year period by Waterworth *et al.* (2007) showed that irrigation plus solid fertiliser (400 kg N ha^{-1} applied at the start of the experiment) increased growth by 84%, compared with a 32% increase for irrigation only and a 2% decrease in growth for fertiliser only treatments. Furthermore, the interactive effect of nitrogen fertiliser plus irrigation on growth response was sustained over time in contrast to the fertiliser only treatment where the response to nitrogen lasted only 5-8 years. Thus, removal of any water limitation effectively produced a type 1 pattern of response to the initial nitrogen fertiliser application.

These results are consistent with those from Carlyle (1998) indicating that water availability can be a key limiting factor to nitrogen response and with May *et al.* (2009) indicating that response to nitrogen may be eroded over time as a result of growth of the fertilised trees being limited by availability of other resources. They suggest that the longevity of growth responses to nitrogen fertilisation in closed-canopy softwood plantations may be greater in high rainfall environments where initial uptake and ongoing nitrogen cycling is greater.

4.3.6 Nitrogen volatilisation

Numerous forestry studies have shown that, under certain conditions, urea fertiliser is subject to substantial nitrogen volatilization losses (eg. Craig & Wollum, 1982; Marshall & DeBell, 1980; May & Carlyle, 2005; Nômmik, 1973). When N is applied as urea ($(NH_2)_2CO$), it is rapidly hydrolysed in the presence of water and the enzyme urease to form ammonium as follows:

$$(NH_2)_2CO + 3H_2O \rightarrow 2NH_4^+ + 2OH^- + CO_2$$

Thus, in addition to ammonium, this reaction produces CO_2 and, importantly, hydroxyl (OH^-) ions that can increase pH in soils or litter layers that have low pH buffering capacity. Under high pH conditions (pH > 7) ammonia volatilization occurs as a result of the conversion of ammonium to dissolved ammonia (through the removal of a proton), which is then released as ammonia gas (Avnimelech & Laher, 1977).

$2NH_4^+(aq) + 2OH^- \rightarrow 2NH_3(aq) + 2H^+ + 2OH^- \rightarrow 2NH_3(g) + 2H_2O$

Since the hydrolysis of urea tends to result in localised increases in pH, there is a high potential for significant volatilisation from urea fertiliser unless the fertiliser is dissolved and leached into a well-buffered soil before these transformations can take place.

Volatilisation losses from urea can be especially high in established softwood plantations with well developed litter layers. Although the litter is often quite acidic, application and hydrolysis of urea results in a rapid increase in pH (May, unpublished data), which reflects the low pH buffering of litter layers.

In a ^{15}N small-plot trial in the Green Triangle, May and Carlyle (2005) demonstrated that nitrogen volatilization from urea fertiliser averaged 41% in the absence of rainfall with around 30% loss occurring during the first 7 days after application. Follow-up studies showed that losses of this magnitude could be typical for urea applications, even in when the season of application is varied and, importantly, even after there is substantial rainfall (150 mm during the first 30 days after application, May and Carlyle, unpublished data). Across a series of four fertiliser experiments, an average of 42% of nitrogen applied as urea (200 kg N ha^{-1}) was lost compared with just 5% for ammonium sulphate or ammonium nitrate. Furthermore, average growth of plots fertilised with urea was 27% less than for those fertilised with ammonium nitrate. Use of a urease inhibitor (which reduces the rate of hydrolysis and thus allows more time for rain to wash the urea into the soil) significantly reduced nitrogen losses and increased the growth response. A comparable overseas studies where urea was applied to plantations with well developed litter layers support these findings, and indicated that, unless rain occurs before the urea is dissolved by morning due, it may not be effective in leaching it into the soil and reducing ammonia (Kissel *et al.*, 2004).

In contrast to the work in pine plantations, there has been little research into the effect of different forms of nitrogen on response in eucalypt plantations. Smethurst (2004) reported a significant response to urea compared with ammonium sulphate and no difference compared with nitrate based fertilisers. Thus, there was no evidence of higher rates of nitrogen loss from urea compared with other forms of nitrogen fertiliser. This difference in volatilisation loss from urea in young eucalypt plantations compared with mid-rotation pines is likely to be due to the differences in the depth and composition of the litter layers. In mid-rotation pine plantations the litter layer is often 5-15 cm thick and is primarily composed of fine material (pine needles in various states of decomposition, including a well-developed F-H layer) which provides an ideal environment for volatilisation of urea as a result of diurnal wetting and drying, low surface area contact and high permeability for gaseous transfer. In contrast, the litter in young eucalypt plantations is far less and is of coarser structure (larger leaves and more woody material). Thus, urea is probably rapidly leached into the soil minimising the potential for ammonification and volatilisation. The potential for volatilisation losses from urea could therefore increase in older eucalypt plantations with better developed litter layers.

4.4 Predicting fertiliser response in thinned stands

Research into fertiliser response prediction in plantations has focussed on the use of readily measureable, and some more difficult to measure, site or stand variables that are related to forest growth and nutrition. Variables studied include stand age, growth rates and water availability, foliar nutrient concentrations, leaf area, soil type and parent material, soil nutrient concentrations, and indices of soil nutrient availability. However, while there has been some success developing fertiliser response relations using selected site or stand variables for specific regions and experimental conditions, application of these prescriptions outside either the spatial or temporal situation for which they were developed and even into operational fertiliser use can lead to major errors (eg. May *et al.*, 2009; Turner *et al.*, 2001). Further, few of the calibrations of predictive relationships derived from these experiments meet the principles of fertiliser response prediction provided by Reuter and Robinson (1997) which include proper validation against an independent dataset and testing across a wide range of sites. As a result, an inability to accurately predict stand responsiveness to fertiliser is still seen as a major impediment to widespread use of fertiliser after thinning across much of Australia's softwood estate. Some of the research into the development of fertiliser prescriptions is outlined below.

4.4.1 Foliar analysis and leaf area

There is a long history of research into relationships between foliar nutrient concentrations and stand productivity and their use for diagnosing nutrient deficiencies. In the 1960's, Raupach *et al.* (1969) developed fertiliser prescriptions for thinned radiata pine stands in the Green Triangle based on foliar nitrogen and phosphorus concentrations from nutrient and growth data from permanent growth plots. This work led to the widespread investigation and adoption of foliar nutrient concentrations as a diagnostic tool for identifying potentially responsive stands for fertiliser application. In New Zealand, Will (1985) developed ranges for adequate, marginal and critical nutrient limitations for radiata pine and Crane (1981) reported that responses to a combination of nitrogen and phosphorus fertiliser in 20 year old stands were negatively related to foliar nitrogen concentrations. However, Mead and Gadgil (1978) reported that, while foliar phosphorus concentrations provided a sound basis for determining phosphorus requirement the same was not true for foliar nitrogen and requirement for N for radiata pines in NZ. These results are consistent with those for Loblolly pine (*P. taeda*) in south-eastern USA (Ballard & Lea, 1986).

In NSW, a survey of Belangalo State forest showed a strong relationship between foliar phosphorus and site quality measured at around 25 years (Lambert & Turner, 1988). Similar relationships were reported for other forests across NSW, but these were found to differ substantially for different soil types and were also influenced by climate (rainfall for the four months prior to sampling) and stand age (Turner & Lambert, 1986). Thus, separate relationships were developed for different soil types (based on parent rock type). Furthermore, the interpretation of foliar phosphorus concentrations was also related to stand age and rainfall. However, it should be pointed out that correlation between productivity and foliar nutrients based on a single experiment or survey approach is not necessarily a good predictor of response to fertiliser addition. Unfortunately, this approach has frequently been used as the basis for developing operational fertiliser criteria in Australia.

In Queensland, Bevege and Richards (1972) reported that critical foliar phosphorus concentrations for slash pine (*P. elliottii* var. elliottii) ranged from 0.075-0.08%, while Simpson and Osborne (1993) reported the critical phosphorus concentration for Caribbean pine (*P. caribaea* var. Honduras) was 0.07% . Follow-up work by Xu *et al.* (1995c) showed there was a significant relationship between stand growth and foliar phosphorus during the first 11.5 years with foliar phosphorus explaining 65% of variation in stand volume at age 9.6 years. They calculated that the optimum foliar phosphorus concentration at which maximum stand growth was obtained ranged from 0.093-0.110%. However, there was a gradual realisation that operational fertiliser requirements could not be adequately assessed by extensive foliar sampling alone due to its cost (Simpson & Grant, 1991). As a result, a set of fertiliser trails were established across a range of sites to identify deficiencies, calibrate foliar data, assess the economics of fertiliser use and ultimately aid in predicting fertiliser requirements. These experiments indicated there was significant variation in response to nitrogen, phosphorus and potassium between soil types, which permitted the development of fertiliser prescriptions based on soil type.

More recently, results from a range of fertiliser experiments in thinned radiata pine stands in the Green Triangle region showed that foliar analysis alone was of limited usefulness in predicting response to either nitrogen or phosphorus applications (May *et al.*, 2009). Other studies have reported similar problems with trying to use foliar nitrogen to predict responsiveness to nitrogen fertiliser in thinned stands of radiata pine (eg. Mead & Gadgil, 1978; Snowdon & Waring, 1995).

There are a number of possible explanations for the lack of a clear relationship between foliar nitrogen and response to nitrogen fertiliser. Firstly, while trees can store excess phosphorus in inorganic form, nitrogen is almost all stored in organic form in foliage. Where nitrogen is in excess, trees will tend to produce more foliage (if no other factor is limiting) and where nitrogen is deficient, trees will respond by producing less foliage. Thus, foliar nitrogen concentrations tend to be a fairly insensitive indicator of stand nitrogen status. Secondly, a strong interaction between nitrogen and phosphorus means that the response to nitrogen fertiliser is often limited by phosphorus availability (Boardman, 1974; Boardman, 1983; Raupach *et al.*, 1969; Snowdon & Waring, 1990). Thus, low nitrogen concentrations do not necessarily mean that a stand will respond to nitrogen fertiliser, while stands with apparently adequate nitrogen concentrations may give good responses if foliar phosphorus concentrations are also high. However, total foliar nitrogen concentrations have been shown to be related to the response to combined nitrogen plus phosphorus fertiliser treatments, indicating that, once the phosphorus limitation to growth is corrected, foliar nitrogen concentrations could be used for predicting response to nitrogen fertiliser (May *et al.*, 2009). This result is consistent with that of Turner *et al.* (2001) showing that foliar nitrogen concentrations were closely related to response to nitrogen alone, where there was no phosphorus limitation, or, where phosphorus was limiting, response to nitrogen plus phosphorus.

Foliar N: P ratios have been suggested as potential indicators of responsiveness to fertiliser, as these, at least partially, take into account both nitrogen and phosphorus limitations. In loblolly stands in the south-eastern USA, McNeil (1988) reported that N: P ratios in needles and litter were significantly related to responses to either nitrogen or phosphorus fertiliser. Koerselman and Meuleman (1996) went further to suggest that vegetation N: P ratios could be used as general indicators of nitrogen or phosphorus limitation at a community level with ratios <14 indicating nitrogen limitation and ratios >16 indicating phosphorus limitation. Judd *et al.* (1996) found that diameter growth of *E. nitens* was related to foliar N: P ratio with an envelope curve that indicated that maximum growth could be achieved only where this ratio was 15-16 with other ratios indicating deficiency in either nitrogen or phosphorus. However, Smethurst *et al.* (2004) reported that results from fertiliser experiments in Tasmania did not support the generalized use of either foliar N: P ratios or total nitrogen concentrations as indicators of nitrogen deficiency.

Another issue with foliar analysis is that, while it provides an indication of concentrations of nutrients in individual needles, it does not reveal the total amount of nutrients in the canopy. This is especially important in thinned stands where foliar nutrient concentrations can change rapidly as a result of expansion of the canopies of retained trees (Carlyle, 1998). Furthermore, nutrient concentrations can vary considerably with season and needle age (Fife & Nambiar, 1982; 1984) and rainfall (Lambert & Turner, 1988).

Stand leaf area is one of the main factors influencing growth rate and is often limited by nutrient availability (Carlyle, 1998; Fox *et al.*, 2007). Thus, measurement of leaf area index has been suggested as a possible alternative to foliar analysis for predicting response of conifers to fertiliser (Fox *et al.*, 2007; Vose & Allen, 1988). Leaf area index has also been reported to be a reliable indicator of nutrient status in eucalypt plantations and a useful tool for assessing fertiliser requirements and responses (Smethurst *et al.*, 2003). In the Green Triangle, May *et al.* (2009) found that leaf area index alone could explain 85% of the variation in response to nitrogen plus phosphorus fertiliser across 10 stands aged between 24 and 35 years. However, the relationship was weaker when applied across a wider range of sites, time periods and stand ages. Similar research undertaken in mid-rotation loblolly pine (*P. taeda*) plantations in the southern US indicated that leaf area could be used to target responsive stands for fertiliser application (T. Albaugh, Department of Nth Carolina State University, Pers. Comm.). In that region, leaf area has now replaced foliar analysis as the primary diagnostic tool for estimating potential responsiveness to nitrogen and phosphorus fertiliser application (Fox *et al.*, 2007).

Foliar sampling and leaf area measurement both pose operational challenges when used in older plantations (Turner & Lambert, 1985). Foliar sampling requires adequate sampling to provide a representative measurement, and careful standardisation of season, height of collection and needle age class in order to provide a useful indication of nutrient status. Similarly leaf area measurement using instruments such as the LICOR LAI-2000 requires specific lighting conditions and standardised operating procedures to avoid bias. However, recent research into the use of remote sensing to estimate both foliar nutrient concentrations and leaf area is providing promising results (Chen *et al*., 2002; Coops *et al*., 2003; Flores *et al*., 2006). The use of satellite or aerial imagery to assess large areas could thus provide a relatively low cost, reliable means of assessing nutrient deficiencies and selecting responsive stands for fertiliser application.

4.4.2 Soil analysis

Soil nutrient analysis is another option for predicting response to fertiliser. In contrast to foliar analysis, which provides an indication of current stand nutrient status, soil analysis provides an index of nutrient supply. Thus, after thinning in particular, the supply of nutrients from soil is likely to provide a better indication of potential response to fertiliser than foliar nutrient analysis.

Operational application of soil diagnostic tools was reported as far back as the 1940's in SE Queensland where a soil fertility index based on the concentration of total phosphorus in soil was used to determine the species to be planted and fertiliser requirements (Simpson & Grant, 1991). However, because this method proved to be unreliable as planting expanded to cover a wider range of sites it was discontinued in the early 1950's. Soil analysis has since been shown to have the potential to predict response to nitrogen and phosphorus fertilizers in Australia and overseas (Ballard, 1974; Hopmans *et al*., 1993; Hunter *et al*., 1986). Hunter *et al.* (1986) showed that, across 44 stands in New Zealand, 60% of the variation in response to nitrogen fertiliser could be explained by total soil nitrogen, available soil phosphorus (Bray), stand age, percent clay and stand factors such as thinning and pruning. Powers (1984) suggested that an index of soil mineralizable nitrogen could be used to predict growth response of Californian forests to nitrogen fertilizer.

In Australia, there have been a number of studies into the use of soil testing to predict response to fertiliser. Cromer *et al.* (2002) reported that concentrations of total nitrogen and phosphorus in surface soil provided useful indicators of nitrogen and phosphorus requirements and suggested that exchangeable potassium concentration could provide an indicator of potassium deficiency. Total nitrogen concentrations have also been found to be useful indicators of nitrogen status in other studies (Moroni *et al*., 2004; Wang *et al*., 1996). Moroni (2004) reported that nitrogen deficiency could be expected within the first 3 years where total nitrogen in the surface soil was less than 0.5%, while Smethurst *et al.* (2004) suggested that total nitrogen concentrations could be used as an indicator of the optimum timing of fertilisation in young *E. nitens* plantations. Other promising indicators of soil nitrogen supply in eucalypt plantations include C:N ratios, anaerobic mineralizable nitrogen and soil solution NO_3 and NH_4 concentrations (Smethurst *et al*., 2004; Wang *et al*., 1996).

For assessing phosphorus requirements, Ballard (1975) demonstrated that a number of soil phosphorus extracts were effective predictors of response to phosphorus fertiliser. However, the only soil-based index of phosphorus availability found to be consistently related to response to phosphorus fertiliser in the Green Triangle was forest floor total phosphorus concentration (May *et al*., 2009). In eucalypt plantations, Mendham *et al.* (2002) showed that Bray- or $CaCl_2$-P concentrations were more reliable than total phosphorus as an indicator of the need for phosphorus fertiliser in southern bluegum plantations growing on highly phosphorus fixing ferrosols and suggested a critical value of $CaCl_2$-P of 0.0005 ug P kg^{-1}.

For pines, Carlyle and Nambiar (2001) demonstrated that 90% of the variation in nitrogen mineralization across sites could be explained using a relationship incorporating both total nitrogen and organic phosphorus in soil. Research by May *et al.* (2009) investigated relationships between response to fertiliser and a range of indicators of soil nitrogen and phosphorus status in thinned stands. Initial work indicated that anaerobically mineralizable nitrogen in the surface 15 cm of soil was related to response to nitrogen plus phosphorus fertiliser across 10 sites while a combination of anaerobic nitrogen and forest floor phosphorus was related to response to nitrogen alone. However, subsequent experiments covering a wider range of fertiliser treatments and sites failed to reproduce these relationships. This experience indicates the potential danger in extrapolating soil based relationships across stand conditions and fertiliser treatments beyond the original data set especially those based on variable indices such as nitrogen rates of nitrogen mineralisation. Total nitrogen may be a more robust, if less sensitive indicator of nitrogen status. This index was significantly related to response to nitrogen plus phosphorus fertiliser across 16 sites and multiple fertiliser treatments.

Analysis of litter or forest floor material has been previously suggested as an alternative to foliar nutrient analysis for *P. radiata* in New Zealand (Hunter *et al.*, 1985) and other species (Mahendrappa & Weetman, 1973; Miller & Miller, 1976). However, its application has been limited by generally weak relationships between foliar nutrient concentrations and those in litter and by differences in the relationships between different regions (Hunter *et al.*, 1985; Romanya & Vallejo, 1996). Prescott *et al.* (1992) showed that nutrient concentrations in the forest floor litter layer were useful as an index of nutrient supply rate in a range of forest types. In Australia, Carlyle (1998) showed that nitrogen concentrations fresh litter were correlated with stand growth but not nitrogen uptake. However, the only published research into the use of forest floor nutrient concentrations for diagnosing nutrient deficiency or predicting response to fertiliser in Australia is from the Green Triangle (May *et al.*, 2009). In this study, total nitrogen concentrations in forest floor of thinned pine plantations were significantly correlated with response to nitrogen plus phosphorus fertiliser while total phosphorus concentrations were related to response to phosphorus fertiliser.

Despite extensive research into the use and application of various soil analyses for predicting response to fertiliser, uptake of these for operational application has been relatively poor. Schoenholtz *et al.* (2000) suggested that this is a result of a lack of understanding of the relationships between soil chemical properties and forest productivity and the way these relationships vary with changes in stand age and structure over time. It is also probably due to cost and inadequate information on the spatial and temporal variability of indices of nutrient availability, operational difficulties associated with collecting and storing soil samples and the absence of a single test, or group of tests that have been shown to work across a range of soils and climates.

To be operationally useful, any measurement of stand nutrient status must be fast, cheap and robust enough to be economic to implement. Measurement of nitrogen mineralization tends to be too slow and labour intensive for routine operational application across a large number of sites. In contrast, measurement of total nitrogen or phosphorus in soil and forest floor samples is much faster and cheaper and is less prone to issues associated with storage and timing that can influence measurement of nitrogen mineralization. However, use of these more robust indicators of nutrient availability requires calibration for the specific site and stand conditions before being applied operationally.

4.4.3 Stand growth

An alternative indicator of response to fertiliser is site index or productivity. This overcomes the key limitations foliar, litter or soil sampling which include the cost of collection and chemical analysis, difficulties in obtaining samples (especially foliage), and the sampling intensity required to cope with large spatial variability in nutrient availability in soil and nutrient concentrations in litter and foliage. It is also normally readily available and thus requires little or no extra effort or resources to collect. However, it also has some major limitations in its usefulness as a prediction tool.

Site index integrates all factors that influence stand growth including soil physical and chemical characteristics, water availability, and early stand management. Thus, where nutrients are limiting, stands with slower growth rates could be expected to give larger responses to fertiliser. This principle has been shown to hold for forest overseas with or without the inclusion of other stand variables such as stocking, basal area and dominant height (Carter *et al.*, 1998). Crane (1981) reported that responses to nitrogen plus phosphorus fertiliser were inversely proportional to growth rates of stands in the year prior to treatment. A study in the Green Triangle indicate that site index alone is a useful indicator of relative response to fertiliser, explaining 41% of variation in relative response to nitrogen plus phosphorus and 31% of variation in relative response to nitrogen only (May *et al.*, 2009). However, since a large response in a slow growing stand can produce a similar increase in wood yield to a small response in a fast growing stand, site index is less useful for predicting absolute response. Furthermore, site index does not show which nutrient is limiting growth and therefore what type of fertiliser to apply. However, in situations where the general nutrient requirements for a species across a region or soil type are known and no other information (eg. foliar or soil measurements) is available, site index can provide a useful guide for targeting potentially responsive sites.

However, productivity can be useful indicator of declines in growth that may be related to nutritional limitations. For example, in Tasmania, initial fertiliser requirements at establishment are based on key site indices including site history, soil type and condition, rainfall and topography, but requirements for remedial fertiliser applications in older stands are determined by from deviations in productivity from the expected growth curve based on the initial site measurements and assessing crown condition for signs of nutrient deficiencies (Adams *et al.*, 2007).

4.5 Economics of fertiliser use

Crane (1981) reported that post-thinning fertiliser application could increase growth by 37% and could at least break even in economic terms while providing a useful means to boost harvest yields at relatively short notice required by harvesting schedules. In a subsequent desktop study, Sar and Crane (1984) calculated that, from a range of fertiliser options including establishment, and thinning at different stages of the rotation, economic returns were highest when fertiliser was applied after the final and penultimate thinnings. Similarly, Turner *et al.* (1992) argued that the greatest financial gain would result from fertilising the stands after final thinning, because in older stands a) the value of wood was greater, and b) the time until final harvest was shorter. However, they also showed that it is the absolute volume response that is the most important factor in determining overall profitability.

Knott and Turner (1996) conducted an economic analysis of the optimum fertiliser treatments applied across NSW sites. This analysis indicated that rates of return on investment could be expected to exceed 8% across most sites based on stratification of stands and fertiliser strategies by parent rock type. However, there was considerable variation within each stratum with average NPV's (net present value) ranging from \$62 to \$1169 ha^{-1}. This inability to accurately identify stands that would give the best response to fertiliser was the key limitation to broader use of fertiliser in plantations (Knott *et al.*, 1996).

May *et al.* (2009) conducted an economic analysis of different fertiliser strategies in mid-rotation radiata pine plantations in the Green Triangle including types (nitrogen, phosphorus or nitrogen plus phosphorus) forms (urea, ammonium sulphate or ammonium nitrate), rates and timing (post 2^{nd} thinning, post third thinning or both). Estimated NPV 6 years after fertilisation at 2^{nd} thinning varied from -\$48 to \$513 for nitrogen (200 kg N ha^{-1} as urea), -\$640 to \$305 for phosphorus (80 kg P ha^{-1} as triple super phosphate) and from -\$195 to \$701 for nitrogen plus phosphorus using a discount rate of 7.5%. This provided average internal rates of return of 25% for nitrogen, -14% for phosphorus and 21% for nitrogen plus phosphorus. Over successive thinnings, the most profitable fertiliser strategy for most sites was nitrogen plus phosphorus fertiliser at second thinning followed by nitrogen alone at third thinning with a net present value to time of harvest of \$361 ha^{-1} and an internal rate of return of 13%. Optimum economic rates of fertiliser application determined from nitrogen and phosphorus rate x form experiments were 200 kg ha^{-1} for urea, 100-200 kg ha^{-1} for ammonium based fertilisers, and 40 kg ha^{-1} for P. Although most of the value of fertiliser use arose from the increased wood production, increased log size (and therefore unit wood value) was also an important factor in determining overall profitability.

Smethurst *et al.* (2001) modelled the economics of applying nitrogen fertiliser to shining gum (*E. nitens*) pulpwood plantations in Tasmania. This analysis showed that nitrogen fertiliser was profitable for plantations with medium to high growth response (> 13 m^3 per 100 kg N applied). For a base case scenario (400 kg N ha^{-1} at $700 per t nitrogen applied 8 years prior to harvest with a discount rate of 8% and a wood value of $10 m^{-3}), positive NPV's were achieved provided the total yield response exceeded 50 m^3 ha^{-1}. This is equivalent to a growth response of around 30% for a stand growing at a rate of 20 m^3 $ha^{-1\ year-1}$. Internal rates of return varied from 5-14% as the total response varied from medium (40 m^3 ha^{-1}) to high (80 m^3 ha^{-1}). Thus, nitrogen fertiliser application was likely to be profitable provided the most responsive sites were targeted. However, a subsequent analysis of response to nitrogen fertiliser across 14 sites indicated that only one site had a yield response in excess of 13 m^3 per 100 kg nitrogen applied (Smethurst *et al.*, 2004). This analysis indicated that fertiliser application was unlikely to be profitable on most ex-forest pulpwood-only sites without other complementary factors (eg. increase in wood value, lower opportunity cost and other organizational specific considerations). The fact that many plantation growers in Australia apply nitrogen fertilisers to eucalypt plantations (see later sections) indicates that perceived profitability is greater than this analysis indicated.

4.6 Other considerations

4.6.1 Interactions between fertilisers and pests or diseases

Ratios of nitrogen and sulphur in pines are important in influencing susceptibility to pests and diseases. Turner and Lambert (1986) summarised work in NSW showing that low foliar sulphur concentrations were associated with to the accumulation of the non-sulphur containing amino-acid arginine, which is associated with susceptibility to the fungal pathogen *Dothistroma*. High arginine levels are especially common as a result of N-induced sulphur deficiency, which can arise after applying nitrogen or from planting on ex-pasture sites with high levels of biologically fixed N.

In contrast to early concerns regarding the potential for fertilisers to increase damage to plantations from pests and diseases, recent studies have shown that fertiliser application can actually be beneficial. Pinkard *et al.* (2006a; 2006b) showed that application of nitrogen to bluegums suffering defoliation improved crown condition and increased growth to at least match that of undefoliated trees. Thus, fertiliser application can be a useful management tool for reducing the impacts of defoliation at least in the short term in some situations.

In pines, Hopmans *et al.* (2008) showed that application of NPS to stands damaged by *Essigella californica* reduced defoliation by approximately 20%, corrected nutrient deficiencies, and increased growth. However, application of nitrogen fertiliser alone increased defoliation in stands deficient in phosphorus or sulphur. The benefit of fertilising stands subject to defoliation was due to a combination of enhanced needle retention following correction of phosphorus deficiency, and the greater availability of nutrients increasing the capacity for trees to recover after a defoliation event.

4.6.2 Use of Legumes instead of mineral fertilisers

In times of increasing nitrogen fertiliser prices, legumes offer an alternative to fertiliser application. The only nitrogen fixing trees currently grown in plantations in Australia are *Acacia mangium* on Melville Island in the Northern Territory and *A. melanoxylon* in Tasmania. Native legumes such as *A. dealbata* have been shown to be able to add up to 600 kg/ha over 6 years in native forest in high rainfall environments (May & Attiwill, 2003). In a plantation situation, such species could be planted as an inter-row that is thinned early in the rotation leaving the residues to decompose while woody material is used for either wood products or bioenergy production (P. Lloyd, Auspine, Pers. Comm.).

In New Zealand, Gadgil *et al.* (1983) reviewed the use of *Lupinus arboreus* as an N-fixing understory in young NZ radiata pine plantations. On sandy soils, although response was less than that to nitrogen fertiliser, the effects of the two nitrogen sources were complementary. Turvey *et al.* (1983) analysed the economics of a leguminous understory that regenerates after each thinning in a radiata pine plantation, but showed that the cost of establishment probably exceeded the alternative cost of nitrogen fertiliser. However, the authors suggested that further research was needed to determine the efficiency of supply of biologically fixed nitrogen to the forest crop. In the Green Triangle, research was undertaken into the use of clover following prior to establishment or lupins in older stands soon to be harvested and clover after harvest to increase nitrogen supply to the next crop of trees (Geddes, 1981). After the Ash Wednesday bushfires in SA, this work was accelerated to evaluate the effectiveness of *Lupinus arboreus* in replacing nitrogen lost in the high temperature burn on nutrient poor sandy soils (Nambiar & Nethercott, 1987; Smethurst *et al.*, 1986). However, matching the growth and nitrogen supplied by the understory with the nitrogen requirements of the plantation proved problematic.

Although nitrogen fixing species can increase soil nitrogen availability, they also compete for other resources especially light, water, and nutrients (eg. Nambiar & Nethercott, 1987; Smethurst *et al.*, 1986; Smethurst *et al.*, 1986; Turvey *et al.*, 1983). Thus, if resources other than nitrogen limit growth, legumes can reduce the total volume production of the main crop. However, if an economic use can be found for the N-fixing biomass, total stand value could be enhanced. Khanna (1997) reported that growth of young eucalypts was enhanced by the presence of *Acacia mearnsii* and that height growth of the entire stand was maximized by a 1:1 planting ratio of eucalypts and acacias. This result indicates that total biomass production is likely to be greater for a mixed planting incorporating nitrogen fixing species than for a mono-culture of eucalypts or pines. This hypothesis was confirmed in a subsequent study where mixed plantings were twice as productive as *E. globulus* monocultures as a result of the acacias adding an estimated 38 kg N ha^{-1} $year^{-1}$ (Forrester *et al.*, 2004; Forrester *et al.*, 2007).

The use of mixed plantations that incorporate N-fixing species warrants further research especially given the current high prices for nitrogen fertiliser. In particular, the growing interest in the use of forest biomass for bioenergy or biofuel production provides a potential market for N-fixing trees removed during thinning, leaving the N-rich residues as a slow release source of nitrogen for the remaining trees.

4.6.3 Effects on nutrient imbalances on tree form

Ruiter (1969) correctly identified copper deficiency as the cause of stem deformity of trees growing on nutrient deficient soils fertilised with nitrogen and P. This deficiency was associated with similar problems at other sites on sands in SA (Raupach *et al.*, 1978) and Victoria (Turvey, 1984). In the 1980's problems with the form of trees growing on fertilised ex-pasture sites were identified in NE Victoria, NSW and WA. Pederick *et al.* (1984) demonstrated that this deformity was likely to be due to nitrogen induced copper deficiency, and Downes and Turvey (1990) showed that the problem was due to weakening of the stems as a result of poor lignification of early wood. However, efforts to correct the problem by applying copper fertiliser were generally unsuccessful (Hopmans, 1990) and experiments designed to determine the actual causes of the problem were inconclusive (Turvey *et al.*, 1993).

These and other authors showed that stem deformity was sometimes associated with high copper concentrations. Carlyle *et al.* (1989) concluded that the symptoms were due to previous land-use rather than soil type and were associated with pines growing on highly fertile ex-pasture soils with high nitrate production (Carlyle *et al.*, 1989). Birk (1990) recommended a range of genetic and management alternatives including the use of less susceptible genetic material (Pederick *et al.*, 1984), closer spacing and site specific fertiliser application. Other work indicated that N-fertiliser application on these sites was often unnecessary or even deleterious to growth and nitrogen application at establishment on fertilise ex-pasture site subsequently ceased in most states (Birk, 1994). High nitrogen and phosphorus fertility was also associated with deformities and suspected copper deficiency in Tasmania in both *P. radiata* (Cromer *et al.*, 1985a) and E. nitens (Turnbull *et al.*, 1994).

4.6.4 Effects on wood quality

Concerns have been raised that faster tree growth resulting from fertilisation can reduce wood quality. These concerns have largely been a result of studies in stands with low stocking and fertile ex-pasture sites that had a reduction in wood density and quality as a result of heavy thinning and fertiliser application (eg. Beets *et al.*, 2001; Cown & McConchie, 1981). However, studies in Australia indicate that for appropriately timed fertiliser applications, any reductions in wood quality are minor and tend to be outweighed by the overall increase in volume, and changes can also be absent or positive.

Early studies into the effects of fertiliser on softwood quality were undertaken by a number of Australian researchers. McKinnell (1970) reported that nitrogen, phosphorus, potassium or sulphur fertiliser applied to stands of various ages increased variation in density within rings but decreased variation between rings. Similarly, Rudman (1970) showed that fertiliser significantly affected average density of young *P. radiata*, with phosphorus almost always increasing density, but other nutrients (nitrogen, potassium and sulphur) tended to decrease density, depending on their availability. Nicholls (1971) reported that both thinning and fertilising increased ring width, but did not affect the incidence of spiral grain and reduced only wood density at the highest thinning intensities (from 2500 to 250 stems per ha). Similarly, Nelson *et al.* (1980) showed that, despite large increases in productivity, post-thinning fertiliser produced relatively small reductions in pulp yield and tear strength. In south-east Queensland, Xu *et al.* (2002) showed that various combinations of nitrogen, phosphorus and potassium fertiliser applied at establishment enhanced wood properties of young slash pine including percent latewood, basic density, modulus of elasticity and modulus of rupture.

A comprehensive study of the effects of post-thinning fertiliser application on wood properties of radiata pine was undertaken by Nyakuengama and Downes (2002; 2003). This work showed that, although mid-rotation application of nitrogen, phosphorus or nitrogen plus phosphorus fertiliser reduced density of wood produced in the 5 years post treatment, it increased the proportion of higher density outer wood compared to juvenile wood and thereby increased average tree density. Both nitrogen and phosphorus fertilisers reduced fibre coarseness and fibre wall thickness, while nitrogen also reduced fibre radial diameter. However, these effects peaked 2 years after application and disappeared after 4-5 years. Similarly, McGrath *et al.* (2003) showed that, although nitrogen fertiliser temporally reduced wood density, phosphorus did not despite providing a large and sustained increase in growth. Furthermore, average stem density remained above the minimum for structural grade timber for all fertiliser treatments and unit log value ($\$ m^{-3}$) increased as a result of an increase in the log diameter that increased the proportion of logs classed as sawlogs.

Few Australian studies have assessed the effects of fertiliser on pulpwood quality from short rotation eucalypt plantations. In one study, wood properties including density, fibre length and pulp yield were found to be detrimentally affected by fertiliser at drier sites, but not at wetter sites (Raymond & Muneri, 2000). Goncalves (2004) suggested that overall experience from Australian and overseas studies of the effects of silvicultural treatments on wood properties indicated that fertiliser tends to increase or not affect wood quality although it can increase wood nutrient content. The authors speculated that there could be an interactive effect of nutrition and water availability with fertiliser tending to increase wood density where there was sufficient water to allow increased latewood production, but decreasing density if water availability limited latewood growth and the ratio of early wood was increased.

Studies from overseas indicate that nitrogen and phosphorus fertiliser can increase wood density and improve pulping yield (Toit & Drew, 2003). Recently, Germishuizen (2007) reviewed current knowledge of the effects of fertiliser on the productivity and wood quality of eucalypt pulpwood plantations in South Africa, Australia and South America. In some cases, Kappa numbers (which indicate the lignin content or amount of chemical required to bleach the wood pulp) were increased with high fertiliser application regimes. However, this increase was more than compensated for by an increase in productivity, longer fibre length and an increase in wood density.

These studies show that fertiliser application can influence the quality of wood produced for several years after application. In particular, density is usually reduced for a period after nitrogen application as a result of reduced fibre wall thickness, although it may be increased after phosphorus application. However, where fertiliser is applied to older stands, the benefit of the production of higher value wood normally far exceeds any short term reduction in wood density. Thus average log value appears to be generally increased by fertiliser application.

4.7 Environmental Impacts

4.7.1 Emissions to air

The major emissions to air from fertiliser are in the form of nitrous oxides and ammonia, which can be produced either directly or indirectly as result of nitrogen fertiliser application. These emissions are important from a climate change perspective because N_2O has a global warming potential many times greater than that of CO_2. To allow comparison of the influence of different greenhouse gasses and the combined affects on global warming to be estimated, global warming factors based on the estimated impacts of different gasses on atmospheric warming have been provided by the International Panel of Climate Change. These estimates have changed over time. For example, in 1996 the global warming potential of N_2O over 100 years was estimated to be 310 times that of CO_2. This is the value currently used by the Department of Climate Change in its estimates of Australia's greenhouse gas emissions (DCC, 2008a). However, in 2006 this figure was revised to 298 (IPCC, 2007).

Although in terms of greenhouse gas emissions, N_2O is the most important gas emitted from agricultural soils, emissions of ammonia are also important. These latter emissions are considered to be an indirect source of N_2O as a result of the enrichment of soil or water with a proportion of the ammonia deposited through rainfall. N_2O is produced by microbial transformation of nitrogen in soils and manures, most commonly when nitrogen availability exceeds plant requirements and in association with wet (anoxic) conditions. Ammonia gas is produced primarily from nitrogen volatilisation from urea fertiliser or manures, but with small amounts being produced from ammonium-based fertilisers applied to alkaline soils. In addition, direct emissions of CO_2 arise from urea fertiliser as a result of urea hydrolysis and an emission factor of 20% x 44/12 x total mass of urea is recommended to determine the total production of CO_2 from urea fertiliser (IPCC, 2006). Indirectly though, these fertiliser also promote CO_2 uptake from the atmosphere by promoting plant growth.

There are few data on gaseous emissions from nitrogen fertiliser applied to plantations in Australia or overseas. However, based on the results from May and Carlyle (2005) and May *et al.* (2009), around 40% of nitrogen could be emitted as ammonia from urea fertiliser applied to mid-rotation softwood plantations. However, rates of volatilization are expected to be far lower for urea fertiliser applied to bare soil or in eucalypt plantations (see section 4.3.6). Overseas studies indicate that volatilization losses from urea fertiliser applied to young stands are relatively low. Thus, to accurately estimate gaseous nitrogen losses and greenhouse gas emissions from fertiliser used in plantations, it is necessary to first breakdown fertiliser use by form, age of application, forest type and soil conditions.

4.7.2 Contamination of water

Protection of water quality is critical for the long-term maintenance of water resources and aquatic ecosystems. The quality of water from forested catchments is generally very high (Binkley *et al.*, 1999). Although afforestation can reduce stream flow, nutrient and sediment loads from well managed plantations are generally far lower than from agricultural catchments especially in degraded landscapes (Van Dijk and Keenan 2007). However, specific operations such as fertiliser application can temporarily increase concentrations of nutrients in stream water. The key concerns over contamination of water from fertilisers are associated primarily with impacts on aquatic ecosystems such as changes in stream biota and toxic algal blooms that can result from increasing nitrate and phosphate levels in surface water (eg. Albert *et al.*, 2005). In addition, nitrate or nitrite can be toxic to humans while ammonia can be toxic to fish (Binkley *et al.*, 1999). In Australia, water resources in forested catchments are protected under a national water quality management strategy and through the adoption of the Montreal Process of socio-economic and environmental criteria and indicators for the sustainable management of forests (DPIE, 1998).

The potential export of nutrients from fertilisers to water resources is influenced by fertiliser form, rate of application, soil, climate, forest type and age as well as protective measures such as buffer strips. For example, nitrate tends to be more mobile in soils than ammonium. Thus, application of nitrogen as nitrate can lead to greater nitrogen leaching compared with other nitrogen forms. However, oxidation of ammonium leads to the formation of nitrate over weeks to months after fertiliser application that can also result in nitrate leaching (Binkley *et al.*, 1999). The rate of nutrient loss is influenced by the soils capacity to immobilise nutrients applied as well as the vegetation's capacity to take them up. For example, application of fertiliser at high rates, to newly established stands or to sandy soils will increase the potential for nutrient leaching and export. Thus, both the magnitude and duration of leaching losses from nitrogen fertiliser are influenced by the fertiliser strategy selected for a specific set of stand, soil and climatic characteristics.

Binkley *et al.* (1999) reviewed results from 53 published studies around the world on the impacts of fertiliser use on concentrations of nutrients in streams. These studies covered a wide range of soils, forest types, fertiliser forms and rates and climates (although no published reports for tropical regions were available). Most studies reported peak concentrations of nitrate nitrogen of < 2.0 mg N L^{-1} after nitrogen fertiliser application, although increases as high as 30 mg L^{-1} have been reported in nitrogen saturated ecosystems (Adams *et al.*, 1997). Average annual concentrations of nitrate-N were all < 5 mg L^{-1}. Increases in ammonium-N were usually only marginal except where nitrogen is applied as ammonium nitrate. Substantial increases in total nitrogen concentrations in streams were reported, but these were generally associated with high concentrations of nitrate or the direct input of fertiliser pellets into streams. Similarly, phosphorus fertiliser application increased average phosphorus concentrations in streams several-fold and may have resulted in an increase in stream productivity.

These impacts can be mitigated through the retention of buffer strips around drainage areas and water courses. Perrin *et al.* (cited by Binkley *et al.* 1999) showed that a 50 m buffer strip reduced the increase in concentrations of urea and ammonium from fertiliser by an order of magnitude by reducing the potential for direct input of fertiliser to streams. Buffer strips also reduced increases in stream nitrate concentrations by 60% as a result of uptake and denitrification effects near the stream (Binkley *et al.*, 1999). Thus, buffer strips help to minimise potential increases in nitrate concentrations in streams associated with up-slope use of fertiliser N.

Binkley *et al.* (1999) also showed that nitrate concentrations in streams tend to increase more as a result of application of ammonium nitrate than application of urea. Studies in the Green Triangle indicate that a larger proportion of nitrogen from urea is held as ammonium in the litter layer compared with ammonium and nitrate fertiliser forms (May *et al.*, 2009). Thus, potential for transport to water are greatest for nitrate nitrogen and are likely to be least for urea N.

Successive applications of fertiliser tend to increase concentrations of nitrate in streams more than single applications. Bisson *et al.* (1992) found that average nitrate concentrations increased by 0.3 mg N L^{-1} for a single application of nitrogen fertiliser compared with 0.7 mg N L^{-1} for areas fertilised two or three times. Similarly increasing the rate of fertiliser application also tended to increase the average concentration of nitrate nitrogen in stream waters (Binkley *et al.*, 1999).

Binkley *et al.* (1999) concluded that the greatest potential for increases in streamwater nutrients were associated with a) direct application of fertiliser to streams, b) the use of ammonium nitrate fertiliser and c) high application rates or repeated doses of fertiliser. However, these authors noted that, even in these situations, the impacts might be too small to degrade water quality.

In New Zealand, Neary and Leonard (1978) studied the effects of aerial applications of nitrate and phosphorus over forested catchments. Application of phosphate fertiliser at low rates (36 kg P ha^{-1}) and exclusion of riparian zones increased concentrations of phosphorus in streamwater from 0.02 mg L^{-1} to a maximum of 0.11 mg L^{-1}, while application at a higher rate (112 kg P ha^{-1}) over the entire catchment including riparian zones increased peak concentrations to 52 mg L^{-1} immediately after treatment. However, in both cases, concentrations returned to pre-treatment levels within a few months after treatment. Total losses of phosphorus fertiliser to streams from these treatments were 0.06% of applied phosphorus when riparian zones were fertilised or 0.01% when these areas were excluded. Application of urea at a rates of 230 kg N ha^{-1} and 90 kg N ha^{-1} across the entire catchment (i.e. including riparian zones) increased nitrate nitrogen concentrations to 1.2 mg L^{-1} and 0.8 mg L^{-1}, respectively. Estimated losses of nitrogen fertiliser to streams within 21 weeks of treatment application were 0.3% for the high rate and 0.5% for the low rate.

Only a few Australian studies have been published that measure nutrient transfers from fertiliser to surface water. Hopmans and Bren (2007) reported the impacts of conversion from native forest to intensively managed pine plantation on streamflow and water quality in a paired catchment study at Croppers Creek in NE Victoria (annual rainfall 1400 mm). At 23 years the pine plantation was thinned and aerially fertilised with 100 kg P ha^{-1} as phosphate (18% phosphorus, 9% sulphur and 14% calcium) followed by 139 N kg ha^{-1} as urea (46% N) two years later. In the fertilised catchment, concentrations of phosphorus in stream water increased from 0.002 mg L^{-1} to a maximum of 0.010 mg L^{-1}, while concentrations of nitrate-N increased from 0.04 mg L^{-1} to 0.07 mg L^{-1} under normal rainfall conditions. Phosphate concentrations remained significantly above pre-treatment levels for 42 months after treatment, but nitrate concentrations returned to pre-treatment levels 30 months after treatment. Although the phosphate fertiliser also contained sulphur and calcium, there was no significant increase in concentrations of these nutrients compared with the unfertilised eucalypt catchment. However, there was a significant increase in phosphorus concentrations of sediments, indicating that some fertiliser phosphorus was transported attached to suspended clay particles. Estimated total exports of fertiliser nitrogen and phosphorus were 1.2 kg N ha^{-1} and 0.70 kg P ha^{-1}. These values represent less than 0.9% of the total amount of nitrogen and 0.7% of the total amount of phosphorus applied as fertiliser. The small losses of fertiliser nitrogen and phosphorus after fertiliser application in plantations is consistent with results from other studies (Binkley *et al.*, 1999; Neary & Leonard, 1978) reflecting the low potential for export of fertiliser-N or -P provided direct application of fertiliser to waterways is avoided.

Other studies indicate that underlying concentrations of available nitrogen and phosphorus in plantation soils is generally low, and C:N ratios high relative to pasture soils reducing the risk of fertiliser leaching (O'Connell *et al.*, 2003; Wang *et al.*, 1996). Furthermore, water-use studies have shown that evapo-transpiration from established plantations is equal to or slightly less than annual rainfall indicating that the movement of water (and thus fertiliser) through the soil profile is minimal (Benyon *et al.*, 2006). The potential for nutrient losses may be greater from plantations in the relatively high rainfall sub-tropical and tropical zones of Queensland. However, in a study of nutrient transport in a well-drained catchment, Bubb *et al.* (2002) reported that there was no effect on either stream or ground water quality from harvest operations or plantation re-establishment, including fertiliser application. This catchment study did not focus on the impacts of fertiliser application *per se*, but instead integrated a range of site disturbances associated with forest management. In contrast, Forsyth *et al.* (2006) showed that significant increases in nitrogen and phosphorus concentrations in surface and ground water were possible in coastal lowland plantations subject to seasonal water logging. In this study, nutrient concentrations in runoff were 4 times greater for nitrogen and 20 times greater for phosphorus after application of fertiliser

(60 kg N ha^{-1} plus 23 kg P ha^{-1} as MAP) compared with controls from small plots after simulated rainfall. Total exports of nitrogen and phosphorus in surface water for the fertilised treatment were increased by 0.9 kg N ha^{-1} and 1.43 kg P ha^{-1}, indicating that 3.9% of fertiliser nitrogen and 2.4% of fertiliser phosphorus could be lost due to surface runoff. However, losses from an entire forest catchment were considered to be far lower due to the presence of riparian buffers.

Current fertiliser use in plantations in Australia is governed by stringent environmental controls, including the use of buffers, and by the desire to avoid overuse of fertiliser by matching nutrients supply in fertiliser with demand for nutrients by trees. Across most planted areas southern Australia, water-use studies indicate that, once stands reach canopy closure, leaching of nutrients past the root zone and into ground water is unlikely as a result of annual evapo-transpiration rates being equal to rainfall (Benyon and Doody 2002). Thus, leaching rates in mid-rotation and older stands are probably negligible. Furthermore, in areas with the greatest potential for nutrient export (i.e. pine plantations in Queensland) rates of fertiliser usage are among the lowest in the country, with virtually no fertiliser being applied to mid-rotation stands. In the absence of specific data on the effects of different fertiliser forms, rates, stand and site characteristics and management strategies, it is not possible to accurately estimate total transfers of fertiliser nutrients from plantations in Australia. However, the figures from Hopmans and Bren (Hopmans & Bren, 2007) and Forsyth *et al.* (Forsyth *et al.*, 2006) provide in indication of the potential upper and lower limits of leaching of nitrogen (0.9%-3.9%) and phosphorus (0.7%-2.4%). These figures are used in the following section to provide an indication of leaching losses from fertiliser based on the amounts applied across Australia.

5. CURRENT FERTILISER USAGE IN PLANTATION FORESTRY

5.1 Methodology

5.1.1 Survey method

To review current fertiliser usage and strategies in forest plantations in Australia, major forest owners were surveyed across the country. The survey encompassed the period 2002-06 and covered the following information:

- general plantation information (areas, rotation length, growth rates, rainfall and key nutrient deficiencies),
- types and rates of fertiliser applied at different periods during the rotation,
- areas fertilised,
- costs of fertiliser and application,
- application methods,
- criteria and methods used to select sites for fertiliser application,
- estimated accuracy of selection method,
- estimated average responses, and
- key considerations used in fertiliser programs.

Four different rotation stages were selected for both hardwood and softwood plantations. These were establishment, young, mid-rotation and later age. Because of the different rotation lengths used for pulpwood (typically hardwood plantations) and sawlog regimes (typically softwood plantations); different age classes were specified for the two plantation types as follows:

Rotation Stage	*Hardwood*	*Softwood*
Establishment:	0 years	0 years
Young:	1-3 years	1-10 years
Mid-rotation:	4-10 years	11-20 years
Later-age:	>10 years	>20 years

5.1.2 Coverage

Altogether, eight softwood and six hardwood growers or managers responded to the survey covering 784,000 ha of softwood plantation and 391,000 ha of hardwood plantation (Table 6). These areas represented 50% of the total hardwood plantation area (740,000 ha) and 84% of total softwood plantation area (929,000 ha) in 2006 (Table 7). The poorer coverage of hardwoods, which are planted on both former native forest and agricultural land and thus may have diverse fertiliser usage and requirements, indicates that caution should be used in interpreting some of the results.

The different species covered in the survey responses included *E. globulus*, *E. nitens*, *E. dunnii* and *A. mangium* for hardwoods and *P. radiata*, *P. pinaster*, *P. caribaea*, *P. elliottii* and their hybrid for softwoods. Coverage was excellent for the dominant softwood plantation species (*P. radiata*, 92%), and was reasonable for the main hardwood plantation species (E. globulus 56%). The tropical softwood species (*P caribaea* / *P. elliottii*) were also well covered (94%).

Table 6: List of survey respondents showing plantation type, ownership and estimated plantation area.

Respondant	Plantation Type	Ownership	Area (ha)
Auspine Ltd.	Softwood	Private	42,000
ForestrySA	Softwood	Public	91,719
GTFP	Softwood	Private	21,770
HVP	Softwood	Private	140,750
Forestry NSW	Softwood	Public	241,000
Forestry Plantations Qld.[1]	Softwood	Public	180,769
FPC	Softwood	Public	67,000
Rayonier	Softwood	Private	45,000
Forestry NSW	Hardwood	Public	50,000
Forestry Tasmania	Hardwood	Public	50,000
Great Southern Ltd.	Hardwood	Private	72,491
Hansol	Hardwood	Private	15,000
HVP	Hardwood	Private	8,000
ITC	Hardwood	Private	50,000
Timbercorp	Hardwood	Private	95,000
WAPRES	Hardwood	Private	31,000
Total	Softwood		830,008
	Hardwood		371,491
	Total		1,201,499

[1]Includes 45,575 ha of *A. cunninghamii*

Table 7: Areas covered by the survey, total areas in Australia and % coverage for the different hardwood and softwood plantation species. Survey areas are based on estimates of respondents and total areas are based on National Plantation Inventory data (Parsons *et al.*, 2006).

Type	Species	Survey Area (ha)	Total Area (ha)	Coverage
Hardwood				
	E. globulus	252,812	454,095	56%
	E. nitens	51,017	142,943	36%
	E. dunnii	4,000	24,170	17%
	E. spp.	54,071	86,307	63%
	A. mangium	9,591	26,000	37%
	Other	0	6,646	0%
	Total hardwoods	371,491	740,161	50%
Softwood				
	P. radiata	624,239	740,547	84%
	P. pinaster	25000	44,195	57%
	P. caribaea/P. elliottii	135,194	144,103	94%
	A. cunninghammii	45,575	45,575	100%
	Other	0	15,614	0%
	Total softwoods	830,008	990,034	84%
Total		1,201,499	1,730,195	69%

5.1.3 Calculations

Amounts and rates of application of individual nutrients were calculated from the different fertiliser forms applied and their elemental analysis as provided by survey respondents. Where elemental analysis data were lacking or incomplete, data from fertiliser suppliers was used (eg. Incitec, 2003). Elemental analyses of the major fertiliser forms are shown in Table 8. Rates of application of each element were expressed both in terms of the total plantation area and the area actually fertilised. Where multiple fertiliser forms containing similar nutrients were used over the same plantation age class, it was assumed that these were applied to different areas unless otherwise specified (eg. where a DAP urea mix was used).

To estimate average rates of application per area fertilised, rates of fertiliser use were weighted by the area fertilised by each survey respondent. Similarly, average fertiliser usage across the total estate was waited by the total plantation area of each respondent. For estimating rates of application at different stages of the rotation (i.e. establishment, young, mid-rotation or later age), amounts were weighted by the area fertilised at each rotation stage. Weighted averages and standard deviations were calculated as follows:

$$\bar{a} = \frac{w_1 * a_1 + w_2 * a_2 + \ldots\ldots + w_i * a_i}{w_1 + w_2 + \ldots\ldots + w_i}$$

$$SD^2 = \frac{w_1 * (a_1 - \bar{a})^2 + w_2 * (a_2 - \bar{a})^2 + \ldots\ldots + w_i * (a_i - \bar{a})^2}{w_1 + w_2 + \ldots\ldots + w_i}$$

where:

a1, a2,…ai are the average rates of application of each fertiliser form or nutrient by each respondent (i),

w1, w2,…wi are the weighting factors (total plantation areas or to areas fertilised) by each respondent,

ā is the weighted average, and

SD^2 is the weighted variance of the mean.

Where separate data for different species or regions was provided by a single respondent these were considered to comprise separate responses. Thus, in total there were 15 samples for softwood plantations and 14 separate samples for hardwood fertiliser use. Costs of fertiliser and application were based on information provided by survey respondents. These were expressed as annual amounts per ha fertilised and amounts per total plantation area using the same method as for fertiliser amounts.

To estimate total amounts of different fertiliser forms and elements applied, total areas fertilised and total dollars spent in fertilising hardwood and softwood plantations across Australia, the rates per ha of plantation were multiplied by the total areas of hardwood and softwood plantations (Table 7).

Average rainfall, growth rates and rotation lengths for hardwood and softwood plantations were provided by survey respondents and were weighted according to total plantation area. Some non-numeric data such as site fertility and estimated accuracy of site selection were first converted to indices based on rankings from 1-10 and then averaged across respondents, again weighted either by the area fertilised (for estimated accuracy) or total plantation area (for site fertility). Other non-numeric data included key nutrient deficiencies, methods of site selection and application methods. This data was expressed in terms of the proportion of responses (with different plantation species managed by a single respondent considered to be different responses) that used each method or reported a particular nutrient deficiency.

Table 8: Elemental analysis of major fertiliser types used in plantation forestry.

Chemical Name	Fertiliser name	Analysis										Source
		N %	P %	K %	S %	Ca %	Zn %	Cu %	B %	Mg %	Mn %	
Ammonium sulphate	Sulphate of ammonia	20.5	-	-	24.0	-	-	-	-	-	-	Incitec (2003)
Calcium ammonium nitrate	Cal-am	27.0	-	-	-	8.0	-	-	-	-	-	Incitec (2003)
Copper sulphate	Copper oxy sulphate	-	-	-	2.5	-	-	25.0	-	-	-	Incitec (2003)
Diammonium phosphate	DAP	18.0	20.0	-	1.6	-	-	-	-	-	-	Incitec (2003)
Magnesium sulphate	Magnesium sulphate	-	-	-	12.4	-	-	-	-	9.6	-	Incitec (2003)
Manganese sulphate	Manganese sulphate	-	-	-	18.0	-	-	-	-	-	31.0	Incitec (2003)
Mono-ammonium phosphate	MAP	10.0	21.9	-	1.5	-	-	-	-	-	-	Incitec (2003)
Potassium chloride	Muriate of potash	-	-	50.0	-	-	-	-	-	-	-	Incitec (2003)
Potassium sulphate	Sulphate of potash	-	-	41.0	18.0	-	-	-	-	-	-	Incitec (2003)
Super phosphate	Super	-	8.8	-	11.0	20.0	-	-	-	-	-	Incitec (2003)
Triple super phosphate	PPP, Trifos	-	20.7	-	1.0	15.0	-	-	-	-	-	Incitec (2003)
Sodium calcium borate	Ulexite	-	-	-	1.2	9.9	-	-	15.0	0.6		Paton (2008)
Urea	Urea Granular	46.0	-	-	-	-	-	-	-	-	-	Incitec (2003)
Urea Sulphur Coat	Gold N, SCU	41.0	-	-	-	-	-	-	-	-	-	Hifert (2008)
Zinc sulphate hepta-hydrate	Zinc sulphate	-	-	-	10.5	-	22.0	-	-	-	-	Incitec (2003)

5.2 Results

5.2.1 Reported deficiencies

Across both hardwood and softwood plantations, nitrogen and phosphorus were the most commonly noted deficiencies among respondents. For hardwood plantations, 85% of respondents reported both nitrogen and phosphorus as being deficient. For softwood plantations, all respondents reported phosphorus as being deficient while 70% reported nitrogen as being deficient. However, it should be noted that these figures give no indication of the frequency of these deficiencies across the plantation estate. Other major deficiencies in hardwood plantations were zinc (45% of respondents), potassium (40% of respondents), copper (20% of respondents) and sulphur (15% of respondents). In softwood plantations, copper was reported as deficient in 40% of cases, zinc and boron in 35% of cases and potassium in 30% of cases. Respondents (15%) also reported deficiencies in sulphur, magnesium or manganese.

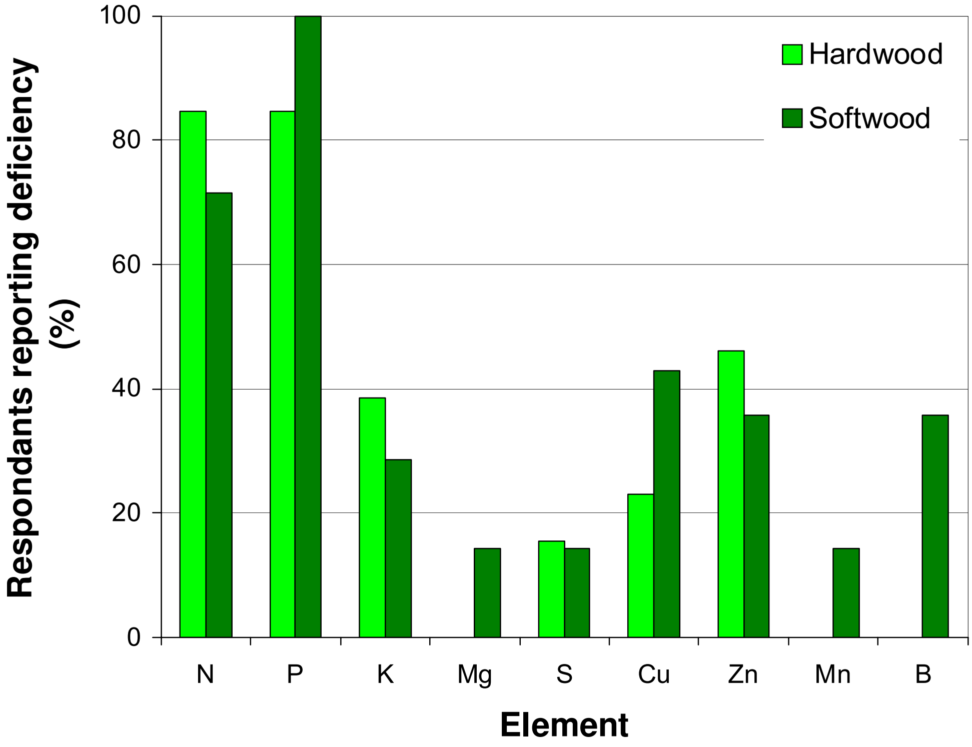

Figure 2: Reported nutrient deficiencies for hardwood and softwood plantations expressed in terms of percent of respondents.

5.2.2 Types and amounts of nutrients applied

Each year, a total of approximately 173,000 ha hardwood plantations and 84,000 ha softwood plantations are fertilised. The main macro-elements applied across hardwood plantations included nitrogen, phosphorus, potassium and sulphur. In terms of total amount applied across the national estate, nitrogen was the main nutrient applied with a total of 10,400 t $year^{-1}$ (Table 9). A total of 4,300 t $year^{-1}$ phosphorus, 3,800 t $year^{-1}$ sulphur and 2,500 t $year^{-1}$ potassium were also applied. Calcium was also applied in association with phosphorus as triple super or super phosphate and in NPK mixes. However, concentrations of calcium in NPK mixes were not specified. Because it was not considered a limiting nutrient by any of the respondents, calcium application is not reported here. Major micro-nutrients applied across hardwood plantations included copper, zinc, manganese and boron. Estimated total amounts of these elements were 120 t $year^{-1}$ for copper, 71 t $year^{-1}$ zinc, 33 t $year^{-1}$ manganese and 29 t $year^{-1}$ boron.

Altogether, areas of hardwood plantations fertilised with macro-nutrients varied from 148,000 ha for nitrogen to 20,000 ha for magnesium (Figure 3a). For major trace elements 65,000 ha were fertilised with copper and 55,000 ha were fertilised with zinc. Across softwood plantations, areas fertilised ranged from 45,000 ha for nitrogen or sulphur to just 200 ha for magnesium (Figure 3b).

Despite the area of softwood plantations being 25% greater than that of hardwood plantations, the total amounts of most nutrients applied were around half those used in hardwood plantations. As for hardwood plantations, the dominant nutrient used in softwood plantations was nitrogen with a total of 3,300 t $year^{-1}$ applied across Australia. Other important macro-elements included phosphorus (1,500 t $year^{-1}$) and sulphur (1,200 t $year^{-1}$). Relatively little potassium and virtually no magnesium were applied. Major micronutrients included copper (19 t $year^{-1}$), zinc (12 t $year^{-1}$) and boron (13 t $year^{-1}$).

Table 9: Total amounts, rates and types of fertiliser applied in hardwood and softwood plantations. Averages (Avg.) and standard deviations (in brackets) are weighted by area of plantation fertilised with each element for each respondent with "n" indicating the number of respondents. Pr indicates the probability that the rates of application are different between the types of plantations. NA indicates no data are available.

Element	Total (t/y)			Application Rate (kg/ha)						
	Hardwood	Softwood	Total	Hardwood			Softwood			*Pr*
				Avg.		*n*	Avg.		*n*	
N	7,144	3,260	10,404	48	*(26)*	14	72	*(30)*	15	***0.029***
P	2,789	1,524	4,313	25	*(17)*	14	42	*(15)*	15	***0.007***
K	2,089	448	2,537	26	*(20)*	10	34	*9*	6	*0.374*
Mg	77.9	0.7	78.6	1.5	*NA*	2	7.3	*NA*	1	*NA*
S	2,613	1,178	3,791	20	*(16)*	14	26	*(19)*	15	*0.381*
Cu	101.7	18.5	120.2	1.6	*(1.7)*	10	1.2	*(2.0)*	8	*0.681*
Zn	58.6	12.4	70.9	1.1	*(0.9)*	7	0.8	*(0.9)*	8	*0.641*
Mn	32.1	1.0	33.2	1.6	*(1.0)*	1	3.3	*(0.0)*	1	*NA*
B	15.7	13.4	29.1	2.1	*NA*	1	8.4	*(1.0)*	4	*NA*

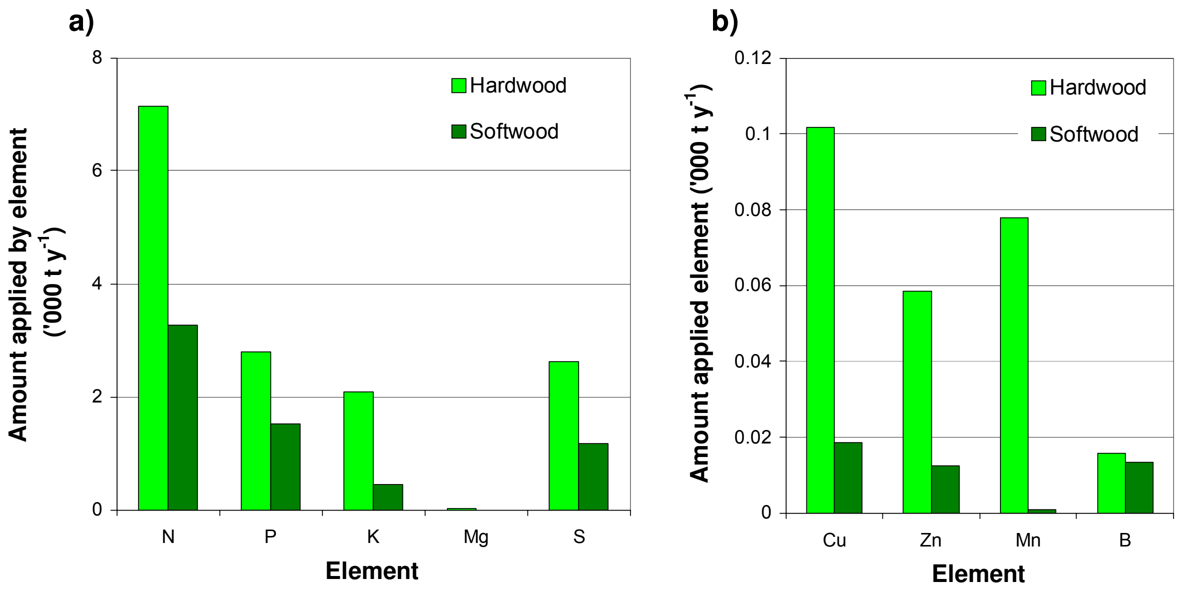

Figure 3: Estimated total amounts of a) macro – and b) micro - nutrients applied in hardwood and softwood plantations across Australia by element.

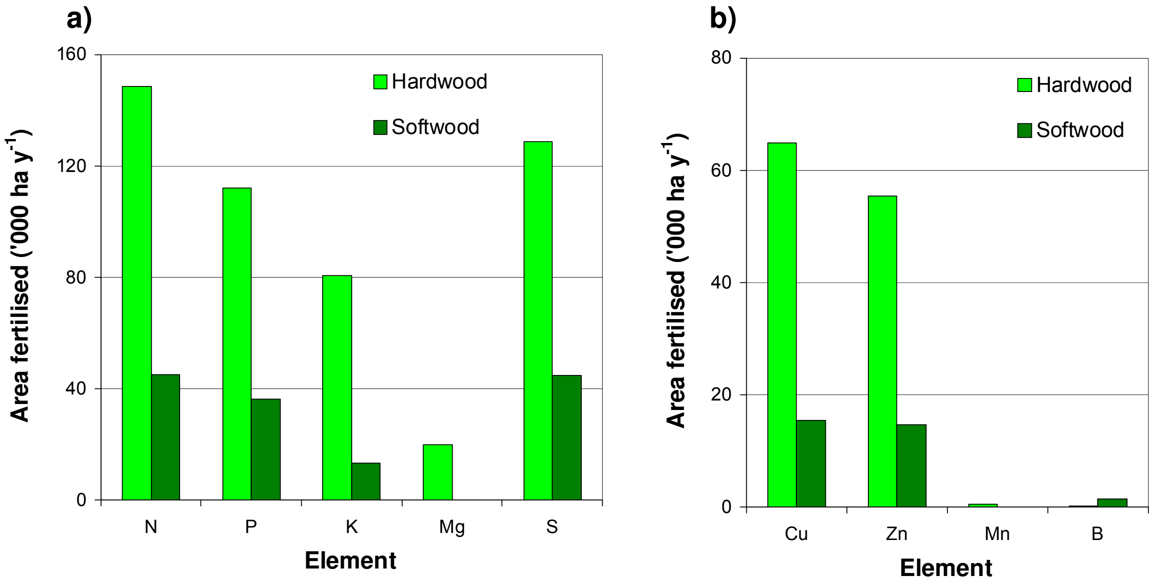

Figure 4: Total areas fertilised with a) macro – and b) micro – nutrients across hardwood and softwood plantations across Australia by element.

5.2.3 Rates of application

In contrast to total fertiliser usage, rates of application (expressed in terms of the area fertilised with individual elements) of macro nutrients tended to be greater for softwood plantations than for hardwood plantations (Table 9). The average rate of nitrogen application was 48 kg ha^{-1} (SD 26 kg ha^{-1}) for hardwoods compared with 72 kg ha^{-1} (SD 30 kg ha^{-1}) for softwoods. Similarly, rates of application of phosphorus, potassium and sulphur were 25, 26 and 20 kg ha^{-1} respectively for hardwood plantations compared with 42 kg ha^{-1}, 34 kg ha^{-1} and 26 kg ha^{-1} for softwood plantations. However, only the rates of nitrogen and phosphorus application differed significantly (Pr < 0.005).

Rates of application of most micro-nutrients were similar for the two plantation types. Application rates of copper, zinc and manganese ranged from 1.1 to 1.6 kg ha^{-1} in hardwood plantations compared with 0.8 to 3.3 kg ha^{-1} for softwood plantations. However, application rates of boron were four times greater in softwood plantations (8.4 kg ha^{-1}) compared with hardwood plantations (2.1 kg ha^{-1}).

In terms of the proportion of the total plantation estate fertilised in any one year, fertiliser usage was more widespread in hardwood plantations than softwood plantations. On average, between 10 and 20% of the total hardwood estate was fertilised with nitrogen, phosphorus, potassium or sulphur while 3-10% was fertilised with magnesium, copper or zinc (Figure 5). In contrast nitrogen, phosphorus and sulphur were applied across just 4-5% of the total softwood estate and other elements (potassium, magnesium, copper and zinc were applied across 0-2% of the estate. However, because of high variability, only the differences in nitrogen and sulphur use were significant ($P < 0.005$).

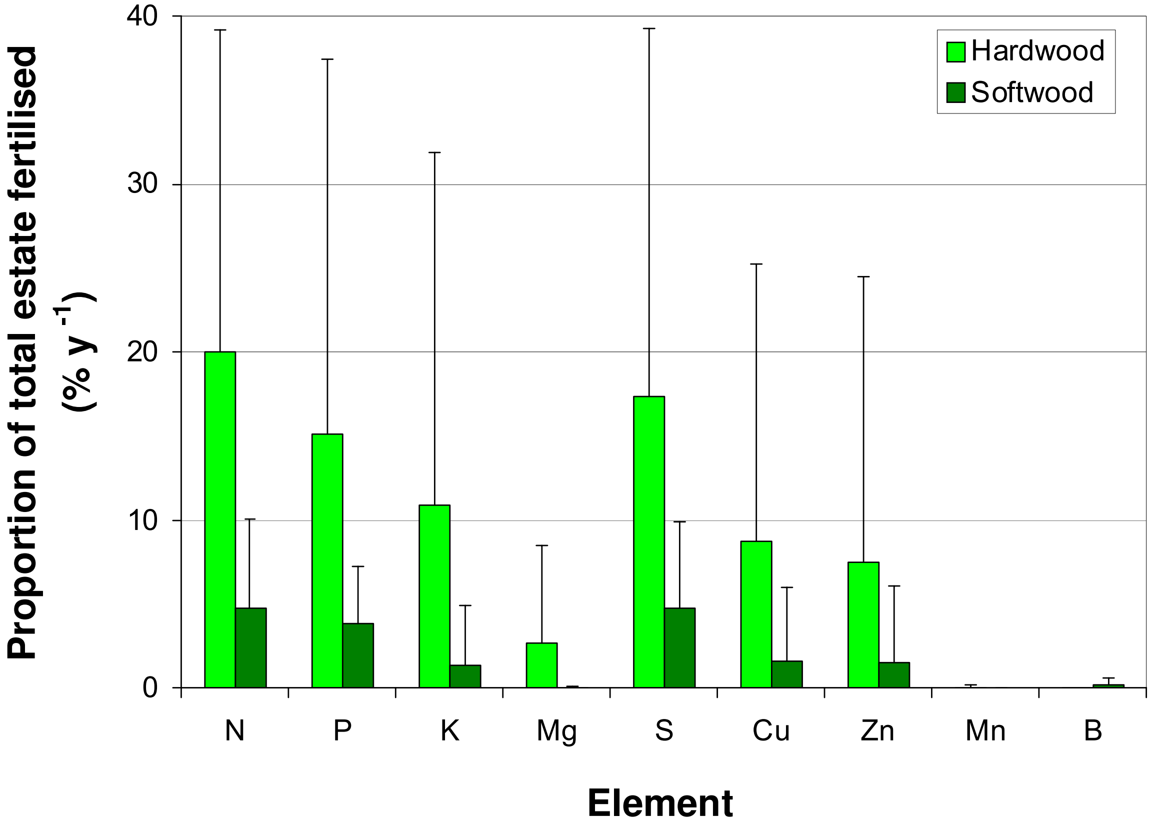

Figure 5: Proportion of total estate fertilised with different elements. Error bars represent standard deviations. Averages and standard deviations are weighted by area of plantation fertilised with each element for each respondent.

As a result of the larger amounts of fertiliser used across hardwood plantations combined with the smaller plantation area, rates of fertiliser use expressed in terms of total plantation area were generally three to four times those for softwood plantations (Figure 6). However, again, because of the large variation in fertiliser usage between different growers, only the difference in nitrogen application (9.7 kg ha^{-1} $year^{-1}$ for hardwood plantations cv. 3.5 kg ha^{-1} $year^{-1}$ for softwoods) was significant (*P* = 0.041). Rates of phosphorus, potassium and sulphur use ranged from 2.8 to 3.8 kg ha^{-1} $year^{-1}$ for hardwood plantations and from 0.5 to 1.6 kg ha^{-1} $year^{-1}$ for softwood plantations. Rates of use of micronutrients (copper, zinc, manganese and boron) across the total estate varied from 0.02 to 0.14 kg ha^{-1} $year^{-1}$ for hardwood plantations and from 0 to 0.02 kg ha^{-1} $year^{-1}$ for softwood plantations.

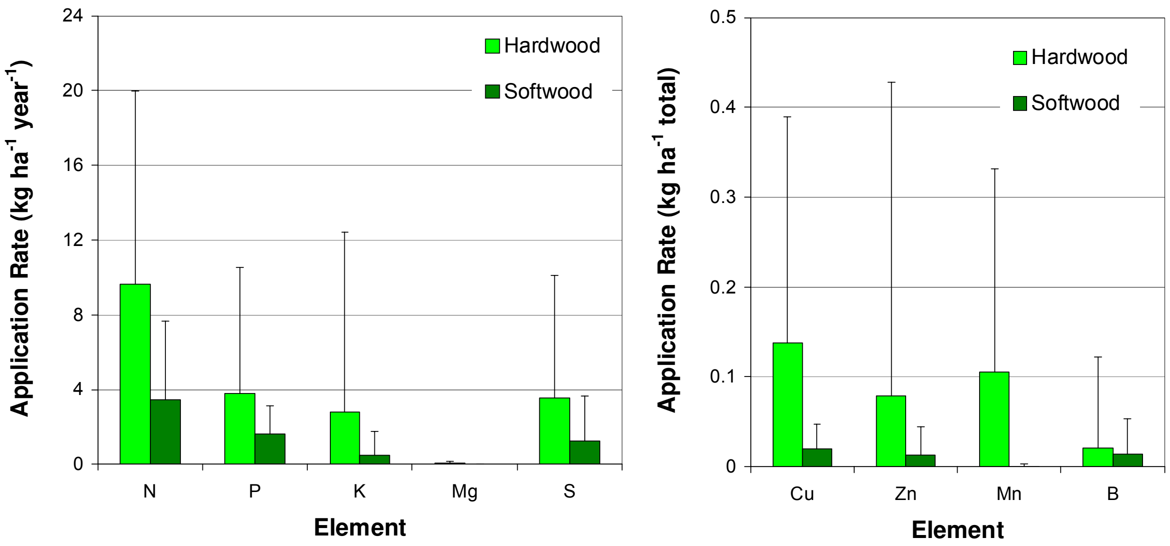

Figure 6: Rate of fertiliser usage relative to total plantation estate area. Error bars represent standard deviations. Averages and standard deviations are weighted by area of plantation fertilised with each element for each respondent.

5.2.4 Forms of fertiliser applied

By far the most common fertiliser forms applied across hardwood plantations were NPKS blends with or without trace elements (Figure 7). These accounted for just over half of the total amount of fertiliser used across the hardwood estate. In contrast, they accounted for only 20% of total fertiliser usage across softwood plantations. The amounts of urea (3,700 t year^{-1}) and DAP (3,400 t year^{-1}) were the same for both hardwood and softwood plantations. However, while urea and DAP represented just 20% of total fertiliser usage in hardwood plantations, they made up almost half the total fertiliser applied to softwood plantations. Other fertiliser forms commonly used in hardwood plantations included sulphur coated urea (2,300 t year^{-1} or 6% of the total), ammonium sulphate (3% of the total), and blends of NPS, PS and PKS + trace elements (15% of the total). Apart from urea and DAP, NPKS blends were the most commonly applied form used in softwood plantations (16% of total). Other major forms used included MAP (5% of the total), triple super phosphate (5% of the total), and various blends of nitrogen, phosphorus, potassium or sulphur with or without trace elements (12% of the total).

Minor fertiliser forms used included single super phosphate, potassium chloride and manganese sulphate (hardwood plantations only), potassium sulphate (softwood plantations only), copper sulphate, zinc sulphate, manganese sulphate and ulexite (Figure 8). Apart from copper sulphate and zinc sulphate, all fertilisers were applied in solid form.

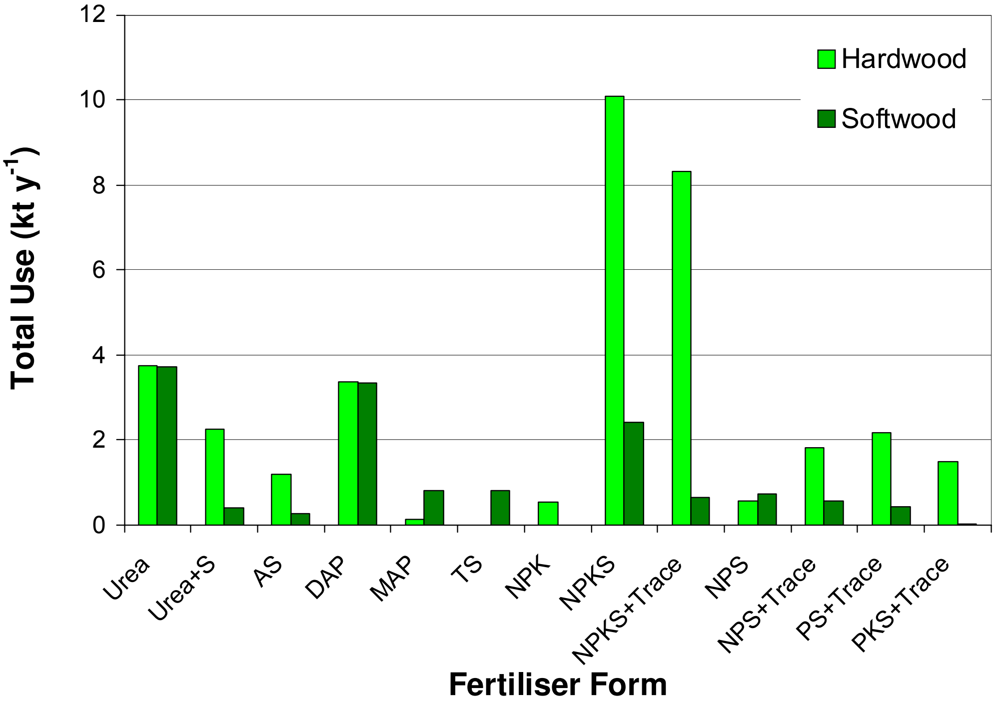

Figure 7: Total use of major fertiliser forms in hardwood and softwood plantations across Australia. Abbreviations are as follows (not all are in this figure – some are in the next): Urea+S - sulphur coated urea; AS – ammonium sulphate, DAP – diammonium phosphate; MAP – mono-ammonium phosphate; TS – triple super phosphate; Super – single super phosphate; K_2SO_4 – potassium sulphate; KCl – potassium chloride; NPKS – various blends of nitrogen, phosphorus, potassium and sulphur; trace – trace elements (eg. copper, zinc, manganese, boron or molybdenum).

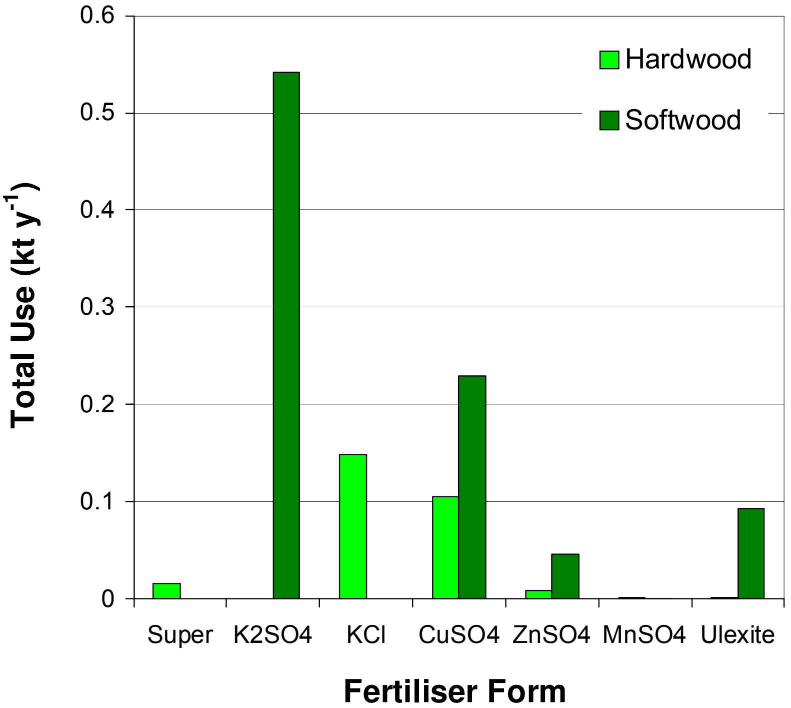

Figure 8: Total use of minor fertiliser forms in hardwood and softwood plantations across Australia. Super – single super phosphate.

The different nutrients applied can also be expressed in terms of the form of fertiliser used. This is most useful for nitrogen and phosphorus, which are available in a range of different forms. In hardwood plantations, most nitrogen was applied as NPKS blends of varying nutrient concentrations (Figure 9). The next most common forms were urea (24%), sulphur coated urea (13%) and DAP (8%). In softwood plantations 52% of nitrogen was applied as urea, with 20% as NPKS blends and 18% as DAP.

For phosphorus, 75% of phosphorus applied in hardwood plantations was in the form of NPKS, NPK or PS blends while virtually all the remainder was applied as DAP. In contrast, in softwood plantations, only 33% was applied as NPK or PKS blends while 44% was applied as DAP either alone or with urea. Of the remaining 23%, about half was applied as MAP with the other half as triple super phosphate.

Different fertiliser forms differ in their uptake efficiency as well as cost. For example, urea has traditionally been favoured in forestry because it is a relatively cost-effective form of N; it has a relative low cost per unit of nitrogen, and its high nitrogen content (46%) minimises application costs. However, nitrogen volatilisation losses from urea may negate this cost advantage in some stands conditions (eg. mid-rotation softwood plantations). In contrast to nitrogen, experiments with different forms of phosphorus showed no difference in response to DAP compared with triple super phosphate (May *et al.*, 2009). Thus, the main difference in these forms is related to cost and requirements for nitrogen plus phosphorus (as DAP contains both elements) compared to phosphorus alone (as with triple super phosphate). Rock phosphate has been suggested as a possible release form of phosphorus (Will & Hunter, 1983). Although initial results from trials in Australia showed no benefit of rock phosphate as opposed to ordinary super phosphate, longer-term experiments showed a significant increase in foliar phosphorus concentrations for the latter (Gentle *et al.*, 1986; Turner *et al.*, 2002). However, different sources of rock phosphate vary dramatically in their solubility and content of available phosphorus. Furthermore, there could be an interaction with soil type as rock phosphates are less soluble (and thus the availability of P lower) in alkaline to neutral soils than in acidic soils.

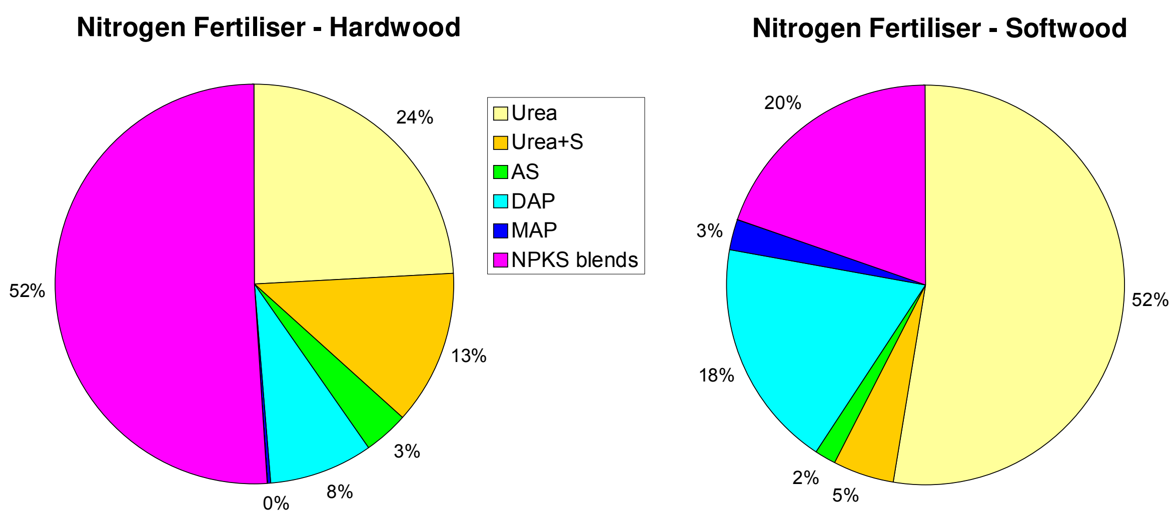

Figure 9: Proportion of different forms of nitrogen fertiliser used in softwood and hardwood plantations by mass of elemental nitrogen.

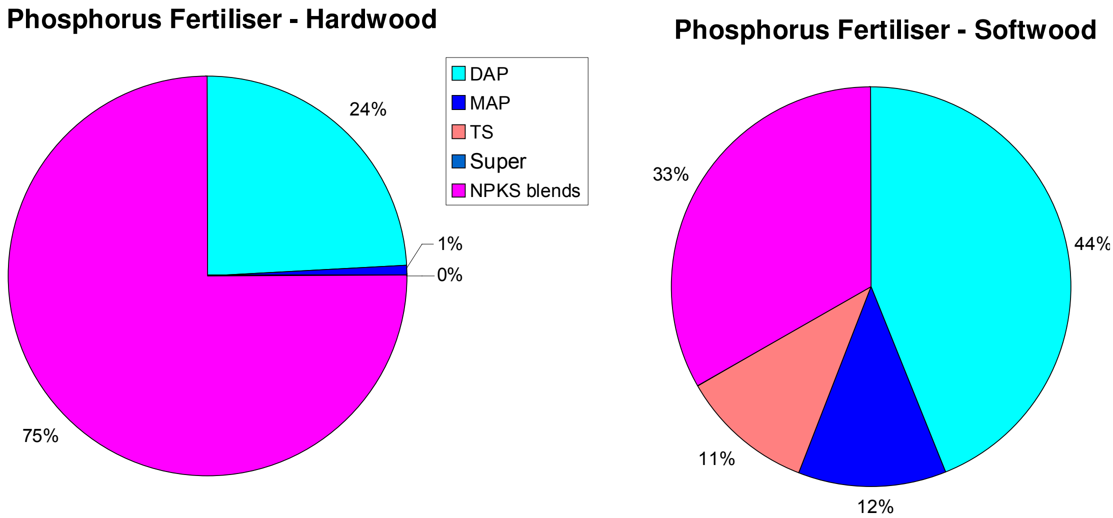

Figure 10: Proportion of different forms of phosphorus fertiliser used in softwood and hardwood plantations by mass of elemental phosphorus.

5.2.5 Fertiliser use at different stages of the rotation

Fertiliser application across hardwood plantations was approximately equally distributed, based on the area fertilised, across newly established stands (within the first year of planting), young plantations (1-2 years) and mid-rotation stands (3-11 years, Figure 11). However, across softwood plantations, there was a small bias to mid-rotation stands (11-20 years) with an average of 2.9% of the total estate fertilised compared with 2.3-2.4% for newly established and young stands (1-10 years) and 0.9% for later aged stands (> 20 years).

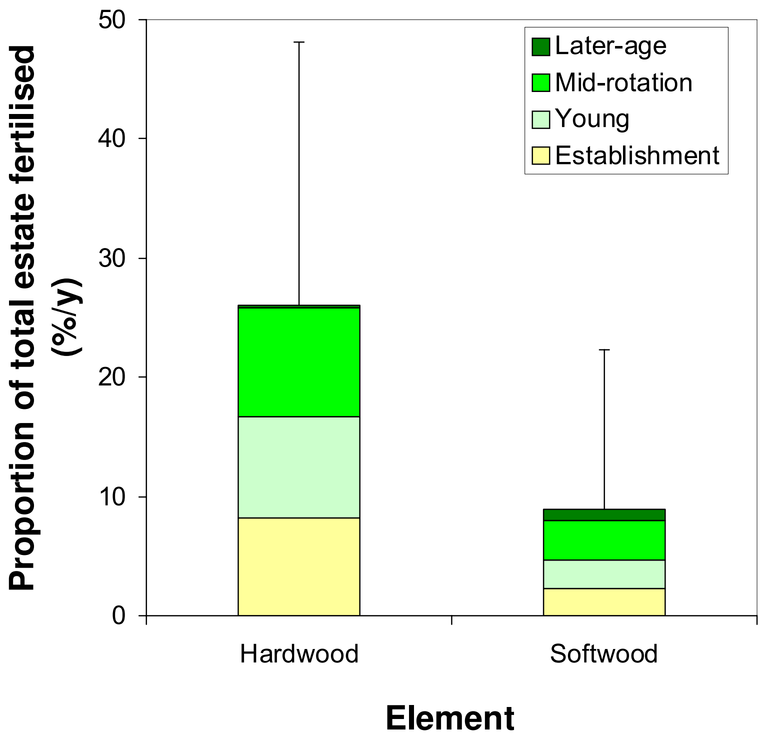

Figure 11: Average proportion of total estate fertilised for hardwood and softwood plantations. Error bars represent standard deviations. Averages and standard deviations are weighted by total plantation area of each respondent.

The amounts of different elements applied at different rotation stages varied with plantation type and by nutrient. In hardwood plantations, 52% of all nitrogen, 76% of magnesium, 56% of copper, 66% of manganese and 68% of boron was applied at the mid-rotation stage. Application of phosphorus and sulphur was fairly evenly distributed across different rotation stages, while potassium and zinc were primarily applied at establishment (Table 10). In softwood plantations, nitrogen was mostly applied to mid-rotation and later age (> 20 year old) stands, with 45% applied to those aged 11-20 years and 29% to older stands. Potassium and sulphur were mostly applied to young or mid-rotation stands where over 80% of the total was used. Phosphorus use was fairly evenly distributed between establishment, young and mid-rotation stands. However zinc, magnesium, manganese and boron were primarily applied to young stands, while copper was mostly applied at establishment (40%) or to stands aged 1-10 years (27%).

Table 10: Total amounts of different elements applied at different rotation stages in hardwood and softwood plantations.

	Hardwood (t/y)				Softwood (t/y)			
Age (yrs)	**0**	**1-2**	**3-11**	**>11**	**0**	**1-10**	**11-20**	**>20**
N	1867	1489	3734	54	124	646	1633	856
P	939	808	1030	11	396	483	504	142
K	1161	467	449	11	59	150	206	32
Mg	13.5	5.1	59	0	0.0	0.7	0.0	0.0
S	702	944	927	40	54	511	466	148
Cu	42.1	2.1	57	0	7.4	5.0	3.8	2.4
Zn	31.6	19.2	8	0	0.9	9.5	1.4	0.6
Mn	5.5	4.8	22	0	0.0	1.0	0.0	0.0
B	3.2	2.2	10	0	4.3	9.1	0.0	0.0

Rates of fertiliser use differed for different rotation stages and nutrients (Table 11). Rates of nitrogen application increased with stand age in both hardwood and softwood plantations from 16-33 kg ha^{-1} at establishment to 52-87 kg ha^{-1} for mid-rotation stands. Highest rates were used in softwood plantations aged >20 years (104 kg ha^{-1}). Although the rate of potassium application increased from 16 to 84 kg ha^{-1} with increasing stand age in softwood plantations, it decreased from 30 to 15 kg ha^{-1} in hardwood plantations. Rates of phosphorus application were similar for all plantation stages in both hardwoods and softwoods.

Importantly, previous work in the Green Triangle has indicated that, for urea, the rate of fertiliser application has a critical effect on response. For example, average growth responses across two mid-rotation sites to urea applied at a rate of 100 kg ha^{-1} were only one tenth of those to 200 kg ha^{-1} (May *et al.*, 2009). This difference was suggested to be due to the differing effect of application rate on losses of nitrogen to volatilisation and immobilisation in the soil and forest floor. At low rates of application, volatilisation losses are relatively small, but most of the remaining nitrogen is immobilised in the soil, resulting in low levels of nitrogen availability for the trees (Figure 12). As the rate of application increases, the proportion of nitrogen immobilised declines, but the proportion lost through volatilisation increases due to the increasing effect of the fertiliser on soil pH (Carrier & Bernier, 1971). Thus, it was estimated that there was approximately three times more nitrogen available for uptake by trees after applying 200 kg N ha^{-1} compared with applying 100 kg N ha^{-1}.

In contrast, there was only a 30% reduction in response to nitrogen applied as ammonium nitrate at a rate of 100 kg ha^{-1} compared with 200 kg ha^{-1} indicating that a much larger proportion of nitrogen remained available for plant uptake. The differences between urea and other nitrogen forms are not expected to be so severe in plantations with smaller or less dense litter layers such as hardwood or young softwood plantations.

Table 11: Average application rates of different elements at different stages of the rotation in hardwood and softwood plantations. Averages are weighted by the area fertilised with each element by each survey respondent. Numbers in brackets are standard deviations of the means.

	Hardwood (kg/ha)								Softwood (kg/ha)							
Age (yrs)	0		1-2		3-11		>11		0		1-10		11-20		>20	
N	33	*(26)*	43	*(33)*	52	*(27)*	40	*(11)*	16	*(8.1)*	63	*(23)*	87	*(43)*	104	*(44)*
P	17	*(10)*	27	*(18)*	26	*(25)*	20	-	30	*(15)*	56	*(19)*	46	*(21)*	41	*(21)*
K	30	*(27)*	26	*(14)*	15	*(6.8)*	20	-	16	*(17)*	36	*(9.5)*	41	*(11)*	84	-
Mg	1.5	-	-	-	-	-	-	-	-	-	7.3	-	-	-	-	-
S	13	*(17)*	25	*(16)*	19	*(18)*	39	-	3	*(2.6)*	52	*(14)*	35	*(23)*	31	*(31)*
Cu	1.6	*(0.6)*	0.1	*(1.0)*	2.2	*(2.8)*	-	-	1.9	*(2.3)*	0.7	*(0.6)*	0.7	*(2.0)*	7.1	*(2.4)*
Zn	1.5	*(0.7)*	0.9	*(0.7)*	0.3	*(0.3)*	-	-	0.4	*(0.4)*	1.3	*(1.1)*	0.3	-	4.0	-
Mn	0.3	*(1.5)*	1.0	*(2.0)*	0.9	*(1.4)*	-	-	-	-	0.3	*(3.0)*	-	-	-	-
B	2.1	-	-	-	-	-	-	-	12.2	-	7.3	*(1.3)*	-	-	-	-

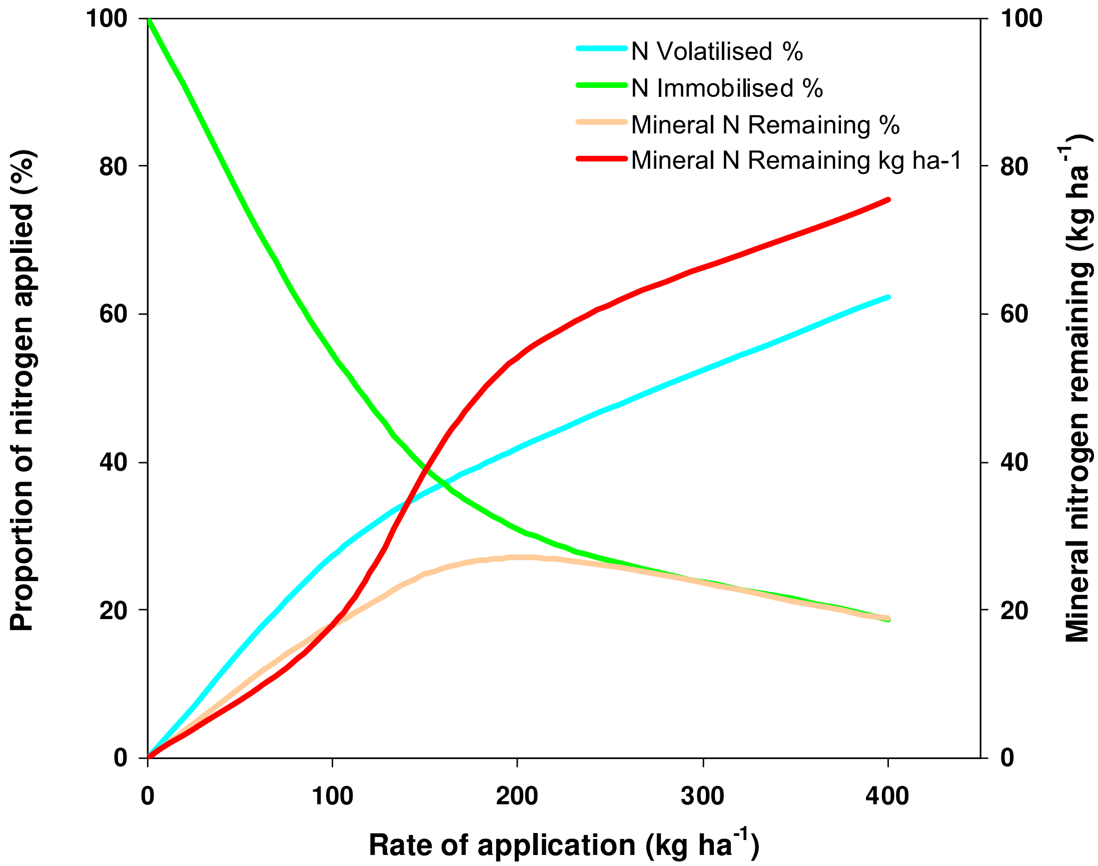

Figure 12: Relationship between rate of nitrogen application and immobilization and volatilization losses from urea applied to thinned radiata pine plantations. Data from May *et al.* (2009).

5.3 Key factors in fertiliser decisions

Forest growers were asked to rank a range of factors including nutrient deficiency, profitability, cost of fertiliser, new land for planting, wood price, wood quality and market demand according to their importance in influencing fertiliser decisions. For both hardwood and softwood growers, the most important factor was amelioration of nutrient deficiencies with an average ranking of 8 out of 10 (Figure 13). This factor was followed by increasing profitability, need to increase wood production and fertiliser cost with average rankings of 6-7. Moderately influential factors for softwood growers included the quality, market demand, wood price, environmental considerations, and maintenance of sustained wood yield. In contrast, only wood price and environmental considerations were important considerations for most hardwood growers. Land price was put down as the least important consideration for fertiliser decisions for both hardwood and softwood growers.

These rankings, though crude, provide an interesting insight into the key drivers behind fertiliser decisions and their differences between hardwood and softwood plantations. For example, although profitability of fertiliser use was an important driver, amelioration of nutrient deficiencies remains the key concern of most growers. Also, it is the cost of fertiliser (the input) rather than the value of wood (the output) that is seen as most important for influencing profitability. This result is due to the relatively long time frame between fertiliser application and harvest of the wood, combined with the large fluctuations in fertiliser cost compared with wood values. The difference in the ranking of market demand and wood quality for hardwood compared with softwood growers is probably a result of the need for the latter to provide individual sawmills with the amount and type of softwood product required, the potentially large impact of fertiliser on sawlog characteristics compared with pulping characteristics, and the presence of domestic markets. The low ranking given to land price was unexpected as this is often cited as a key driver for using fertiliser to increase the production of an existing estate instead of purchasing land for new plantations (Cromer *et al.*, 1977).

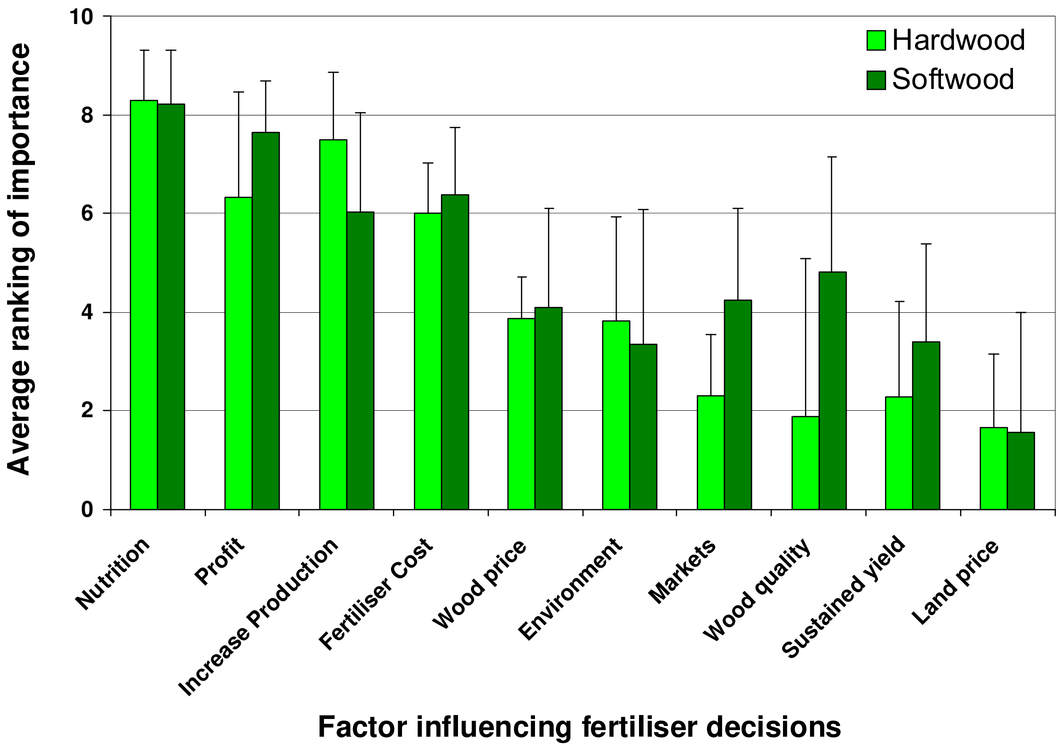

Figure 13: Average ranking of relative importance of different objectives in fertiliser usage across hardwood and softwood plantations. Error bars represent standard deviations. Averages and standard deviations are weighted by total plantation area of each respondent.

5.4 Site selection methods for fertiliser application

A number of key diagnostic properties are used to identify potentially responsive sites to fertiliser application or to predict growth response. These include analysis of nutrients in foliage, analysis of nutrients and their availability in soil, soil classification or description, and stand growth rate. Other factors include rainfall, stand age and location. Growers provided information on the major selection methods used for stands at different stages of the rotation.

In hardwood plantations, soil analysis and soil characterization were the primary methods used for selecting which newly established stands to fertilise and what to apply (Figure 14). In contrast, foliar analysis, sometimes in conjunction with soil characterization or growth monitoring was the main method for selecting young stands. Growth monitoring, often in combination with foliar analysis or, less frequently, soil characterisation, was the main method used for selecting mid-rotation or later-age stands. Other methods used included, leaf area assessment, forest health assessment, or blanket application at certain plantation stages.

In softwood plantations, soil characterization was the predominant method used to select sites to fertilise at establishment, although, sometimes, growth of previous rotation was also used. In established stands, foliar analysis was the primary method for deciding which to fertilise and what to apply. In young stands, soil characterization was main alternative method, while, in mid-rotation and later age stands, soil analysis and growth monitoring were often used instead of or in conjunction with foliar analysis. Other diagnostic and selection methods included leaf area assessment, litter analysis and forest health assessment.

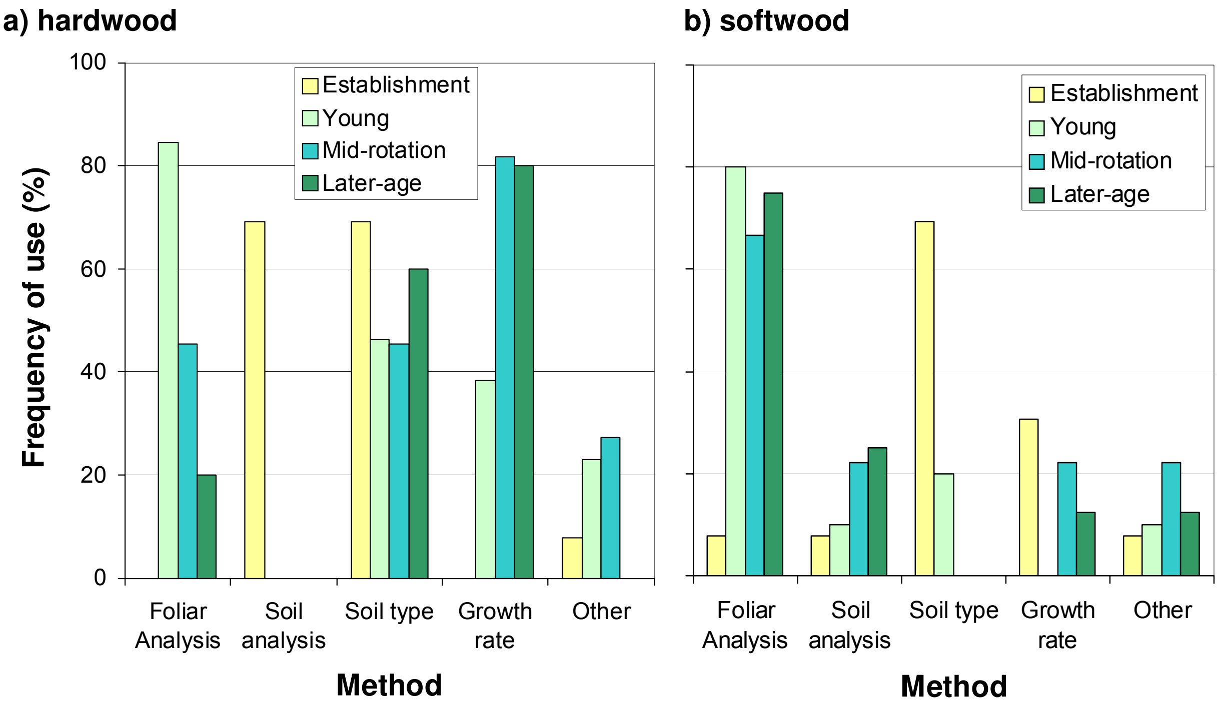

Figure 14: Frequency of use of different methods for selecting potentially responsive sites for fertiliser application at different stages in the rotation for a) hardwood and b) softwood plantations.

Confidence of growers in the accuracy of the various diagnostic or prediction methods for identifying potentially responsive sites was, on the whole reasonably good. On a scale of 1-10 with 0 poor and 10 excellent, average accuracy in hardwood plantations (6.5) was only slightly lower than that in softwood plantations (7.4). However, while estimated accuracy tended to improve with stand age in softwood plantations increasing from 6.9 at establishment to 8.1 in later age stands, it tended to decline with increasing age of hardwood plantations (Figure 15). The lower confidence in predicting responsiveness of older hardwood stands was generally ascribed to the lack of time to assess responsiveness as a result of the generally younger age profile of hardwood stands. In contrast, results from the large number of research trials established over the years in thinned softwood plantations provide a higher degree of confidence in the general range of responses that may be expected from fertilising these stands. However, while there is reasonable confidence in the average response across a plantation estate, responses of individual stands to different fertiliser combinations and forms remain uncertain even in softwood plantations.

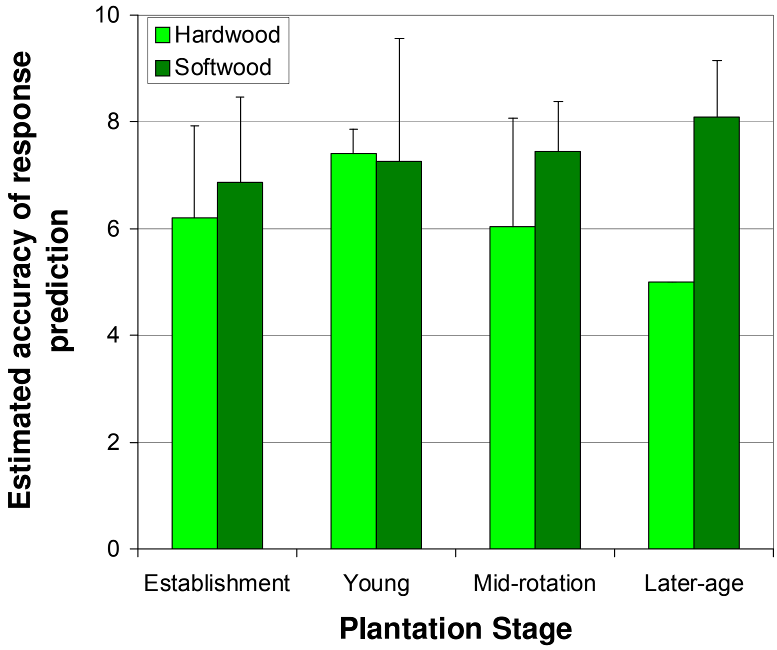

Figure 15: Average estimated accuracy of response prediction criteria across hardwood and softwood plantations with 10 excellent and 0 poor. Error bars represent standard deviations. Averages and standard deviations are weighted by total area fertilised.

5.5 Application methods

At planting, fertiliser is usually applied by hand in spots or bands around seedlings. In established stands, liquid fertiliser (copper, zinc and other trace elements) is sprayed from air using helicopters or small fixed wing aircraft. Solid fertiliser is often applied from air from hoppers attached to helicopters (Figure 16a) or from specialized medium-sized fixed wing aircraft. Solid fertiliser is also applied from the ground as broadcast applications in thinned stands. Ground applications are made using adapted skidders or tractors with attachments (Figure 16b) that are designed to fling the granules into the bays of trees on either side of the thinned 'outrow', down which the vehicle drives.

Application costs were variable depending on the amount and type of fertiliser applied. However, per hectare costs tended to decrease with increasing stand age (Table 12). For hardwood plantations, average cost varied from \$103 ha^{-1} at establishment to \$43 ha^{-1} for mid-rotation stands and were just \$13 ha^{-1} for the few organisations fertilising older hardwood sawlog plantations. Similarly, application costs for softwood plantations decreased from \$82 ha^{-1} at establishment to \$22-40 ha^{-1} for older stands. As a percentage of total cost, application cost comprised 40% of the total cost of fertilizing newly established hardwoods and 66% of the total cost of fertilizing newly established softwoods. This proportion decreased through the rotation to 32% for older hardwoods and to 19%-25% for mid-rotation and later age softwoods. This was a result of higher rates of fertiliser used and the less labour intensive application methods used in established stands.

a) **b)**

Figure 16: Methods of fertiliser application in plantations showing a) helicopter plus hopper used for spreading granular fertiliser in established stands and modified skidder with hopper and rotor (circled) which flings fertiliser into adjacent rows of trees. Photos courtesy of McDermott aviation and ForestrySA.

5.6 Total cost

Expenditure on fertiliser and application varied considerably between growers. Average total cost per hectare fertilised was \$182 for hardwood plantations and \$124 for softwood plantations (Table 13). However, as a result of large variation between growers, this difference was not significant (P = 0.22). This expenditure consisted of an average application cost of \$54 ha^{-1} and an average cost of fertiliser of \$102 ha^{-1}. Thus, cost of application made up about 30% of the total cost of fertiliser use.

Altogether, between 2004 and 2006, an estimated total of \$20 million year^{-1} was spent on fertiliser for hardwood plantations, compared with \$7 million for softwood plantations (Table 13). A further \$11 million year^{-1} was spent on application costs in hardwood plantations and 3.3 million year^{-1} in softwood plantations. Thus, total expenditure on purchasing and applying fertiliser across hardwood and softwood plantations is estimated to be almost \$42 million year^{-1}. On a unit total plantation area basis, the amount spent on fertiliser plus application was \$43 ha^{-1} for hardwood plantations and \$11 ha^{-1} for softwood plantations (Table 13).

In comparison with the value of logs produced from softwood and hardwood plantations between 2004-05 and 2006-07, estimated annual expenditure on fertiliser represents just 1.2% of the total value of softwood production (\$850 million year^{-1}), compared with 14% of the total value of hardwood production (\$227 million year^{-1}, (DPIE, 1998). However, these figures are somewhat misleading as the production from hardwood plantations is expected to increase from an average 3.6 million m^3 year^{-1} (for 2004-05 to 2006-07) to over 14 million m^3 year^{-1} by 2010-2014, while that from softwood plantations is expected to stabilize at around 30 million m^3 from 26.9 million m^3 year^{-1} currently (Parsons *et al.*, 2007). If the total value of log removals increases in line with production, current expenditure on fertiliser will represent around 1.1% of the future production value for softwood plantations and 3.6% of future production value of hardwood plantations.

Table 12: Expenditure on fertiliser and application costs expressed on a per hectare fertilised basis and as estimated total expenditure in hardwood and softwood plantations at different stages of the rotation. Numbers in brackets are standard deviations of means.

Item	Hardwood				Softwood			
Age (yrs)	0	1-2	3-11	>11	0	1-10	11-20	>20
Amount per ha fertilised ($ ha^{-1})								
Fertiliser	153 *(184)*	72 *(90)*	92 *(47)*	26 *(13)*	51 *(33)*	85 *(33)*	97 *(57)*	128 *(54)*
Application	103 *(100)*	34 *(19)*	43 *(12)*	13 *(9)*	82 *(41)*	67 *(41)*	22 *(52)*	40 *(21)*
Total	256 *(230)*	105 *(105)*	135 *(49)*	39 *(22)*	124 *(58)*	119 *(58)*	119 *(89)*	161 *(69)*
Total ($ million y^{-1})								
Fertiliser	9.3	4.5	6.3	0.03	1.1	1.9	3.0	1.1
Application	6.3	2.1	2.9	0.02	1.6	0.7	0.7	0.3
Total	15.6	6.6	9.2	0.05	2.7	2.7	3.7	1.4

There was wide variation in the cost of fertiliser and application on a per hectare basis depending on the type of fertiliser or application method used. For example, trace elements, which are normally applied at a low rate per hectare, cost much less on a per hectare basis compared with macro-nutrients. However, there was a clear trend, terms of the amount spent on fertiliser alone, of increasing expenditure per hectare with increasing stand age in softwood plantations that contrasted with decreasing expenditure with stand age in hardwood plantations (Table 12). Thus, three times more per hectare was spent on fertiliser for newly established hardwood plantations ($153 ha^{-1}) compared with newly established softwood plantations ($51 ha^{-1}) compared with five times more per hectare spent fertiliser for later age softwood plantations compared with later age hardwood plantations.

Apart from newly established and later age hardwood plantations, average costs of fertiliser plus application were similar for hardwood and softwood plantations throughout the rotation varying from $105 ha^{-1} to $161 ha^{-1}. However, as a result of the larger area fertilised in hardwood plantations, total expenditure was three to six times greater for newly established to mid-rotation hardwood plantations compared with softwood plantations (Table 13).

Table 13: Amount spent on fertiliser and application in hardwood and softwood plantations on a per hectare basis and total expenditure. Averages are weighted by the total area fertilised by each survey respondent and numbers in brackets are standard deviations of means.

Hardwood Softwood Total	Hardwood			Softwood			Total		
	Avg.	SD	*n*	Avg.	SD	*n*	Avg.	SD	*n*
Amount per ha fertilised ($ ha^{-1})									
Fertiliser	116	*(130)*	14	84	*(36)*	15	102	*(101)*	29
Application	66	*(61)*	14	40	*(36)*	15	54	*(53)*	29
Total	182	*(171)*	14	124	*(59)*	15	156	*(136)*	29
Amount per total area ($ ha^{-1})									
Fertiliser	27	*(74)*	14	8	*(8)*	15	14	*(43)*	29
Application	15	*(37)*	14	4	*(3)*	15	7	*(21)*	29
Total	43	*(104)*	14	11	*(11)*	15	21	*(60)*	29
Total ($ million y^{-1})									
Fertiliser	20.2			7.1			27.3		
Application	11.4			3.3			14.7		
Total	31.5			10.5			42.0		

5.7 Estimated growth responses and economics of fertiliser use

Forest managers provided estimates of average responses of stands of different ages to fertiliser application. While many of these estimates were based on data from in-house or published fertiliser trials, a number were based on educated guesses. Thus, these results should be viewed with caution. However, they provide useful information regarding the optimum timing of fertiliser applications through the rotation and estimated profitability.

Average estimated growth responses to fertiliser in hardwood plantations varied from 20% for later-age stands to 49% for mid-rotation stands (Figure 17). However, there was wide variation with estimates varying from <5% to >50% for responses to mid-rotation fertiliser application. At least two hardwood growers stated that there were still insufficient data to estimate the response of these stands. Average estimated responses to fertiliser applied to softwood plantations ranged from 13% for young stands to 31% for mid-rotation stands and, apart for newly established stands, tended to be lower than those for hardwood plantations.

No information on the profitability of fertiliser use was available for either hardwood or softwood plantations. However, using a simple model, the economics of various fertiliser scenarios could be estimated based on other information provided by growers. This included average fertiliser cost, age of application, growth rate and rotation length, and estimated average relative response to fertiliser. For softwood plantations, timing and intensity of thinning and average log prices were based on information from growers in the Green Triangle and south west WA. For hardwood plantations, stumpage prices were based on information from Green Triangle. Growth rates were based on modelled growth of an average hardwood plantation (MAI = 20 m^3 ha^{-1} $year^{-1}$ over 12 years) using the 3PG model, and site quality curves from the Green Triangle (Lewis *et al.*, 1976) for a radiata pine plantation with an MAI of 18 m^3 ha^{-1} $year^{-1}$ at age 30 (Figure 18). The duration of the response was assumed to be 10 years and the discount rate used was 7.5%.

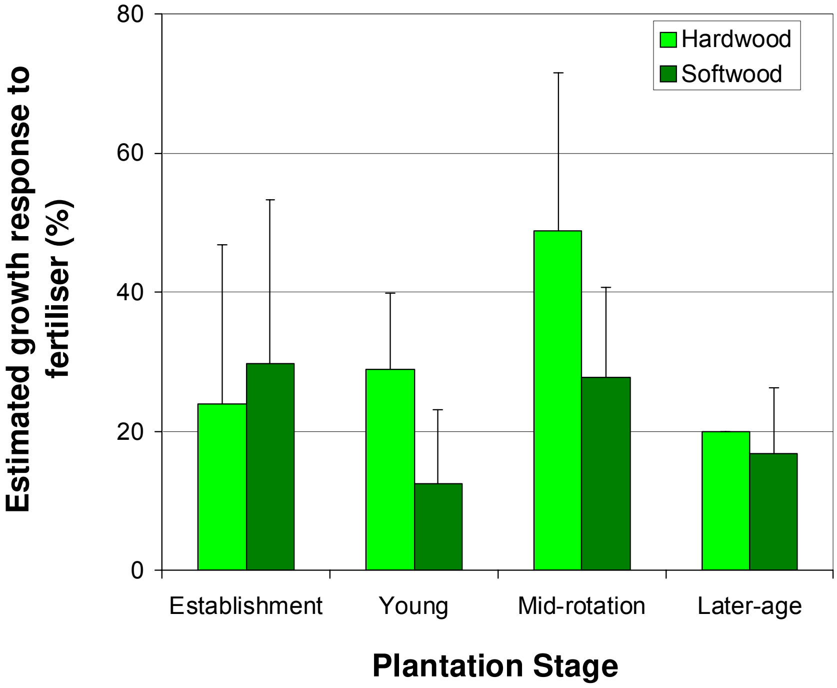

Figure 17: Average estimated growth response over 6 years to fertiliser applied at different stages in the rotation to hardwood and softwood plantations. Error bars represent standard deviations. Averages and standard deviations are weighted by total area fertilised.

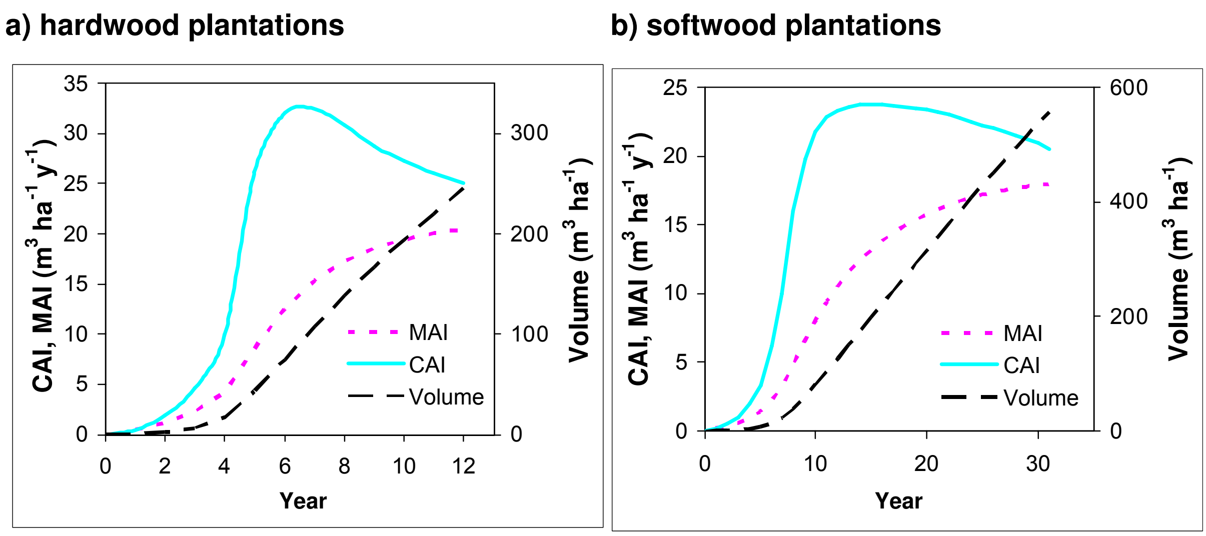

Figure 18: Assumed growth curves for unfertilised plantations of (a) hardwoods and (b) softwoods. Curves based on a 3PG growth model for hardwoods and standard growth curves for softwood plantations in the Green Triangle (Lewis *et al.*, 1976). Mean annual increments for softwoods (19 m^3 ha^{-1} $year^{-1}$) and hardwoods (20 m^3 ha^{-1} $year^{-1}$) based on data provided by survey participants.

The economic analysis indicated that, for short term (Type 1) responses to fertiliser in both hardwood and softwood plantations, the profitability of fertiliser application tended to be greatest in mid and late rotation stands (Table 14). Based on the assumptions used, fertilising at establishment did not appear to be profitable for either softwood or hardwood plantations. In contrast, fertilising young or mid-rotation hardwood plantations was highly profitable with NPV's in excess of $400 ha^{-1} (IRR = 27%) for young plantations and $1200 ha^{-1} (IRR = 72%) for mid-rotation stands. Similarly, for older softwood stands NPV's were $568 and $513 for mid-rotation and later age stands respectively with internal rates of return of 41-59%. The greater profitability of fertilising older stands was due to a combination of faster growth rates, larger relative responses (especially in hardwood plantations) and shorter time to final harvest when most of the profits are realised.

Table 14: Results of an economic model used to estimate the value of fertilizing hardwood and softwood stands of different ages assuming a type 1 response to fertiliser lasting 6 years. Values not in italics are based on average estimates provided by forest growers.

Parameter	Unit	Plantation Type						
		Hardwood			Softwood			
Age at fertiliser application	years	**0**	**2**	**7**	**0**	**5**	**15**	**25**
Fertiliser								
Cost	$ ha^{-1}	256	105	135	124	119	119	161
Age at application	years	0	2	7	0	5	15	25
Average response	%	24	29	49	30	13	28	17
Rotation Length	y	12	12	12	31	31	31	31
Response period	years	*6*	*6*	*5*	*6*	*6*	*6*	*6*
Total Wood Production								
Unfertilised	m^3 ha^{-1}	*245*	*245*	*245*	*557*	*557*	*557*	*557*
Fertilised	m^3 ha^{-1}	*263*	*285*	*313*	*561*	*570*	*597*	*579*
Increase in production	m^3 ha^{-1}	*18*	*39*	*67*	*4*	*12*	*39*	*21*
Total Revenue								
Unfertilised	$ ha^{-1}	7359	7359	7359	24053	24053	24053	24053
Fertilised	$ ha^{-1}	7899	8541	9380	24175	24431	25786	25127
Increase in Revenue	$ ha^{-1}	*540*	*1182*	*2021*	*123*	*379*	*1734*	*1074*
Profitability								
Discount rate	%	*7.5*	*7.5*	*7.5*	*7.5*	*7.5*	*7.5*	*7.5*
Discounted revenue increase	$ ha^{-1}	*227*	*573*	*1408*	*29*	*126*	*687*	*674*
Discounted profit	$ ha^{-1}	*-29*	*468*	*1272*	*-96*	*8*	*568*	*513*
IRR	%	*6*	*27*	*72*	*0*	*8*	*29*	*34*

Assumptions: tree growth responds to fertiliser for 6 years, age of clearfelling is 12 years for hardwood (pulpwood regime) and 31 years for softwood (pulp plus sawlog regime), age of thinning for softwoods is 12, 19 and 25 years, percent volume harvested is 50% at first thinning, 25% at second thinning and 20% at third thinning, stumpage values are $30 m^{-3} for hardwood (B. Bradshaw, Timbercorp *Pers. Com.*) and $20 m^{-3} at first thinning for softwoods, $30 m^{-3} at second thinning, $40 m^{-3} at third thinning and $50 m^{-3} at clearfelling (D. Turner, HVP, *Pers. Comm.*).

The effect on profitability of fertilising hardwood and softwood plantations of varying the magnitude and duration of response was calculated to assess the impact on the optimum timing of fertiliser application. For a type 1 response (longevity of 6 years) these scenarios indicate that profitability tends to increase with increasing age of application (at least up to 25 years for softwood sawlog and 7 years for hardwood pulpwood plantations) given the same relative response (Figure 19). Application of fertiliser at establishment was not profitable in softwood plantations and was only profitable in hardwood plantations if the response exceeded 30%. The model indicated that fertilising established stands was could be profitable provided the response exceeded 10% in 6 year old softwood stands and 5% in older softwood stands and hardwood stands aged 2 years or more.

The scenarios for type 2 responses (where the response continued for the duration of the rotation) were more profitable than those for type 1 responses (Figure 20). For a given relative response, the most profitable age to fertilise was two years for hardwoods and 16 years for softwoods, while the least profitable age to fertilise was at establishment or 7 years for hardwoods and at establishment for softwoods. Fertiliser application was profitable provided responses exceeded 5% for all stands except newly established hardwood plantations where a 10% response was the minimum required for a positive NPV.

The effect of a long term (type 2) growth response to fertiliser was assessed by assuming the increase in growth rates carries through to the end of the rotation. This alternative scenario indicated that fertiliser application at all stages in the rotation could be profitable provided the growth response persists (Table 15). However, again, the most profitable ages to fertiliser were around 7 years for hardwood plantations and 15 years for softwood plantations. This yielded NPV's of around $1,300 for hardwood plantations (IRR 72%) and $1,500 for softwood plantations (IRR 34%).

Table 15: Results of an economic model used to estimate the value of fertilizing hardwood and softwood stands of different ages assuming a Type 2 response to fertiliser lasting till the end of the rotation. Values not in italics are based on average estimates provided by forest growers. Other assumptions are the same as those listed in

The economic analysis indicated that, for short term (Type 1) responses to fertiliser in both hardwood and softwood plantations, the profitability of fertiliser application tended to be greatest in mid and late rotation stands (320HTable 14). Based on the assumptions used, fertilising at establishment did not appear to be profitable for either softwood or hardwood plantations. In contrast, fertilising young or mid-rotation hardwood plantations was highly profitable with NPV's in excess of $400 ha-1 (IRR = 27%) for young plantations and $1200 ha-1 (IRR = 72%) for mid-rotation stands. Similarly, for older softwood stands NPV's were $568 and $513 for mid-rotation and later age stands respectively with internal rates of return of 41-59%. The greater profitability of fertilising older stands was due to a combination of faster growth rates, larger relative responses (especially in hardwood plantations) and shorter time to final harvest when most of the profits are realised.

Table 14.

Parameter	Unit	Plantation Type						
		Hardwood			Softwood			
Age at fertiliser application	years	**0**	**2**	**7**	**0**	**5**	**15**	**25**
Fertiliser								
Cost	$ ha^{-1}	256	105	135	124	119	119	161
Age at application	years	0	2	7	0	5	15	25
Average response	%	24	29	49	30	13	28	17
Clearfell age	y	12	12	12	31	31	31	31
Total response period	years	*12*	*10*	*5*	*31*	*26*	*16*	*6*
Total Wood Production								
Unfertilised	m^3 ha^{-1}	*245*	*245*	*245*	*557*	*557*	*557*	*557*
Fertilised	m^3 ha^{-1}	*304*	*316*	*313*	*723*	*627*	*658*	*579*
Increase in production	m^3 ha^{-1}	*59*	*70*	*67*	*166*	*69*	*100*	*21*
Total Revenue								
Unfertilised	$ ha^{-1}	7359	7359	7359	24053	24053	24053	24053
Fertilised	$ ha^{-1}	9124	9472	9380	31173	27025	28765	25127
Increase in Revenue	$ ha^{-1}	1765	2113	2021	7120	2972	4712	1074
Profitability								
Discount rate	%	*7.5*	*7.5*	*7.5*	*7.5*	*7.5*	*7.5*	*7.5*
Discounted revenue increase	$ ha^{-1}	*741*	*1025*	*1408*	*996*	*593*	*1639*	*674*
Discounted profit	$ ha^{-1}	*485*	*920*	*1272*	*872*	*475*	*1520*	*513*
IRR	%	*17*	*35*	*72*	*18*	*18*	*35*	*34*

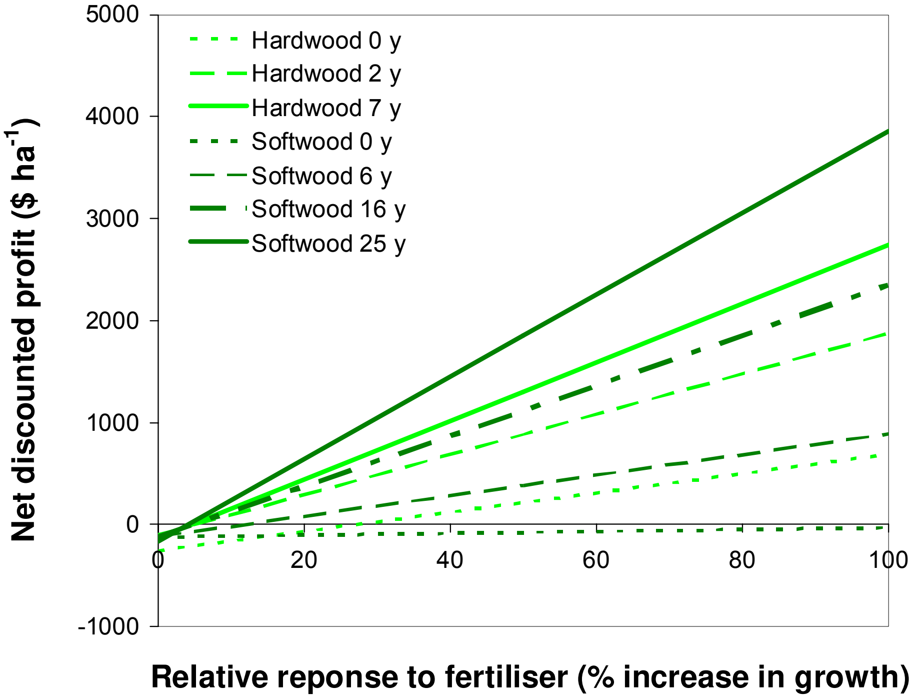

Figure 19: Modelled effect of varying response to fertiliser, assuming a 6 year response period (i.e. Type 1 response) on net discounted profitability of applying fertiliser at different ages in hardwood and softwood plantations. Growth rate, fertiliser cost, silvicultural regime, wood price and discount rate are based on values in Figure 18.

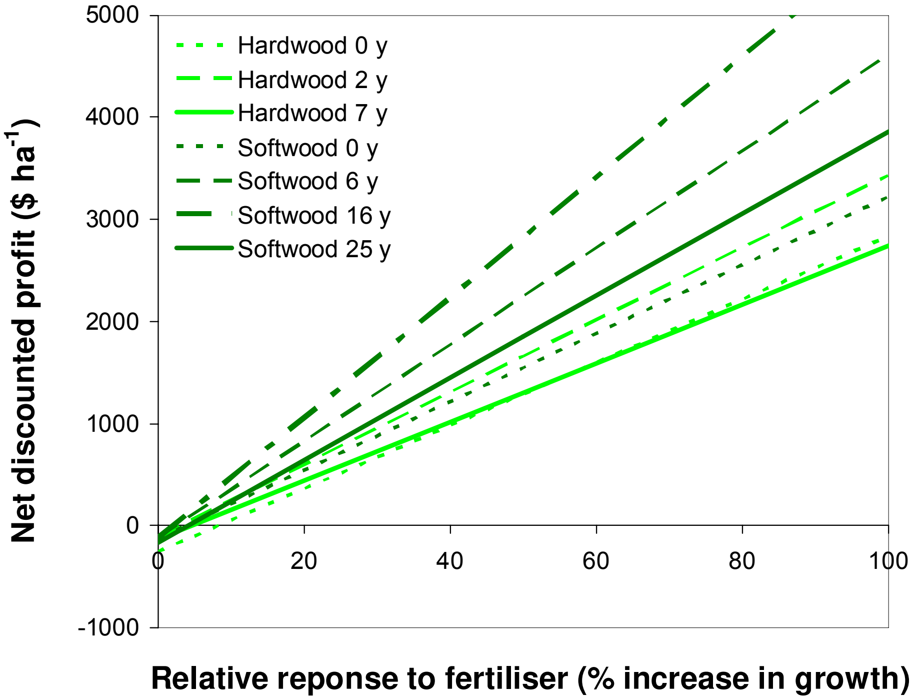

Figure 20: Modelled effect of varying response to fertiliser, assuming a 30 year response period (i.e. Type 2 response) on net discounted profitability of applying fertiliser at different ages in hardwood and softwood plantations. Growth rate, fertiliser cost, silvicultural regime, wood price and discount rate are based on values in Figure 18.

Although these analyses are based on data supplied by forest growers, the results must be viewed with caution because they considers only a small subset of possible fertiliser scenarios and do not include other factors that may influence fertiliser decisions. These include:

- the need for fertiliser application at establishment to allow successful plantation establishment where critical nutrient deficiencies would otherwise reduce tree survival and severely limit growth (eg. on soils deficient in phosphorus or where trees require additional nutrients to outcompete weeds);
- increases unit wood value ($\$ m^{-3}$) and reduced harvesting costs as a result of increased tree size in response to fertiliser;
- growth responses continuing into subsequent rotations after a stand is harvested and replanted (eg. Woollons *et al.*, 1988); and
- other benefits such as increasing stand uniformity or tree form.

These factors could change the relative profitability of different ages of application. For example, removing critical nutrient deficiencies at establishment will increase the profitability of early applications relative to later applications while multi-rotation responses to fertiliser would tend to improve the relative profitability of later-age fertiliser applications.

Despite these limitations, the analysis provides useful information regarding optimum timing for different fertiliser types. As discussed, type 2 responses occur when the capacity for a site to supply a limiting nutrient is enhanced and sustained for the long-term (Snowdon, 2002). Because of the low phosphorus status of many Australian soils type 2 responses are typically associated with application of phosphorus fertiliser (eg. Gentle *et al.*, 1986; Woollons *et al.*, 1988). Thus, phosphorus application may be profitable earlier in the rotation on phosphorus deficient sites. In contrast, nitrogen application is often associated with type 1 responses (eg. Ballard, 1984; Foerster, 1990; McGrath *et al.*, 2003b) indicating that the profitability of nitrogen application could be expected to be greater in mid-rotation and later age stands.

5.8 Environmental Considerations

5.8.1 Emissions to water

Leaching losses of nitrogen and phosphorus from fertiliser used in plantation forestry can be estimated from the average figures of rates of loss reported previously (see section 4.7.2) and the amounts of fertiliser applied. Annual exports of nitrogen as nitrate to surface water are estimated to range from 64,000 -280,000 t (0.09-0.38 kg ha^{-1} total area) for hardwood plantations and from 29,000 to 130,000 t $year^{-1}$ (0.03-0.13 kg ha^{-1}) for softwood plantations (Table 16). Similarly, annual losses of phosphorus as phosphate to surface water are estimated to range from 22,000-67,000 t $year^{-1}$ (0.007-0.022 kg ha^{-1}) for hardwood plantations and from 12,000-37,000 t $year^{-1}$ (0.006-0.017 kg ha^{-1}) for softwood plantations.

On an area fertilised basis, average emissions from fertilising hardwood plantations range from about 0.3-1.5 kg ha^{-1} for nitrate and 0.2-0.5 kg ha^{-1} for phosphate, while those for softwood plantations range from about 0.4-1.7 kg ha^{-1} for nitrate and 0.3-1.0 kg ha^{-1} for phosphate. These rates of nutrient loss are negligible compared to those from intensive agricultural operations. This is consistent with results from overseas which indicate that water quality from forested catchments is superior to that from catchments dominated by agriculture (Antikainen *et al.*, 2008; Binkley *et al.*, 1999; Burford *et al.*, 2007; Van Dijk & Keenan, 2007). Thus, provided best forest management practise are adhered to (i.e. retention of a litter layer, use of riparian buffer strips, and prevention of direct application to waterways, and avoiding overuse of fertiliser) transfers of nutrients to waterways from forestry fertiliser operations are unlikely to cause a decline in water quality.

Table 16: Estimated emissions of nitrate (NO_3^-) and phosphate (PO_4^{3-}) to water from different forms of nitrogen fertiliser applied to hardwood and softwood plantations. Amounts are expressed as total losses across Australia, rate per hectare fertilised and rate per total planted area.

Estimate	Unit	Emissions to water								
		Hardwood			Softwood			Total		
		Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Total										
NO_3^-	t N/y	171	64	279	78	29	127	250	94	406
PO_4^{3-}	t P/y	45	22	67	24	12	37	69	35	104
Amount per total area										
NO_3^-	kg N/ha/y	0.23	0.09	0.38	0.08	0.03	0.13	0.15	0.06	0.24
PO_4^{3-}	kg P/ha/y	0.015	0.007	0.022	0.011	0.006	0.017	0.013	0.006	0.019
Amount per area fertilised										
NO_3^-	kg N/ha	0.91	0.34	1.47	1.02	0.38	1.65	0.93	0.35	1.50
PO_4^{3-}	kg P/ha	0.34	0.17	0.51	0.65	0.32	0.97	0.40	0.20	0.61

5.8.2 Emissions to air

The IPCC recommends a default emission factor of 1.25% for N_2O emissions from synthetic fertilisers (IPCC, 2006). However, this has a wide range (0.25-2.25%) as it can vary considerably with the agricultural system, fertiliser type and climate (DCC 2006). Thus, separate emission factors have been established for different Australian cropping and pastoral systems (Galbally *et al.*, 2005). These range from 0.03% for irrigated cotton with a 100 kg N ha^{-1} treatment to 2.8 % for irrigated maize with 300 kg N ha^{-1} under a stubble burning system. The only non-irrigated system reported (rain-fed wheat with 83 kg N ha^{-1} with direct drilling) has a very low emission rate (0.05-0.1%). However, these figures are based on measurements from dryland sites in WA and northern Victoria and there is no information for emission factors for more temperate regions which may be more applicable to plantation forestry. Based on information from Europe, higher emission factors could be expected in these zones (DCC, 2008b).

Under updated IPCC guidelines (IPCC, 2006), greenhouse gas emissions from nitrogen fertiliser are divided into direct and indirect emissions. Direct emissions are associated with emissions from the fertiliser itself or from the soil to which it is applied. In contrast, indirect emissions consist of a) volatilization of nitrogen as NH_3 or nitrous oxides (NO_x) and subsequent deposition of these gases and their products NH_4^+ and NO_3^- onto soils and lakes and other water bodies, b) leaching and runoff from land of nitrogen from synthetic or organic fertilisers, or c) increased mineralization of nitrogen as a result of the loss of soil carbon. These indirect emissions result in increased nitrification of land and water generally resulting in increased rates of N_2O gas production, which is emitted into the atmosphere.

Generic figures have been developed to estimate both direct and indirect N_2O emissions from nitrogen fertiliser application. However, these have large uncertainties associated with them. For direct emissions, a figure of 1% (uncertainty range 0.03-3%) of applied nitrogen is assumed (IPCC, 2006). For indirect emissions, associated with volatilization and deposition 1% (range 0.2-5%) of NH_3 and NO_x emitted from fertiliser is assumed to be converted to N_2O. For indirect emissions arising from nitrogen leaching or runoff, a figure of 0.75% (range 0.05-2.5%) of leaching losses is recommended. In the absence of data for volatilization or leaching rates, a figure of 10% loss (range 3-30%) is suggested for NH_3 volatilisation losses and 30% (range 10-80%) is suggested for leaching losses where the net excess water in the rainy season (i.e. rainfall - potential evapo-transpiration) is greater than the soil water holding capacity.

Using the estimates for volatilization losses from different nitrogen fertiliser forms applied to plantations, leaching of nitrate from plantations and the IPCC estimates for direct and indirect N_2O emissions, we can estimate total greenhouse gas emissions from nitrogen fertiliser (IPCC, 2006). Ammonia volatilization losses were assumed to average 30-40% for urea applied to established softwood plantations, 5-15% for urea applied to hardwood plantations or to softwood plantations at establishment, and 0-10% for ammonium-based fertilisers. NPK blends were assumed to contain 70% urea.

Based on these assumptions, direct emissions as a result of N_2O production from denitrification after fertiliser application comprised 76% of total fertiliser emissions for hardwood plantations and 71% of total fertiliser emissions from softwood plantations (Figure 21). Indirect emissions as a result of NH_3 volatilisation and nitrate leaching made up 17% of total emissions for hardwoods and 22% of the total for softwoods while CO_2 released during the process of urea hydrolysis comprised 7% of emissions. Total emissions of N_2O-N were equivalent to 1.2% of the nitrogen applied as fertiliser for hardwood plantations, and 1.3% of nitrogen applied to softwood plantations.

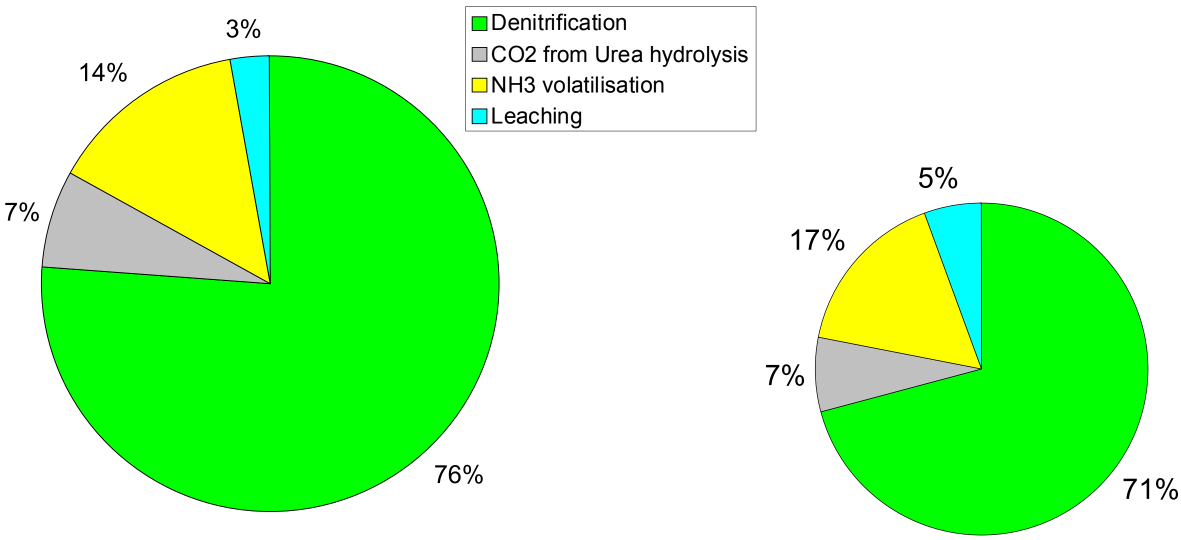

Figure 21: Sources of total GHG emissions from nitrogen fertiliser use in a) hardwood plantations and b) softwood plantations. Relative sizes of charts indicate relative total emissions.

Total direct and indirect N_2O emissions from fertiliser use in plantations, were estimated to average 140 t year^{-1} (0.19 kg ha^{-1} year^{-1} per total area planted) for hardwood plantations and 67 t N_2O year^{-1} (0.07 kg ha^{-1} year^{-1}) for softwood plantations (Table 17a and b). In addition, an estimated 3,100 t CO_2 year^{-1} (4.2 kg CO_2 ha^{-1} year^{-1}) were emitted as a result of urea hydrolysis in hardwood plantations and 1,600 t CO_2 year^{-1} (1.7 kg CO_2 kg ha^{-1} year^{-1}) were emitted as a result of urea hydrolysis in softwood plantations. Thus, each year, a total of 46,000 t CO_2-e (range 13,000 – 150,000 t) is estimated to be emitted from hardwood plantations and 22,000 t CO_2-e (range and 6,000 – 76,000 t) is estimated to be emitted from softwood plantations as a result of nitrogen fertiliser use. The wide ranges indicate the large uncertainty associated with figures for direct and indirect emissions of N_2O. In terms of emissions per total plantation area, these figures are equivalent to rates of 62 kg CO_2-e ha^{-1} year^{-1} for hardwood plantations and 24 kg CO_2-e ha^{-1} year^{-1} for softwood plantations. In terms of emissions per unit area fertilised, emissions from hardwood plantations were estimated to average 300 kg CO_2-e ha^{-1} (range 80-1000 kg CO_2-e ha^{-1}) while those from softwood plantations averaged 500 kg CO_2-e ha^{-1} (range 140-1,700 kg CO_2-e ha^{-1}, Table 17a and b). Emissions were greatest from urea (390 kg CO_2-e ha^{-1} for hardwoods and 970 kg CO_2-e ha^{-1} fertilised for softwoods) and least from ammonium-based fertilisers (100-110 kg CO_2-e ha^{-1} fertilised).

Table 17: Estimated direct and indirect emissions of greenhouse gasses to air from nitrogen fertiliser use in a) hardwood plantations and b) softwood plantations based on IPCC (2006) methodology. Amounts are expressed as total national losses, amounts per total planted area, and rates per hectare fertilised. For calculating CO_2-e, a global warming factor of 310 for N_2O was assumed.

a) Hardwood plantations

Estimate and Type	Unit	Greenhouse gas emissions from fertiliser use in softwood plantations								
		Direct			Indirect				Total	
		Denit.	Urea	Total	NH_3 volatilisation		Leaching	Total	N_2O	CO_2-e
		N_2O	CO_2	CO_2-e	NH_3	N_2O	N_2O	CO_2-e		
Total										
Urea	t/y	41	1,260	14,100	747	11.7	1.7	4,200	55	18,200
Ammonium	t/y	14	-	4,200	43	0.7	0.6	400	15	4,600
Blend	t/y	57	1,880	19,700	561	8.8	1.6	3,200	68	22,900
Total	t/y	112	3,140	38,000	1,351	21.2	3.9	7,800	137	45,700
Amount per total area planted										
Urea	kg/ha/y	0.06	1.7	19.0	1.0	0.02	0.00	5.6	0.07	24.6
Ammonium	kg/ha/y	0.02	-	5.7	0.1	0.00	0.00	0.5	0.02	6.2
Blend	kg/ha/y	0.08	2.5	26.6	0.8	0.01	0.00	4.4	0.09	31.0
Total	kg/ha/y	0.15	4.2	51.3	1.8	0.03	0.01	10.5	0.19	61.8
Amount per area fertilised										
Urea	kg/ha	0.87	37	308	15	0.23	0.04	83	3.2	390
Ammonium	kg/ha	0.30	-	94	1	0.02	0.02	9	1.0	100
Blend	kg/ha	0.44	14	151	4	0.07	0.01	25	0.5	180
Total	kg/ha	0.73	20	246	9	0.14	0.03	51	0.9	300

b) Softwood plantations

Fertiliser Type	Unit	Greenhouse gas emissions from fertiliser use in softwood plantations								
		Direct			Indirect				Total	
		Denit.	Urea	Total	NH_3 volatilisation		Leaching	Total	N_2O	CO_2-e
		N_2O	CO_2	CO_2e	NH_3	N_2O	N_2O	CO_2e		
Total										
Urea	t/y	29	1,260	10,400	608	9.6	1.7	3,500	41	13,900
Ammonium	t/y	12	-	3,600	37	0.6	0.6	400	13	4,000
Blend	t/y	10	330	3,500	113	1.8	1.6	1,100	13	4,500
Total	t/y	51	1,590	17,500	758	11.9	3.9	5,000	67	22,400
Amount per total area planted										
Urea	kg/ha/y	0.03	1.3	11.0	0.6	0.01	0.00	3.7	0.04	14.7
Ammonium	kg/ha/y	0.01	-	3.8	0.0	0.00	0.00	0.4	0.01	4.2
Blend	kg/ha/y	0.01	0.3	3.7	0.1	0.00	0.00	1.1	0.01	4.8
Total	kg/ha/y	0.05	1.7	18.5	0.8	0.01	0.00	5.2	0.07	23.7
Amount per area fertilised										
Urea	kg/ha	2.07	88	729	43	0.67	0.12	245	7.5	970
Ammonium	kg/ha	0.34	-	104	1	0.02	0.02	11	2.7	110
Blend	kg/ha	1.08	35	369	12	0.19	0.17	112	1.4	480
Total	kg/ha	1.13	35	387	17	0.26	0.09	109	1.5	500

6. FERTILISER USE IN FORESTRY COMPARED WITH SELECTED AGRICULTURAL CROPS

6.1 Fertiliser consumption and prices in Australia

6.1.1 Fertiliser consumption

Currently, approximately 1.1 million tonnes of nitrogen, 0.5 million tonnes of phosphorus and 0.2 million tonnes of potassium are used each year across Australia (ABARE, 2007). Total nitrogen use has more than tripled since 1986/87, increasing from 330,000 t year^{-1} in 1986-87,000 to 1,000,000 t year^{-1} in 2000-01. However, since 2001, nitrogen use has levelled off (Figure 22). The use of potassium more than doubled over the same period, increasing from 110,000 t year^{-1} in 1986-87 to 240,000 t year^{-1} in 2004-05. The increase in phosphorus fertiliser consumption has been less marked over the period, rising from 380 to 520 kt year^{-1}. Recent figures for fertiliser consumption are not available from ABARE since, as of 2004-05, these data are no longer collected.

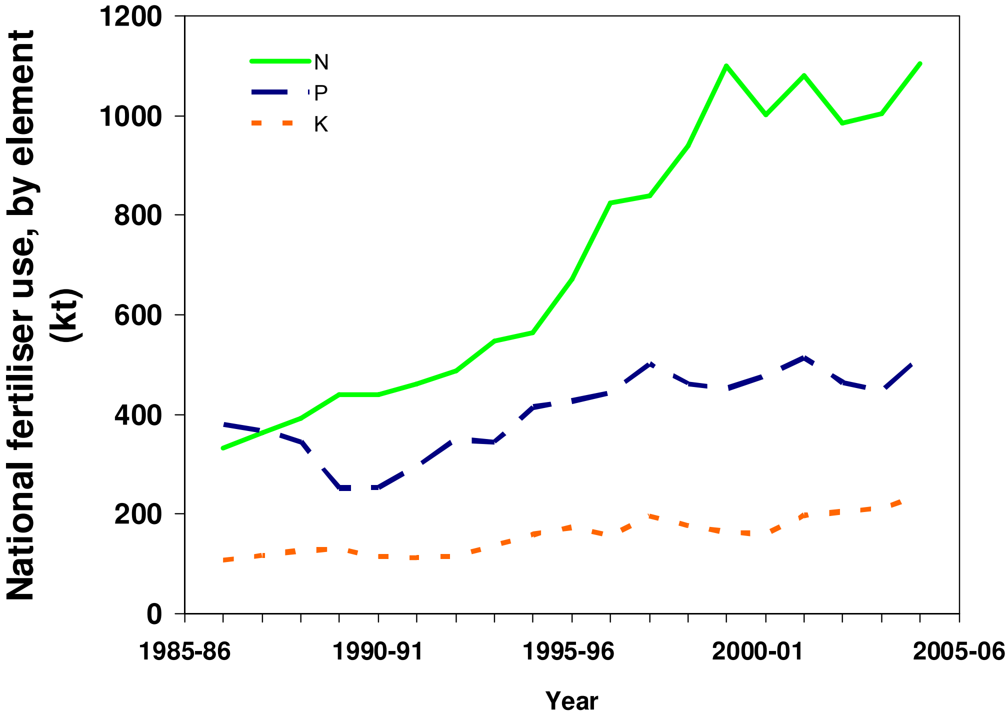

Figure 22: Total consumption of nitrogen, phosphorus and potassium fertiliser across Australia for the period 1987-88 to 2005-06. Relative sizes of charts indicate relative total emissions. Source: ABARE (2007).

The International Fertiliser Association (IFA) publishes statistics on global trends in fertiliser usage (http://www.fertilizer.org/ifa/home-page/statistics). Up to the mid 1970's the trend in fertiliser consumption was towards the use of NPK complex fertilisers, supplemented by straight nitrogen fertilisers depending on the requirements of different crops. Complex fertilisers have the advantage of having each nutrient in each granule in the approximate ratio required by the plant. However, since 1973/74, there has been a trend towards high analysis nitrogen and phosphorus fertilisers such as urea, ammonium phosphates (MAP and DAP) and muriate of potash (KCl). This trend is largely because of the lower cost per unit element contained in the fertiliser. For example, between 1973-74 and 1999-2000, consumption of urea fertiliser increased by 430%, while that of ammonium phosphate increased by 260% and consumption of KCl increased by 40%. As a result, the proportion of nitrogen applied as urea has risen from 22% to 54%, while the proportion of phosphorus applied as ammonium phosphates has risen from 20% to 49%, and the proportion of potassium applied as muriate of potash (KCl) has risen from 51 to 61%. However, the IFA (2002) points out that the change towards the high analysis fertilisers "has been driven by economics not by considerations of agricultural efficiency or sustainability".

6.1.2 Fertiliser prices

International fertiliser prices have been rising steadily over the past three decades. Between 1985-86 and 2005-06, the retail price increases ranged from 38%-40% for urea and DAP to 80-90% for single superphosphate and ammonium sulphate. However, between March 2007 and 2008, prices rose sharply in response to a number of factors. The retail price of DAP doubled from \$610 t^{-1} to \$1220 t^{-1} while that of urea increased 30% from around \$550 t^{-1} to \$720 t^{-1} (ACCC, 2008).

The reasons for this recent increase were summarized during an inquiry into the issue by the Australia Competition and Consumer Commission (ACCC, 2008). These include:

- high commodity prices, especially for grains, and a rise in demand for biofuel, resulting in significant increases in fertiliser demand;
- production capacity constraints from fertiliser suppliers;
- increased feedstock prices especially natural gas used to produce nitrogen fertilisers, and rock phosphate, which increased from US \$50 t^{-1} at the start of 2007 to over US \$200 t^{-1} at the start of 2008, (Incitec Pivot , 2008);
- increased international freight rates as a result of increased fuel costs and shortage of shipping capacity;
- reduced exports from China as a result of a rise in export taxes on urea and phosphate fertilisers; and
- increased demand for fertilisers from China in particular as a result of the rapid rise in its economy in recent years.

Similar reasons for the price rises were given in a report at an annual conference organized by the International Fertiliser Agency in May 2008 (Heffer & Prud'Homme, 2008). This report indicated that the price rises indicated a structural change as a result of increased demand for agricultural commodities due to increasing world population, increasing income growth in Asia and increasing production of biofuel combined with increasing costs associated with energy.

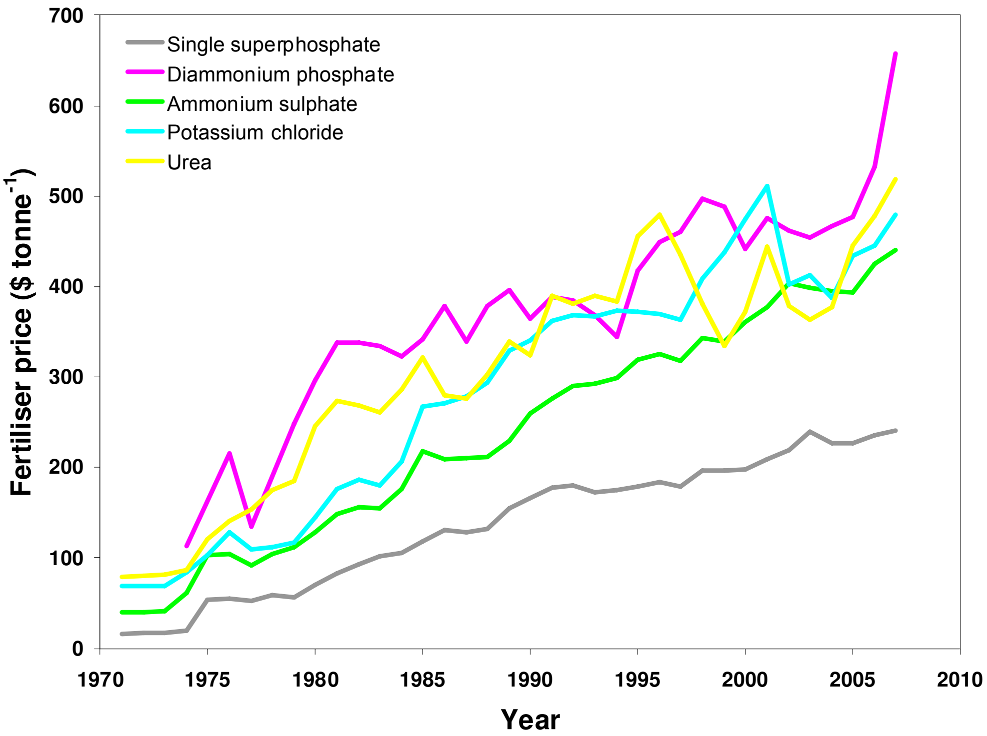

Figure 23: Average price of different fertiliser forms from 1970 to 2007. Source: ABARE (2007).

6.2 Fertiliser usage in different agricultural zones

Fertiliser usage in different agricultural industries and climatic zones across Australia has been summarised by Gourley and Ridley (1989, Table 18). As a result of the inherently low nutrient levels in Australian soils, inorganic fertilisers have traditionally been a significant input for most agricultural enterprises where rainfall is > 500 mm year^{-1}. However, the amount applied varies with agricultural system. For example, virtually no fertiliser is applied across most rangeland used for grazing. However, in most other zones, there has been a significant rise in fertiliser use over the past decade. Amounts of fertiliser applied to irrigated and improved pastures range from 50-200 kg N ha^{-1} year^{-1} for nitrogen and 25-75 kg P ha^{-1} year^{-1} for phosphorus, while amounts applied to intensively managed crops such as sugar-cane, rice, cotton, fruit and vegetables can be even higher. Thus, according to the estimates of Gourley and Ridley (1989), the amount of nitrogen and phosphorus fertiliser used in wheat production and extensive beef and sheep grazing tends to be lower than that for plantation forestry, while that used in dairy production and rice, cotton and fruit and vegetable crops tends to be an order of magnitude greater.

Table 18: Estimated nitrogen and phosphorus fertiliser inputs for different farming regions and production systems. Source: Gourley and Ridley (2005).

Climatic zone	N kg ha^{-1} y^{-1}	P kg ha^{-1} y^{-1}	Production System
Desert Rangeland	0	0	Extensive grazing on native pastures
Mediterranean wheat sheep zone	0	<10	Mixed cropping, extensive grazing on annual pastures
Cool wet to sub humid dryland zones	0	<10	Extensive beef/sheep grazing on improved pastures
Cool wet climatic zone	0	<10	Extensive beef/sheep grazing on improved pastures
Irrigated grassland zone	50-200	25-75	Intensive dairy grazing on improved pastures
Broad acre irrigated cropping	150-250	15-30	Irrigated cotton, rice and tomatoes
Humid, sub-humid tropics	150-250	15-30	Sugar cane, vegetable crops, fruit
Cool wet climate horticultural zones	150-300	50-100	Vegetable crops, fruit

6.3 Total nitrogen, phosphorus and potassium use in different agricultural systems

The more than doubling of nitrogen fertiliser use in Australia during the 1990's from 439,000 t year^{-1} in 1990-91 to 1,002,000 t year^{-1} in 2000-01 has largely been attributed to increased nitrogen fertiliser use on dryland crops such as wheat and oilseeds (Angus, 2001). This increase in nitrogen use was brought about by a) increased responsiveness of wheat to nitrogen fertiliser as a result of improvements in agricultural systems, b) increased demand for high protein wheat, c) increased use of oilseed breakcrops which are responsive to nitrogen fertiliser, and d) reduced reliance of biological nitrogen fixation from pasture legumes (Angus, 2001). Thus, the estimates form Gourley and Ridley (2005) nitrogen use in these crops are likely to be low.

A breakdown of total fertiliser use across different agricultural sectors for the period 1999-2000 is provided by Chudleigh and Simpson (2001). Rates of application were estimated by combining this information with land-use area data from the Australian Bureau of Statistics (2003, Table 19). These estimates indicate that, by far, the largest user of nitrogen fertiliser is the cereal sector with 701 kt N year^{-1} being applied (66% of the total). In comparison, other agricultural sectors used between 5 and 9% of total nitrogen (55 to 96 kt N year^{-1}) while softwood and hardwood plantations used only 1% (10 kt N year^{-1}). Estimated rates of nitrogen fertiliser use ranged from 3 kg N ha^{-1} year^{-1} for pasture to 224 kg N ha^{-1} year^{-1} for sugarcane and averaged 21 kg N ha^{-1} year^{-1} across all sectors (excluding native pastures where little or no nitrogen is applied). The estimates are broadly consistent with those used by Department of Climate Change (DCC) to estimate N_2O emissions from these sectors. Average application rates assigned to the different crops by the DCC were 80 kg N ha^{-1} for irrigated crops 40 kg N ha^{-1} for irrigated pasture 200 kg N ha^{-1} for cotton and sugar-cane and 125 kg N ha^{-1} for horticulture (DCC, 2008b).

Table 19: Total land-use areas of different agricultural sectors for the period 2001-02, amounts of nitrogen, phosphorus and potassium fertiliser applied in 1999-2000 and estimated fertiliser use in hardwood and softwood plantations. Land-use data from Australian Bureau of Statistics (2003), fertiliser usage data from Chudleigh and Simpson (2001). Plantation fertiliser use data based on survey results for period 2004-06.

Sector	Area[a]	N[b]			P[b]			K[b]		
	'000 ha	kt y^{-1}	kg ha^{-1} y^{-1}	%	kt y^{-1}	kg ha^{-1} y^{-1}	%	kt y^{-1}	kg ha^{-1} y^{-1}	%
Agriculture										
Pasture[c]	25,607	76	3	7	158	6	33	63	2	36
Cereals	16,948	701	41	66	214	13	45	28	2	16
Oilseed/Legumes	5,854	55	9	5	43	7	9	6	1	3
Sugar	428	96	224	9	12	28	3	30	70	17
Cotton	435	56	129	5	4	9	1	3	6	1
Horticultural crops[d]	419	71	169	7	37	88	8	45	107	25
Total Agriculture	49,691	1,055	21	99	468	9	99	174	4	99
Forestry Plantations										
Hardwood	740	7.1	9.7	0.7	2.8	3.8	0.6	2.1	2.8	1.2
Per ha fertilised			48			25			26	
Softwood	944	3.3	3.5	0.3	1.5	1.6	0.3	0.4	0.5	0.3
Per ha fertilised			72			42			34	
Total Forestry	1,685	10.4	6.2	1.0	4.3	2.6	0.9	2.5	1.5	1.4
Per ha fertilised			62			35			30	
Total	51,376	1,065	20.7	100	472	9.2	100	177	3.4	100

[a] Data for 1999-2000 from ABS (2002)

[b] Total fertiliser use for 1999-2000 from Chudleigh and Simpson (2001)

[c] Data for 2000-01 from ABS (2003)

[d] Data for fruit available as number of trees only, so area per tree assumed to be 50 m^2

Compared with rates of nitrogen application used in agriculture, those used in plantation forestry estate were low, ranging from 4 -10 kg N ha^{-1} $year^{-1}$ across the total area. Expressed in terms of rate per area fertilised, application rates in plantations were higher than those used in broadscale agriculture, but were still far lower than those used for sugarcane, cotton or horticultural crops. Since the frequency of application is far lower in forestry (averaging about once every five years in hardwood plantations and once every 21 years in softwood plantations) compared with that in agriculture, the cumulative impact over time is likely to be far less.

Amounts of phosphorus applied across agricultural sectors varied from 4 kt P $year^{-1}$ (1% of the total) for cotton to 214 kt P $year^{-1}$ (45% of the total) for cereals. Far more phosphorus than nitrogen was applied to pasture, which accounted for 158 kt P $year^{-1}$ or 33% of the total. In comparison, phosphorus use in plantation forestry accounted for <1% of the total and rates of application expressed on a total area basis were between 2 and 60 times less than those used across agricultural crops and pasture. Rates per area fertilised were higher in forestry than those used in most agricultural crops except for sugarcane and horticultural crops. However, as with the low frequency of phosphorus application in plantation forestry (around once every 25 years) indicates that the overall impact on soils and waterways is likely to be lower.

Amounts of potassium fertiliser applied varied from 3 kt K $year^{-1}$ (1% of the total) for cotton to 63 kt K $year^{-1}$ (36% of the total) for pasture while rates of application varied from 1 kg K ha^{-1} $year^{-1}$ for cereals to 79 kg K ha^{-1} $year^{-1}$ for horticultural crops. Thus, rates of potassium fertiliser use on pasture, cereals, oilseeds and legumes were similar to those on plantation forests. However, rates of potassium application in plantation forestry were 2 to 12 times less than that for cotton and 25 to 200 times less than those for sugarcane and horticultural crops. As with phosphorus, rates of application in plantations per unit area fertilised were greater than most agricultural systems, but frequency of application was effectively only around once every 9 years for hardwood plantations and once every 72 years (2 rotations) for softwood plantations.

6.4 Spatial distribution of fertiliser use across Australia

The National Land and Water Resources Resources Audit (2001) assessed nutrient additions and losses for agricultural systems in Australia. This provides information on rates of nutrient application for nitrogen, phosphorus and potassium used as well as contributions from nitrogen fixation, nutrient removals, concentrations in ground water and overall nutrient balances.

A large proportion of nitrogen used by crops and pastures is provided through biological nitrogen fixation. According to the National land and water resources audit, N-fixation rates exceeding 300 kg N ha^{-1} $year^{-1}$ are common and N-fixation contributes over 60% of the total nitrogen input across much of southern Australia. However, nitrogen fertiliser is still applied at rates of 40 kg N ha^{-1} $year^{-1}$ or more to crops in NSW, Queensland and south-west WA (Figure 24). Highest application rates (> 200 kg N ha^{-1} $year^{-1}$) occur in northern Queensland, eastern NSW and southern Otway and Gippsland regions of Victoria. Application rates for pastures are lower, being generally < 1 kg ha^{-1} $year^{-1}$ although some intensive pastoral areas have higher rates (> 10 kg ha^{-1} $year^{-1}$, Figure 25).

Despite the high rates of nitrogen input from N-fixation and fertiliser, large areas of western Victoria, the Eyre Peninsula of SA and southern and central Queensland have negative nitrogen balances. This deficit indicates that nitrogen inputs may have to increase in these regions in the future in order to maintain productivity.

Application rates for phosphorus vary from < 1 kg P ha^{-1} in central Queensland to > 50 kg P ha^{-1} in northern Queensland and central NSW (Figure 26, Figure 27). Rates across southwest WA, SA, Victoria and NSW ranged from 5-20 kg P ha^{-1}.

These data indicate that rates of nitrogen fertiliser use in forestry are lower than those used across most cropland regions except those in southern SA and western Victoria, while rates of phosphorus use are less than those used anywhere except parts of inland Queensland and northern NSW and small patches in Victoria, SA and WA. In contrast, rates of nitrogen and phosphorus application in forestry tend to be higher than those used on pasture. However, total nitrogen inputs on pasture are likely to be greater than those in forestry as a result of nitrogen fixation from legumes.

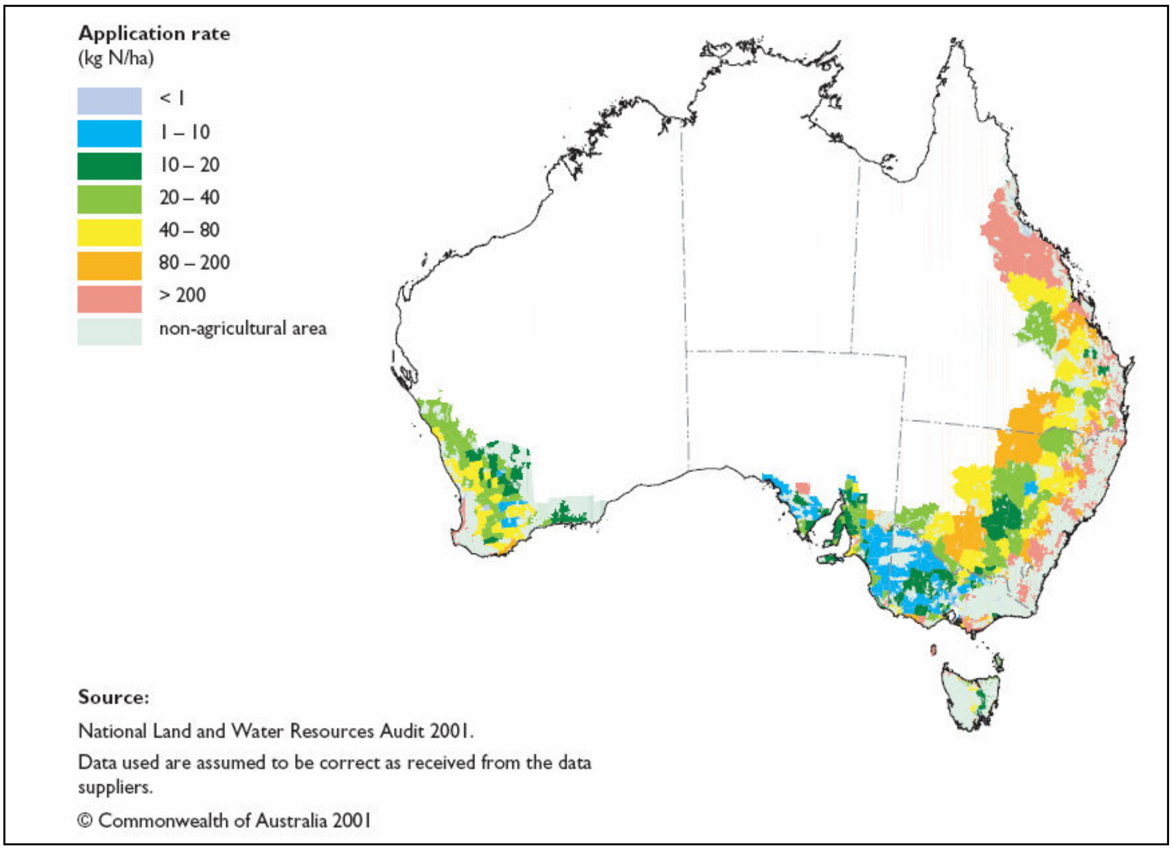

Figure 24: Nitrogen fertiliser application rates for crops by statistical local area (1992-96). Source: National Land and Water Resources Audit (2001).

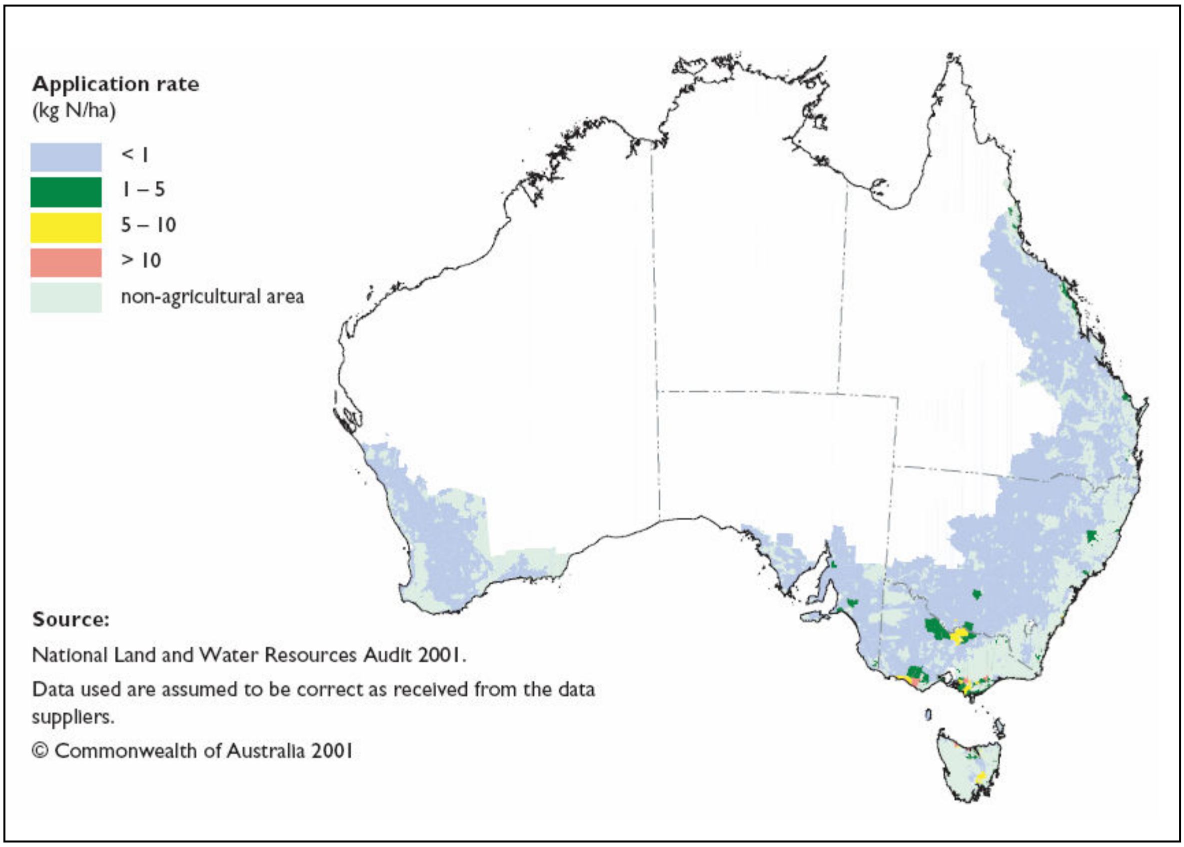

Figure 25: Nitrogen fertiliser application rates for pastures by statistical local area (1992-96). Source: National Land and Water Resources Audit (2001).

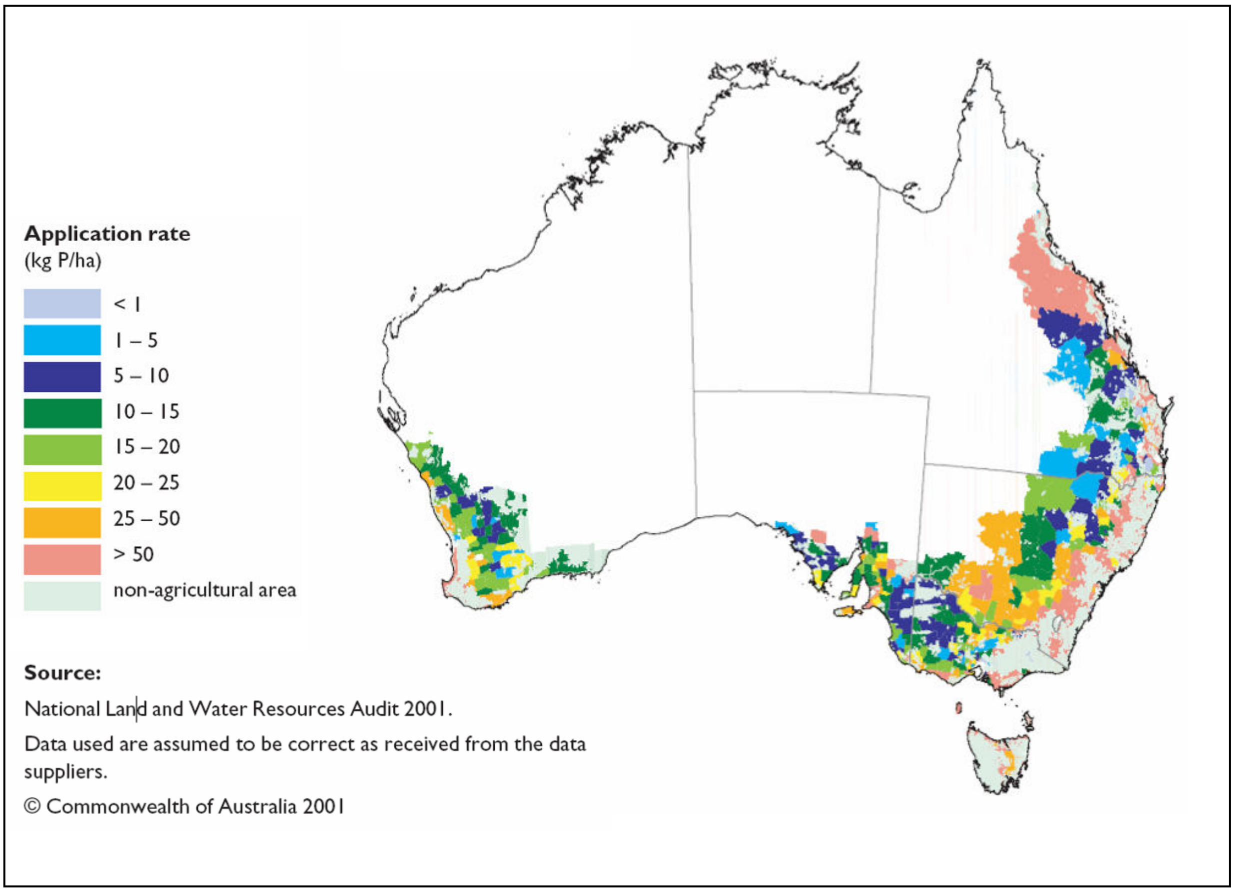

Figure 26: Phosphorus fertiliser application rates for crops by statistical local area (1992-96). Source: National Land and Water Resources Audit (2001).

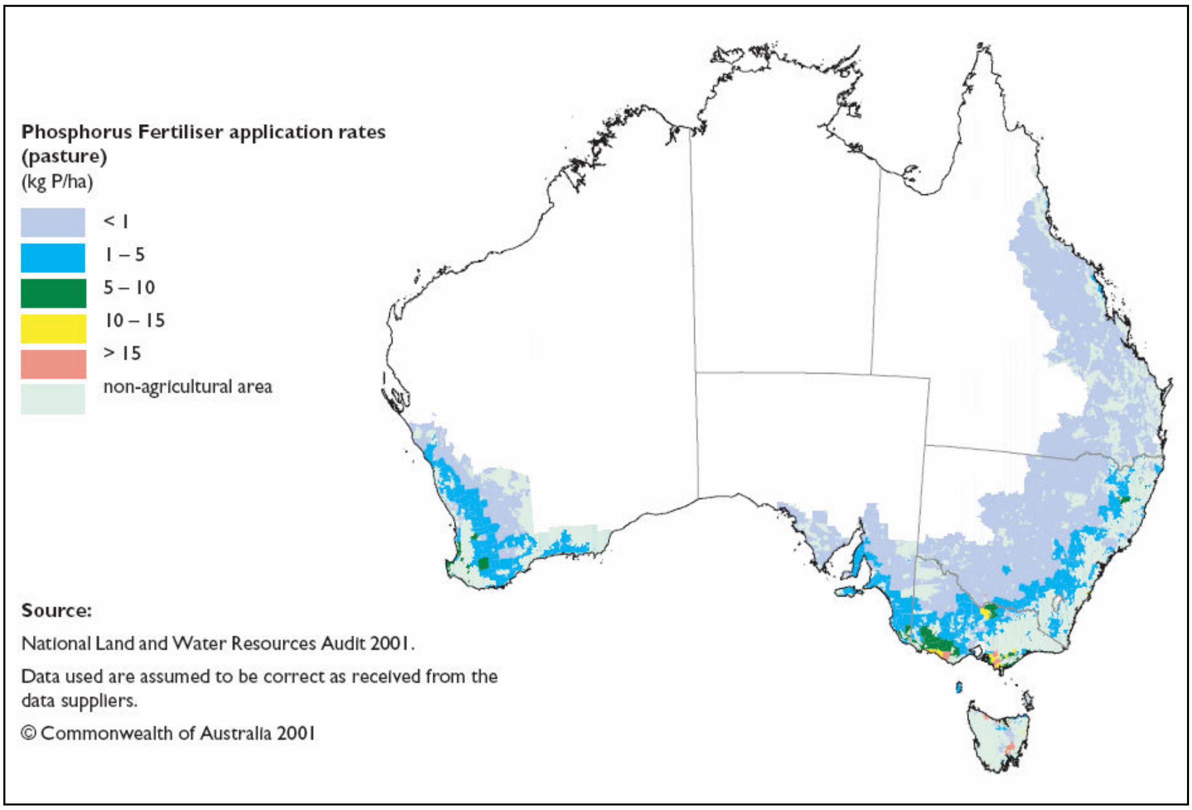

Figure 27: Phosphorus fertiliser application rates for pastures by statistical local area (1992-96). Source: National Land and Water Resources Audit (2001).

6.5 Environmental Impacts

6.5.1 Emissions to air

According to the Australian Greenhouse Gas Inventory, N_2O emissions from agricultural soils in 2006 were 51,000 tonnes (15.8 Mt CO_2-e) and comprised 64% of the total N_2O emissions and 2.7% of total GHG emissions (DCC, 2008a). Furthermore, total emissions of N_2O from agricultural soils increased by 10% between 1990 and 2006 which is 2.5 times greater than the average increase in N_2O emissions for Australia. However, between 2002 and 2006, emissions decreased from 57,000 t year^{-1} to 51,000 t year^{-1} indicating that the trend may be reversing (Figure 28). No information is provided on the contribution of fertiliser use to N_2O emissions from soils. However, it is estimated that these comprised 32% (17,500 t N_2O year^{-1}) of total N_2O emissions from agricultural soils for 1999 (Dalal *et al.*, 2003). In comparison, for the state of Victoria, the direct contribution of N_2O emissions from nitrogen fertiliser is estimated to comprise 20% of the total N_2O emissions from agriculture in that state (Stohlgren, 1988).

Dalal (2003) provided strong evidence that the rapid increase in agricultural N_2O emissions in the 1990's was largely a result of increasing nitrogen fertiliser use (which rose from 0.44 million t in 1990-91 to 1.10 million t in 1999-2000). Thus, it is likely that the reduction in N_2O emissions since 2002 is a result of declining nitrogen fertiliser use. Unfortunately, ABARE stopped collecting fertiliser use data after 2004-05 and the available data provide no conclusive evidence of any decline. However, fertiliser sales data sourced from FIFA (N. Drew, Pers. Comm.) indicate that nitrogen fertiliser use has indeed declined in line with N_2O emissions from agricultural soils. Differences between the estimates from ABARE and FIFA are most likely due to differences in the assumptions used by the different organizations (Chudleigh & Simpson, 2001).

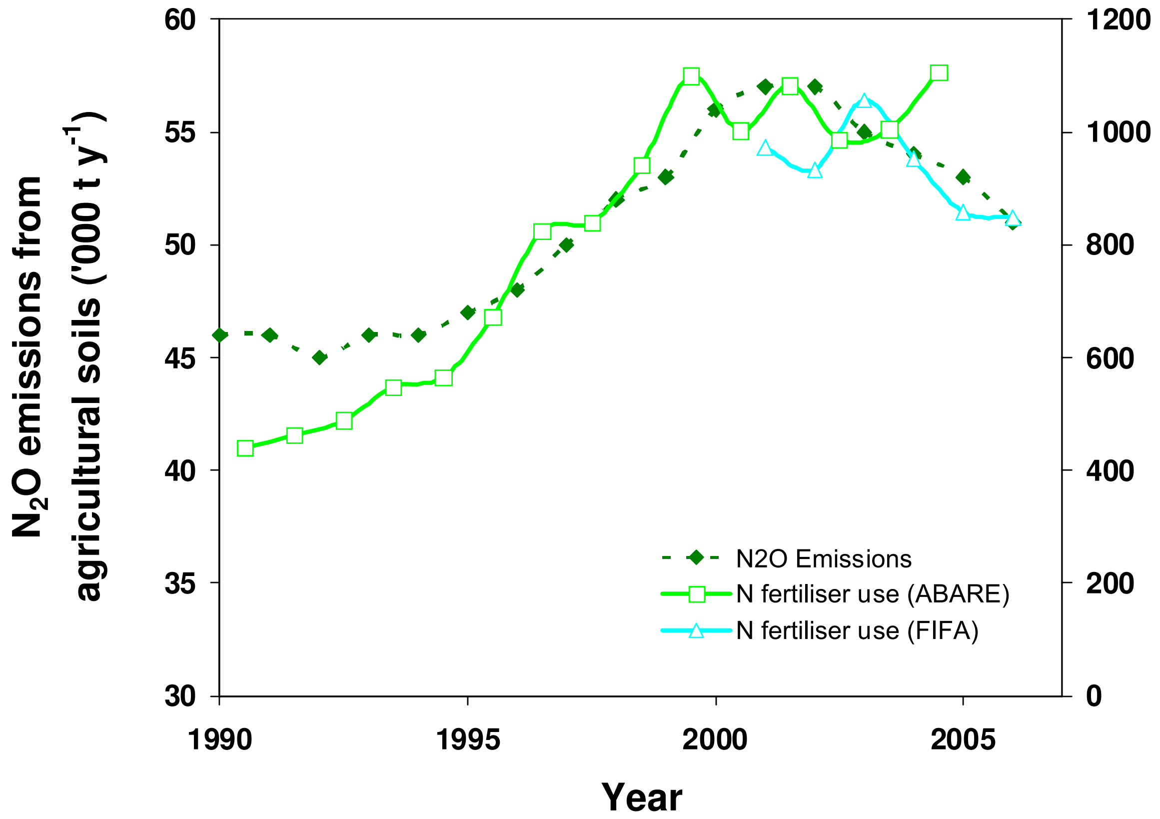

Figure 28: N_2O emissions from agricultural soils and nitrogen fertiliser use from 1990 to 2006. Source: N_2O emissions - DCC (2008a), nitrogen fertiliser use – ABARE (2008), and FIFA (N. Drew, FIFA, Pers. Comm.).

Total emissions of N_2O can be estimated based on emission factors provided by the Department of Climate change, (DCC, 2008) together with the estimates of fertiliser use from Chudleigh and Simpson (2001). Since the DCC provides separate factors for irrigated and non-irrigated crops, fertiliser use for grains and oilseeds from Chudleigh and Simpson (2001) was split into irrigated and non-irrigated systems using landuse data from BRS (http://adl.brs.gov.au/mapserv/landuse/docs/2001_02_Nat_Luse_Summary_Stats.pdf) assuming the same rate of application for each.

Based on these estimates, total N_2O emissions from nitrogen fertiliser use in agriculture are around 9,500 t N_2O $year^{-1}$ compared with 210 t N_2O $year^{-1}$ used on plantation forests (2.1% of the total, Table 20). This is almost 50% less than the estimate of 17,500 t N_2O $year^{-1}$ for 1999 from Dalal *et al.* (2003). The reasons for this difference are partly due to differences in assumptions of fertiliser use for different agricultural sectors (Chudleigh & Simpson, 2001; DCC, 2008a). However, a large amount of this difference is likely to be attributed to the reduction in nitrogen fertiliser use in general.

Table 20: Estimated total emissions of N_2O from nitrogen fertiliser across different agricultural sectors and states. Results based on fertiliser use data (Table 19) and estimated emissions factors for different systems (DCC, 2008b).

Sector	Area[a]	N fertiliser applied[b]	Emmission factor[c]	N_2O emissions[d]		
	'000 ha	kt y^{-1}	t N_2O-N/t-N	t N_2O y^{-1}	kg N_2O ha^{-1}	%
Agriculture						
Pasture[e]	25,607	76	0.004	500	0.02	5
Cereals						
Non-Irrigated	16,266	673	0.003	3,200	0.20	33
Irrigated	682	28	0.021	900	1.32	9
Total	16,948	701		4,100	0.24	
Oilseed/Legumes						
Non-Irrigated	5,816	55	0.003	300	0.05	3
Irrigated	39	0	0.021	10	0.26	0.1
Total	5,854	55		310	0.05	
Sugar	428	96	0.013	1,900	4.44	20
Cotton	435	56	0.005	400	0.92	4
Horticultural crops	419	71	0.021	2,300	5.48	24
Total Agriculture	49,691	1,055		9,510	0.19	98
Forestry Plantations[f]						
Hardwood	740	7.1	0.012	140	0.19	1.4
Softwood	944	3.3	0.013	70	0.07	0.7
Total Forestry	1,685	10.4		210	0.12	2.2
Total	51,376	1,065		9,720	0.19	100

[a] BRS (http://adl.brs.gov.au/mapserv/landuse/docs/2001_02_Nat_Luse_Summary_Stats.pdf)

[b] Chudleigh and Simpson (2001)

[c] DCC (2008)

[d] Ratio of atomic mass of N_2O : N = 1.57

[e] Excludes native pastures which are assumed to have no fertiliser applied but includes hay and silage

[f] Forestry fertiliser data for period 2004-06

Despite this reduction in N_2O emissions, emissions from fertiliser are equivalent to 2.9 Mt CO_2-e or 0.5% of Australia's total GHG emissions (DCC, 2008a). The largest emitter from agriculture is non-irrigated cereals (3,200 t N_2O year^{-1}), with 2,300 t N_2O year^{-1} from horticultural crops and 1,900 t N_2O year^{-1} from sugarcane (Table 20). In comparison, N_2O emissions from plantation forestry were 210 t N_2O year^{-1} or 2.2% of the total, making forestry the lowest emitter except for irrigated oilseed. On a unit area basis, horticultural crops were the largest emitters (5.5 kg N_2O ha^{-1} year^{-1}) with sugarcane (4.4 kg N_2O ha^{-1} year^{-1}) next highest. Estimated emissions from pasture were very low (0.02 kg N_2O ha^{-1} year^{-1}) as a result of the low nitrogen application rate and low assumed emission factor. Estimated per hectare emissions from plantations (0.19 kg N_2O ha^{-1} for hardwoods and 0.07 kg N_2O ha^{-1} for softwoods) were similar to those from non-irrigated cereals (0.20 kg N_2O ha^{-1}).

Thus, estimated N_2O emissions from fertiliser in plantation forestry are very low relative to those from most agricultural systems both in terms of total amounts and emissions per hectare. Furthermore, emissions from forestry are based on IPCC default factors which probably overestimate potential N_2O loss given the low rates of fertiliser application and low potential for denitrification from forest soils (Barton *et al.*, 1999). As a result, greenhouse gas emissions from fertiliser use in plantation forestry are almost certainly to be insignificant compared with total emissions from agricultural soils.

6.5.2 Contamination of water

Emissions of nitrogen and phosphorus to water are assessed as part of the federal government Department of Environment, Water and Heritage, National Pollution Inventory. Results for these are published on the web at http://www.npi.gov.au/database/download-data.html. The approaches used to estimate emissions from different land-uses across Australian water catchments have been reviewed by Letcher *et al.* (1999). Analysis of these data indicate that, by far the most important sources of emissions of total nitrogen and phosphorus are pasture (104,000 t N year^{-1} or 50% of total nitrogen and 7,700 t P year^{-1} or 27% of total phosphorus emissions) and cropping (53,000 t N year^{-1} or 25% of total nitrogen and 7,200 t P year^{-1} or 25% of total phosphorus emissions, Table 21). In contrast, total emissions from predominantly forestry catchments were estimated to be 5,600 t N year^{-1} for nitrogen (2.7% of the total) and 220 t P year^{-1} for phosphorus (0.8% of the total). Furthermore, these catchments include native forests and woodlands as well as plantations. Thus, emissions from the latter represent only a fraction of the total for forestry catchments.

In comparison to total estimated emissions to water of N (210,000 t N/y) and P (28,400 t P/y), those from fertiser use in forestry are very small (171 t N/y and 45 t P/y, or just 0.1% of total N and 0.2% of total P emissions, Table 16, Table 21). Thus, the estimates from the National Pollution Inventory probably overestimate the contribution of emissions from plantation forests to water contamination.

In 2000, an assessment of surface water quality across Australia was undertaken as part of the Australian Water Resources Assessment in partnership with Environment Australia and State and Territory agencies (NHT, 2000). This assessment indicated that nutrients were a major water quality issue in 61% of assessed basins (70 basins or 30% of the national total). Nutrients exceeded state or territory water quality guidelines in the majority of more intensively developed basins in the north-east coast, south-east coast, Murray-Darling and south-west coast drainage divisions. Nitrogen was a major water quality issue (water quality guidelines exceeded in 33% of the basin) in 38% of assessed basins and a significant issue (water quality guidelines exceeded in 5-33% of the basin) in a further 38%. Similarly, phosphorus was a major water quality issue in 53% of assessed basins and a significant issue in a further 27% of basins.

Average annual total nitrogen loads were estimated to be more than double those prior to European settlement (Figure 29) while average annual total phosphorus loads were estimated to be almost triple those prior to European settlement (Figure 30). Altogether, total annual exports of nitrogen and phosphorus were estimated to be 141,000 t N (0.85 kg N ha^{-1}) and 19,000 t P (0.11 kg P ha^{-1}). Much of the nutrient load was associated with soil erosion, with phosphorus attached to soil particles, as a result of loss of vegetation in the riparian zones. However, a large proportion of the total nitrogen load was in the form of dissolved nitrogen associated with denitrification and fertiliser use.

Table 21: Emissions of total nitrogen and phosphorus to water by source (based on measured emissions and areas of different land-uses in catchments across Australia) and estimated emissions from fertiliser use in plantation forestry (based on data in Table 16). Data from National Pollution Inventory (http://www.npi.gov.au/database/download-data.html).

Emission source	Nitrogen		Phophorus	
	Total	Percent	Total	Percent
	000 t/y	%	000 t/y	%
Agriculture				
Pasture	103.9	49.5	7.72	27.2
Cropping	52.5	25.0	7.19	25.4
Horticulture	1.5	0.7	0.34	1.2
Cotton	1.3	0.6	0.16	0.6
Sugar cane	1.1	0.5	0.20	0.7
General	7.3	3.5	0.95	3.4
Total	167.6	79.8	16.55	58.4
Forestry	5.6	2.7	0.22	0.8
Native vegetation	27.9	13.3	1.80	6.3
Urban and industrial	4.2	2.0	9.56	33.7
Other	4.6	2.2	0.22	0.8
Total	210.0	100.0	28.4	100.0
Forestry fertiliser				
Hardwood plantations	0.17	0.08	0.04	0.16
Softwood plantations	0.08	0.04	0.02	0.09
Total	0.25	0.12	0.07	0.24

The greatest nutrient load impacts were predicted to be in the Burdekin (central-eastern Qld.), Murray-Darling, Murchison and Greenough (both central-western WA) basins (Figure 29 and Figure 30). In addition, phosphorus loads had increased by more than ten times and nitrogen loads had increased by more than four times in rivers along the central Queensland Coast (including the Proserpine, O'Connell and Styx basins) which drain into the Great Barrier Reef. There was also a four fold increase in nitrogen loads in the Wakefield basin of South Australia.

River basins assessed to have nutrient levels within water quality guidelines generally had more extensive vegetation cover and were less intensively developed. These included basins in north-east Victoria, Tasmania and north Queensland and south west WA; all areas with large proportions of land covered by native forest or plantations. Land management systems that minimized soil erosion and which protected or re-established riparian native vegetation improved surface water quality. Since the establishment of trees in landscapes achieves both these objectives, it could be expected that water quality of catchments with forest plantations would be far higher than that in cleared agricultural catchments and that the establishment of forested buffers in the agricultural landscape would improve water quality (Fennessy & Cronk, 1997; Norris, 1993).

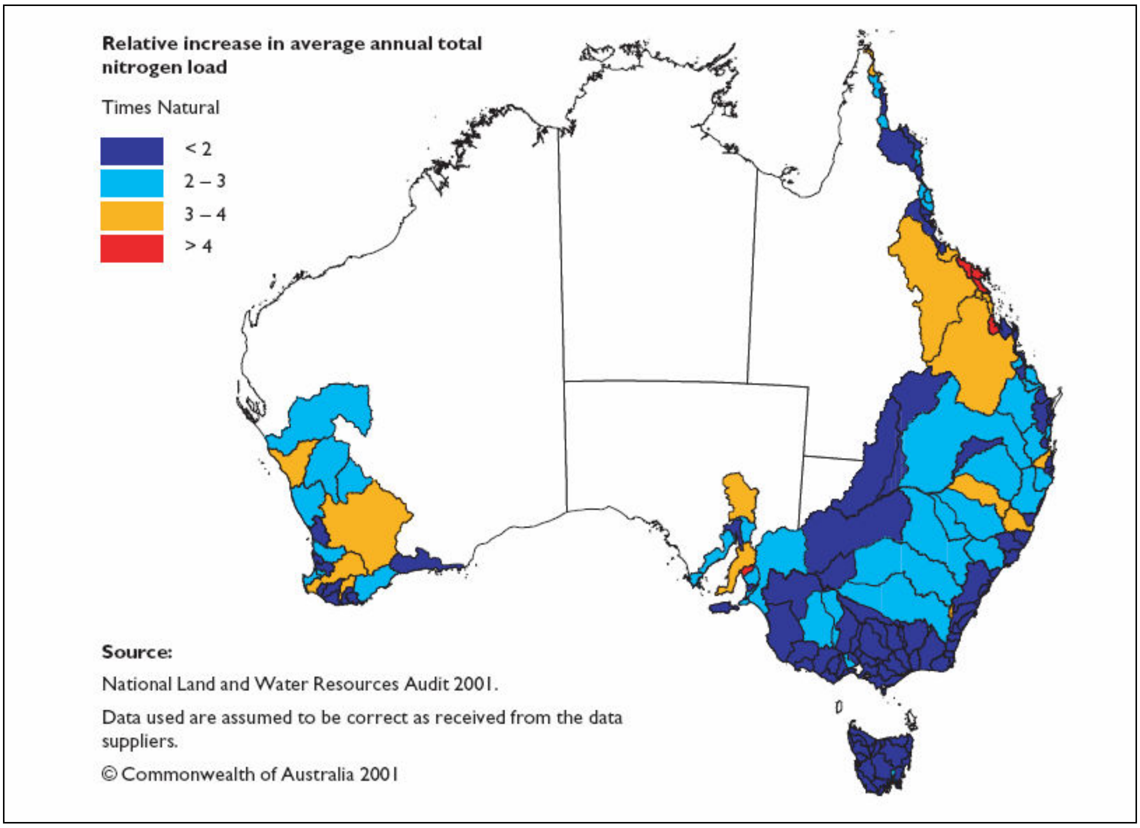

Figure 29: Relative increase in average annual total nitrogen loads by Australian Water Resources Council basin. Source: National Land and Water Resources Audit (2001).

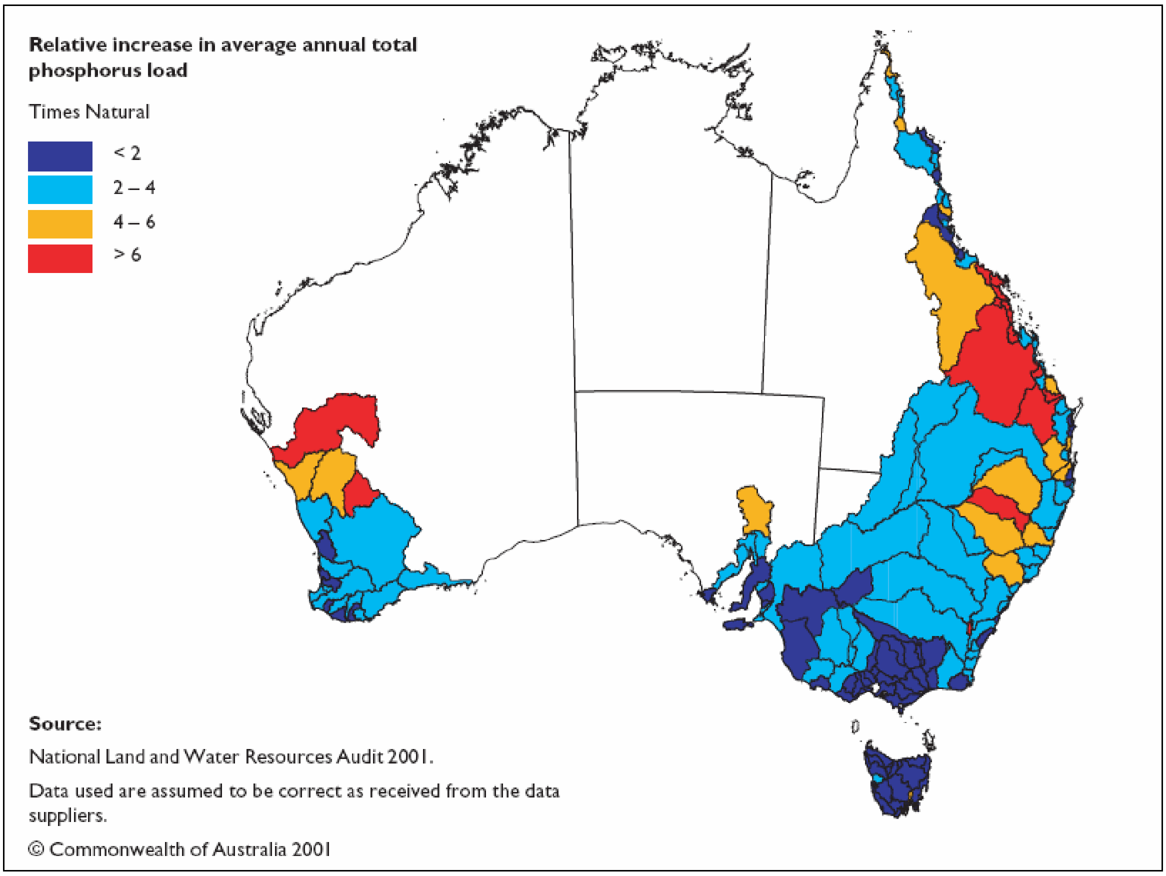

Figure 30: Relative increase in average annual total phosphorus loads by Australian Water Resources Council basin. Source: National Land and Water Resources Audit (2001).

6.6 Fertiliser use and nutrient management for selected agricultural systems

6.6.1 Wheat and oilseeds

Altogether a total of about 21 million ha of land is planted with grain crops each year. In 2006-07, this area included 12.1 million ha wheat, 4.3 million ha barley, 1.0 million ha of oats, 1.1 million ha legumes, 1 million ha canola and 1.2 million ha of other crops (ABS, 2008). There has been a gradual trend of increasing areas planted to wheat, and, more recently canola, as a result of increasing grain prices and falling wool prices.

Traditionally, to supply the majority of crop nitrogen requirements, farmers have relied on mineralisation of soil nitrogen, and biological nitrogen fixation from pasture legumes (Angus, 2001; Hayman & Alston, 1999; McDonald, 1989). However, with the recognition, in the 1980's, that declining soil nitrogen was largely responsible for falling wheat yields (in northern NSW in particular), there was an increase in interest in the use of nitrogen fertiliser to supplement nitrogen exported in harvested grain or lost through leaching, denitrification or volatilisation (Hayman & Alston, 1999). As a result, rates of nitrogen fertiliser addition across the national wheat belt have increased sharply over the past 20 years.

Angus (2001) provided an example of nitrogen balance for a typical Australian wheat crop producing 1.9 t ha^{-1} grain. In this case, 30 kg N ha^{-1} nitrogen fertiliser was required to augment the nitrogen supply from net soil nitrogen mineralisation (71 kg N ha^{-1}) and atmospheric deposition (5 kg N ha^{-1}). Thus, fertiliser nitrogen comprised 20% of total nitrogen inputs. On a national scale, this use of nitrogen fertiliser in wheat crops amounts to around 360,000 t N $year^{-1}$ (based on a total area of 12 million ha) or just over half the total used on grains (Table 19).

Across northern NSW, rates of nitrogen fertiliser application have increased from 20-40 kg N ha^{-1} $year^{-1}$ in 1992 to 51-77 kg N ha^{-1} $year^{-1}$ in 1997 with the greatest increases occurring in the more arid regions (Hayman & Alston, 1999). Despite, this increase in nitrogen fertiliser use, a simple nitrogen balance model (total fertiliser nitrogen minus total nitrogen removed in grain) indicated that nitrogen budgets for more than half the farms surveyed were likely to be negative (average -3.7 kg N ha^{-1} $year^{-1}$). Thus, these nitrogen application rates could be expected to increase further in future if all other factors remain unchanged and the system is to be sustainable from a simple nitrogen balance perspective (Hayman & Alston, 1999).

In other parts of Australia, nitrogen fertiliser rates tend to be lower because of traditionally greater reliance on biological nitrogen fixation from intercropped pastoral legumes such as subterranean clover, or, more recently, crop legumes such as lucerne. However, nitrogen fertiliser usage is also increasing in these systems. Hill and Wallwork (2002) reviewed fertiliser application rates in the high rainfall cropping zone (>750 mm) of WA and showed that average rates of fertiliser use were 56 kg N ha^{-1}, 17 kg P ha^{-1}, 16 kg K ha^{-1} and 9 kg S ha^{-1}. More recently, Simpson (2007) showed that average rates of fertiliser applied to wheat and barley in this region (34-82 kg N ha^{-1}, 3-17 kg P ha^{-1}, 0-50 kg K ha^{-1}, and 4-11 kg S ha^{-1}) were below those required to meet the rain-limited potential crop yields, and fertiliser trials indicated that rates of 104 kg N ha^{-1}, 24 kg P ha^{-1} and 37 kg K ha^{-1} would increase both the yield and profitability of wheat production.

For oilseeds such as canola, Ramsey and Callinan (1994) reported that nitrogen fertiliser recommendations for dryland production range from 25-50 kg N ha^{-1} to 200 kg N ha^{-1} across southern Australia. Based on trials across northern Victoria the authors suggested that the optimum rate of nitrogen application was probably 50 kg N ha^{-1}.

Thus, current annual rates of fertiliser application for wheat and oilseeds appear to range from 50-75 kg ha^{-1} $year^{-1}$. These rates are greater than the average rate for cereals and oilseed/legume crops estimated from the data of Chudleigh and Simpson (41 kg N ha^{-1} $year^{-1}$ for cereals and 9 kg N ha^{-1} $year^{-1}$ for oilseeds/legumes), and are more than 5 times the average rate for hardwood plantations and 15 times the rate for softwood plantations.

6.6.2 Dairy

The most up to date information on land and fertiliser use by the Australian dairy industry are available from the National Land and Water Resources Audit (2002). With the exception of inland irrigation schemes, dairy pastures depend heavily on natural rainfall, although in most regions at least some supplementary irrigation is now used as well. Thus, most dairy farms are located in higher rainfall regions around southern and eastern Australia. The total area of dairy farms in 1998/99 was just over 1,000 ha, with 60% of farms located in Victoria, 14% in New South Wales, 12% in Queensland, and the remainder in Tasmania, South Australia and Western Australia. In 1999/2000, 10.8 billion L of milk were produced, with a gross farm-gate value of $2,853 million.

Historically, most nitrogen supply for dairy pasture has been derived from pasture legumes. However, nitrogen fertiliser is being increasingly applied to enhance productivity. Eckard (2003) states that the use of nitrogen fertiliser on dairy pastures in south-eastern Australia "has increased exponentially over the past 15 years, with over 60% of dairy farmers now topdressing pasture with 25-50 kg N ha^{-1} at least once per year". This is consistent with an estimate from FIFA that 48% of the total value of fertilisers applied to pasture is now applied on dairy farms (National Land and Water Resources Audit, 2002). This figure equates to a total amount of 36,000 t N $year^{-1}$ applied to around 1000 ha of dairy pasture (using figures from Table 19) or about 36 kg ha^{-1}.

However, other reports are much higher than this figure. In a review of fertiliser use and emissions from agricultural sectors, Dalal (2003) indicated that rates applied to dairy pastures were 100-150 kg N ha^{-1} in subtropical pastures of NSW and Queensland, 200 kg N ha^{-1} across most farms in south-eastern Australia, and as high as 300 kg ha^{-1} $year^{-1}$ for other temperate pastures. In addition, a further 30-50 kg N ha^{-1} $year^{-1}$ is added through feed supplements. Effluent from diary farms which has relatively high nitrogen and phosphorus concentrations is also commonly used to irrigate pasture resulting in further inputs of nitrogen and phosphorus.

Deteriorating quality of waterways associated with fertiliser and effluent use on dairy farms is recognised as a regional problem, and nutrient management on dairy farms is being actively researched. In addition, internal transfer losses of nitrogen and potassium are now understood to be considerable. Application of dairy shed effluent to pastures, lessens the loss of nutrients in excreta transfer, but can lead to increased nitrate and phosphate concentrations in groundwater (Hawke & Summers, 2006).

Eckard *et al.* (2007; 2003; 2004) has extensively studied the effects of nitrogen fertiliser use on leaching and denitrification from dairy pastures in south eastern Australia. These studies showed that annual nitrate leaching loads varied from 4-15 kg N ha^{-1} for the control to 6-22 kg N ha^{-1} for a urea fertilised treatment (200 kg N ha^{-1} $year^{-1}$), annual denitrification varied from 5-9 kg N ha^{-1} for the control to 8-18 kg N ha^{-1} for the urea treatment, while nitrogen volatilization losses varied from 13-21 kg ha^{-1} for the control to 45-74 kg ha^{-1} for the urea treatment (Eckard *et al.*, 2007). The differences between treatments indicate that, for 200 kg N ha^{-1} applied as urea, 2% (3.3 kg N ha^{-1} $year^{-1}$) is lost through leaching, 3% (6.7 kg ha^{-1} $year^{-1}$) is lost through denitrification and 20% (39 kg ha^{-1} $year^{-1}$) is lost through nitrogen volatilisation.

This estimate for nitrogen volatilisation losses is similar to that of Prasertsak *et al.* (2001) for dairy pastures in the wet tropics of Queensland where 20% of applied nitrogen was volatilised. However, estimated denitrification losses (20%) were much greater, because nitrogen leaching losses were assumed to be negligible.

The National Land and Water Resources Audit (2001) estimated a partial balance of nitrogen, phosphorus and potassium for a typical dairy system in Gippsland Victoria (Table 22). Based on application rates of 20 kg N ha^{-1}, 25 kg P ha^{-1} and 30 kg K ha^{-1} plus inputs from nitrogen fixation and supplementary feed, total nutrient inputs were estimated to be 152 kg N ha^{-1}, 32 kg P ha^{-1} and 62 kg K ha^{-1}. Losses included 23 kg N ha^{-1} through nitrogen volatilisation and 34 kg N ha^{-1}, 4 kg P ha^{-1} and 11 kg K ha^{-1} through leaching and runoff. Thus, around 15% of total nitrogen inputs were estimated to be lost through nitrogen volatilization, while 22% of nitrogen, 13% of phosphorus and 18% of potassium inputs was lost through leaching and runoff.

Based on the results from Eckard and the National Resources Audit, annual application rates of nitrogen, phosphorus and potassium fertiliser are several times greater than the average for either hardwood (10 kg N ha^{-1}, 4 kg P ha^{-1} and 3 kg K ha^{-1}) or softwood plantations (4 kg N ha^{-1}, 2 kg P ha^{-1}, 1 kg N ha^{-1}). Estimated volatilization losses associated with nitrogen fertiliser are at least an order of magnitude greater for dairy pastures compared with plantation forests (hardwoods 1.8 kg N ha^{-1}, softwoods 0.8 kg ha^{-1}). Dentrification losses are over 40 times greater for dairy pastures (hardwoods 0.10 kg N ha^{-1}, softwoods 0.03 kg ha^{-1}), and leaching losses are more than 100 times greater (hardwoods 0.23 kg N ha^{-1}, softwoods 0.08 kg ha^{-1}).

Table 22: Nitrogen, phosphorus and potassium partial balances for a typical Gippsland dairy system expressed as kg nutrient ha^{-1} on an annual basis. Source: National Land and Water Resources Audit (2001).

Inputs and Losses	Nitrogen kg/ha	Phosphorus kg/ha	Potassium kg/ha	Resource
Inputs				
Fertiliser	20	25	30	Gourley et al. 1998
Rainfall	3	<1	4	Greenhill et al. 1983, Eckard et al. 2001
Legume nitrogen fixation	80			Eckhard et al 2001
Supplementary feed	49	7	28	
Total	152	32	62	
Outputs				
Product (milk)	60	8	20	
Excreta transfer	20	2	24	Hancock 1950, Davies et al. 1962
Volatilisation	23			Evans et al. 1998
Leaching	30	0	10	Ledgard et al. 2000; Carey & Metherell 1999
Run-off	4	4	1	Dairy Farms Annual Report 1998/99, Hosking 1986
Total	137	14	55	
Balance	15	19	7	

Note: Denitrification losses of nitrogen, and fixation of applied fertiliser P and potassium were not considered.

6.6.3 Sugarcane

Australian sugar is grown mainly along the east coast of Australia in northern, central and southern Queensland, northern NSW and a small amount is also grown in the WA Ord river region. According to the BRS, the total area farmed in 2001 was approximately 560,000 ha (http://adl.brs.gov.au/mapserv/landuse/docs/2001_02_Nat_Luse_Summary_Stats.pdf) although the Australian Bureau of Statistics reported that only 409,000 ha were cut in 2006-07 with 36.4 million tonnes of cane produced (ABS, 2008). According to the Australian Natural Resources Audit, the sugar industry generates about $1.2 billion in value each year, with 70% of the refined sugar exported to a wide range of markets.

Chudleigh and Simpson (2001) reported that around 9% (96,000 t N $year^{-1}$) of total nitrogen, 3% of phosphorus (12,000 t P $year^{-1}$) and 17% of potassium (30,000 t K $year^{-1}$) fertiliser is applied to sugarcane (Table 19). Rates of application vary from 100 to 300 kg N ha^{-1} (Dalal *et al.*, 2003). Stewart *et al.* (2006) reported that application rates for traditional farming practices in the Burdekin region of central eastern Queensland were 160-220 kg N ha^{-1} $year^{-1}$.

Dalal *et al.* (2003) state that "emissions of N_2O from sugarcane soils in northern NSW and Queensland are among the highest from agricultural soils" and suggested this was due to high nitrogen application rates high soil moisture and high available C source. Weier (1998) estimated that N_2O emissions from nitrogen fertiliser use accounted for 45-78% of total gaseous nitrogen emissions from land under sugarcane and that total N_2O emissions from denitrification totalled 4,400 t N_2O-N $year^{-1}$. Based on an area of 560,000 ha, this is equivalent to a rate of about 18 kg N_2O-N ha^{-1} (28 kg N_2O ha^{-1}). These emissions varied from 1% of applied nitrogen on coarse textured soils to 3-20% of applied nitrogen on a fine textured soil. Furthermore, there was no evidence that improved practices such as retention of sugarcane trash and no-till have reduced total N_2O emissions.

According to the National Land and Water Resources Audit (2002), fertiliser and nutrient management and emissions of chemicals and fertiliser to waterways are among the main environmental issues identified by the sugar industry, with special concern for impacts of outflows to the Great Barrier Reef. In particular, nitrate contamination of groundwater is a significant problem in some sugarcane growing regions of Queensland. Thorburn *et al.* (2003) found that 14-24% of wells in the Bundaberg, McKay and Burdening regions had elevated (>20 mg L^{-1}) nitrate levels, with 5% above the maximum drinking water limit (> 50 mg L^{-1}) and that nitrate in about half the wells with elevated concentrations was likely to have originated from fertiliser use. Direct measurement of nitrate leaching under sugarcane is difficult. However, modelling by Stewart *et al.* (2006) indicated that, for conventional fertiliser treatment of 200 kg N ha^{-1}, approximately 5-25 kg NO_3-N ha^{-1} (3-15%) was lost to ground water.

6.6.4 Horticultural crops

Australia produces a diverse range of annual and perennial horticultural crops, including vegetables, fruits and nuts, and has a well established and expanding viticulture industry. Products include fresh vegetables (e.g. beans and peas, onions, lettuce and carrots) and fresh fruit (e.g. bananas, apples, pears, peaches and oranges). The total area occupied by horticulture across Australia is about 417,000 ha with a total production of 6.5 million t $year^{-1}$ (ABS, 2003). The largest sectors are vegetable production, which occupies 31% of the area and produces 52% of the gross tonnage, and grapes, which occupy 34% of the area and produce 20% of the total tonnage (Table 23).

The horticultural industry is distributed across a wide range of environments, but is primarily restricted by access to irrigation water, quality soils and topography. Major production areas are concentrated in fertile regions with high annual rainfall or abundant water for irrigation. Annual nutrient removal in horticultural crops can be very high. Thus, relatively high rates of fertiliser use are normally used to compensate. Huett and Dirou (2000) compared rates of nutrient removal for three subtropical horticultural fruit crops (avocado, mango and passionfruit crops) with current recommended rates of application (Table 24). This comparison indicated that recommended fertiliser rates are normally 30-50% greater for nitrogen, 50-80% greater for phosphorus and 20-30% greater for potassium than the rate of nutrient removal in harvested product. This was presumably to allow for leaching, runoff and, in the case of phosphorus, fixation in soil. Thus, most recommended fertiliser rates for these crops appear to be excessive (Huett & Dirou, 2000). This is evidenced by reports of losses of nitrogen of 40-70 kg ha^{-1} $year^{-1}$ for commercial stone fruit orchards where fertiliser rates exceeded crop replacement (Huett & Dirou, 2000).

Table 23: Gross area and production from various horticultural crops for 1999-2000. Source ABS (2003).

Crop	Area		Trees	Production	
	'000 ha	%	million	'000 t	%
Citrus	42.5	10	8.5	628	10
Pome	37.6	9	7.5	476	7
Stone	30.4	7	6.1	174	3
Nuts	16.4	4	3.3	32	0
Tropical					
Orchard	7.0	2	1.4	62	1
Other	14.9	4		401	6
Berries	1.2	0		17	0
Grapes	139.9	34		1311	20
Vegetables	127.4	31		3426	52
Total	417			6526	

Table 24: Recommended application rates and nutrient removals for various tropical horticultural crops. Source: Huett and Dirou (2000).

Crop	Element	Recommended application	Removal in crop
		(kg/ha/y)	(kg/ha/y)
Passionfruit	N	400-800	55-205
	P	50-100	6-18
	K	150-800	21-184
Mango	N	100	8-17
	P	25	2-5
	K	100	13-25
Avocado	N	100	11-61
	P	18-85	2-10
	K	100-150	20-96

Daniells (1995) reported that a survey of banana producers in Queensland indicated that annual rates of nutrient addition were 519 kg N ha^{-1}, 68 kg P ha^{-1} and 750 kg K ha^{-1}. Nutrients except for phosphorus are usually side dressed generally at 4-8 weekly intervals or applied through fertigation at intervals ranging from every irrigation (1-2 days in hot weather) to once per fortnight. Phosphorus is usually applied once at planting or broadcast at six monthly intervals. Nitrogen and phosphorus balances have been estimated for an intensively monitored experiment where nitrogen additions were considerably less than the industry average (238 kg N ha^{-1} and 138 kg P ha^{-1}, Moody *et al.*, 1996). Estimated exports of nitrogen included 80-140 kg N ha^{-1} leached, 5-105 kg N ha^{-1} gaseous losses and 30-80 kg N ha^{-1} removed in harvested fruit. Most phosphorus was fixed in soil, with negligible losses due to leaching or runoff. Since the amounts of nitrogen were less than half the current industry average, leaching and volatilisation losses in typical plantations are likely to be even greater than those measured in the experiment.

In comparison with plantation forests, application rates for tropical horticultural crops are many times greater. More importantly, they appear excessive in comparison to the requirements of the plants and as a result emissions to soil and water are likely to be at least an order of magnitude greater than those from tropical plantations.

6.7 Summary of fertiliser use and environmental impacts in agriculture compared with forestry

Over the past 20 years there has been an increase in fertiliser usage in agriculture. This increase has been most striking for nitrogen which has more than doubled over the period 1990-2000. The key drivers for increased fertiliser usage include: growing indications of nutrient limitations in grain crops in particular (as a result of depletion of soil nutrient stores), reduced use of legume break crops, and a need to increase productivity per unit land area. More recently, large increases in fertiliser prices have lead to a slight decline in nitrogen use.

Rates of fertiliser use vary widely between agricultural systems, with lowest rates for pastoral systems (excluding dairy where rates can be up to 200 kg N ha^{-1} and 75 kg P ha^{-1}) and highest rates for sugarcane (220 kg N ha^{-1}, 28 kg P ha^{-1} and 70 kg K ha^{-1}) and horticultural crops (170 kg N ha^{-1}, 90 kg P ha^{-1} and 110 kg K ha^{-1}). Compared with most agricultural systems, fertiliser usage in plantation forestry is minimal, both in terms of the total amount of fertiliser used and the rate of application expressed on a unit land area basis. Total fertiliser use in hardwood and softwood plantations represents only 1.0% of total nitrogen, 0.9% of total phosphorus and 1.4% of total potassium use in Australia. Rates of application in both hardwood and softwood plantations are among the lowest of any agricultural systems except for legume crops and dryland cattle and sheep grazing. Rates of fertiliser application expressed per unit area fertilised were similar to those used in most agricultural systems except sugarcane and horticulture which were generally higher. However, the frequency of application was between 5 and 9 times lower for hardwood plantations and 21 to 72 lower for softwood plantations compared with that used in agriculture.

As a result of the lower fertiliser usage in forestry, emissions to air and water are far less from forestry compared with most agricultural systems. Estimated emissions of N_2O from forestry were only 2.2% of total emissions from fertiliser and just 0.4% of total N_2O emissions from agricultural soils for the year 2006. Similarly, total leaching of nitrate and phosphate to water from forestry activities were 2.7% and 0.8% of total emissions for nitrogen and phosphorus respectively. While excessive concentrations of nitrate in particular are a serious issue in many agricultural catchments, water quality in forested catchments is generally much better than that in agricultural catchments as a result of reduced erosion risk, reduced drainage and the retention of buffer strips adjacent to waterways and lakes.

On an average per hectare area basis, estimated annual emissions of N_2O air from softwood and hardwood plantations ranged from 0.07-0.19 kg ha^{-1} y^{-1}, (Table 20). Annual emissions to water are estimated average 0.08-0.23 kg N ha^{-1} y^{-1} as NO_3^- and 0.006-0.022 kg P ha^{-1} y^{-1} as PO_4^{3-}. In comparison, emissions of N_2O from agriculture are estimated to range from 0.002 kg ha^{-1} y^{-1} for dryland pasture to 5.5 kg ha^{-1} y^{-1} for horticultural crops. For selected crops, annual emissions of N_2O are estimated at 8-18 kg N y^{-1} (13-28 kg N_2O y^{-1}) from dairy, 18 kg N ha^{-1} (28 kg N_2O ha^{-1}) from sugarcane and 5-105 kg N ha^{-1} (8-165 kg N_2O ha^{-1}) for bananas. Similarly, annual leaching of nitrate is estimated to be 34 kg N ha^{-1} for dairy, 5-25 kg N ha^{-1} for sugarcane and 80-140 kg N ha-1 for bananas. Thus, emissions of N_2O from nitrogen fertiliser use in these agricultural crops are between 50 and 1500 times greater while emissions of nitrate are between 20 and 1700 times greater compared with those from fertiliser use in plantations.

7. KNOWLEDGE GAPS AND OPPORTUNITIES

There has been extensive research into nutrient requirements and fertiliser responses in softwood plantations. However, many uncertainties remain regarding accurate methods to predict fertiliser response especially in older stands, interactions between different nutrients, the effect of fertiliser form and rate on response, optimal timing of fertiliser application during the rotation and the development of economic models which can accurately indicate the potential profitability of different fertiliser strategies. Thus, despite studies showing the potential profitability of mid-rotation fertiliser application, uncertainty regarding accurate targeting of responsive sites for treatment has slowed or even reversed the rate of adoption of this practice operationally in many regions, especially throughout NSW.

Research into fertiliser use in hardwood plantations has, so far, been far more limited, at least in Australia. Because of the young age of most plantations, this research has tended to focus on establishment fertiliser additions with large uncertainties in the potential responsiveness of older stands or second rotation stands. As the hardwood plantation estate approaches harvesting, this is a critical area that requires attention in order to avoid problems similar to those experienced almost half a century ago in second rotation pine stands across southern Australia.

Despite the development of numerous soil and foliar based diagnostic methods for predicting response to fertiliser, these tend to be applicable only to certain regions, sites, species or age classes of plantation. The soil classification system developed by Turvey *et al.* and adapted for site specific management of plantations across NSW and Tasmania shows potential for providing broad guidelines for fertiliser requirements. However, other methods such as foliar or soil analysis are still necessary to fine tune this system. Unfortunately, the cost of collecting, analysing samples and interpreting the results often makes these systems uneconomic. Thus, developments in the use of remote sensing to measure leaf area or foliar nutrients may provide a valuable tool for forest managers.

Apart from a lack of methods to accurately predict fertiliser response, forest managers are limited in their capacity to evaluate the effects on wood production and economics of different fertiliser strategies. Decision support models have now been developed for radiata pine plantations in the Green Triangle which enables the user to quickly assess increases in wood production, value and profitability of different fertiliser strategies for thinned plantations through the rotation (May *et al.*, 2009). This system is based on stand growth rates, responses to fertiliser and predictive relationships developed specifically for the region, but can be modified to allow its use in other regions. Other decision support systems are being developed for other forest types and regions (eg. EucFert for eucalypt plantations in Tasmania, Adams et al 2007). These show promise for improving the selection of responsive stands and the overall efficiency of fertiliser use. However, further work is required to improve these fertiliser decision support systems, increase the accuracy of their response prediction and incorporate their outputs with process-based growth models such as Cabala and 3PG.

Another important area for further research is the impact of fertiliser use on greenhouse gas emissions. Currently, default IPCC factors are the only published information available for estimating direct and indirect N_2O emissions from fertiliser. However, it is likely that these factors, which are based on overseas agricultural systems, overestimate emissions from plantation systems. More is known about leaching losses from fertiliser use. However, recent focus has been more on the impact of plantations on water availability rather than its quality. The comparison in this report on leaching losses from agricultural systems compared with forests indicates that it is important to consider both the amount and the quality of water produced from different land-uses and that decisions based on simply maximising water availability may result in landuse changes that are deleterious to water quality.

Based on the results of past studies opportunities for improving plantation nutrient management are as follows:

- Improved methods for cost effectively predicting fertiliser response in both softwood and hardwood plantations especially the use of remote sensing to assess leaf area and foliar nutrients.
- Nutritional requirements of mid-rotation (5-10 year old) and 2nd rotation eucalypt plantations.
- Quantifying nitrogen volatilisation losses from urea fertiliser for plantations of different ages, species or in different climatic zones and determining optimum rates of application for different nitrogen forms
- Understanding interactions between nutrients and water and between different nutrients (especially nitrogen and phosphorus) applied at different times during the rotation
- Quantification of N_2O emissions and comparison of leaching of nitrate and ammonium from softwood and hardwood plantations under different fertiliser regimes compared with agricultural systems.
- Development or adaptation of tools to assess the economics of different fertiliser strategies and their effects on total wood yield at different stages of the rotation.
- Improving understanding and modelling of soil-plant interactions in nutrient availability, uptake and loss in order to improve the treatment of nitrogen and phosphorus limitations and effects of fertiliser in both process- based and empirical growth models.
- Use of N-fixing associations, intercropping and interplanting, as alternatives to inorganic nitrogen fertiliser.

8. CONCLUSION

As a result of a long history of research into fertiliser use in plantation forestry, much is now known regarding key nutritional deficiencies in different regions potential responsiveness of stands to different types of fertiliser. However, large differences still exist in fertiliser strategies, especially those used in mid-rotation stands between different forestry organisations and regions. While some of these differences probably relate to different nutritional needs of stands in different areas, others may be a result of differing rates of adoption of research findings or major uncertainties still existing regarding growth responses, nutritional requirements and economics of fertiliser use.

Across Australia, fertiliser use in plantations is a critical component of virtually all stand management systems for correcting nutrient deficiencies especially, nitrogen, phosphorus, potassium and trace elements. However, fertiliser use in short-rotation hardwood plantations is far more intensive than that in longer-rotation softwood plantations with more double the amount applied per unit plantation area. The most common types of fertiliser applied include DAP, urea and various NPK blends with or without sulphur and trace elements. This is most likely due to the lower historic costs of DAP and urea compared with other forms. However, recent price rises and research showing the likelihood of substantial volatilisation losses from urea in mid-rotation softwood stands may change this in the future. Based on reported costs of, and responses to, fertiliser, application at establishment appears to be the least profitable, except where substantial, long term growth responses are expected (eg. where critical nutrient deficiencies exist). In contrast, application to mid-rotation hardwood and softwood stands appears to be the most profitable across all scenarios tested. This is reflected in the relatively large proportion of nitrogen in particular used on mid-rotation or later stands. However, inability to accurately predict fertiliser response these stands is still seen as a major constraint by a number of plantation owners.

Fertiliser use in forestry only makes up a small proportion (1-2%) of total use as a result of the low frequency of application and small land areas compared with agricultural systems. Rates of nitrogen and phosphorus application are only a fraction of those used in intensive crops such as sugarcane, cotton and horticulture and on dairy pasture and cereals and are similar to those used for improved pasture and oilseed/ legume crops. Thus, emissions from forestry to both air and water are very low both in terms of amounts per unit plantation area and total amounts emitted. These results indicate that conversion of crop or pasture to plantations and integrated agro-forestry systems should be beneficial, both in terms of improving water quality and reducing greenhouse gas emissions, provided that care is exercised in avoiding overuse of nitrogen in particular and that waterways are protected by riparian buffers.

Substantial research into processes governing nutrient requirements and availability and role of fertilisers has increased the productivity and profitability of growing plantations across Australia in the past. Major improvements in the efficiency of fertiliser use and the long-term sustainability of plantation forestry have resulted. However, substantial challenges remain regarding understanding the nutrition of the recently established large hardwood plantation estate, especially the limitations and requirements of mid-rotation and second rotation stands. Furthermore, there is opportunity for further improving nutrient management of softwood plantations by improving diagnostic tools for predicting fertiliser response in thinned stand in particular and understanding the interactions between different nutrients, fertiliser forms and application times through the rotation. Thus, further research into nutrient management of both hardwood and softwood plantations is warranted and will improve both the future sustainability and profitability of plantation forestry across Australia.

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