Forest & Wood Products Australia

Report

A TOOL TO PREDICT FERTILISER RESPONSE AND PROFITABILITY IN SOFTWOOD PLANTATIONS ACROSS AUSTRALIA

Component 1
South West WA

March 2024

PROJECT NUMBER

VNC476-1819

A tool to predict fertiliser response and profitability in softwood plantations across Australia. Component 1 South West WA

Prepared for

Forest & Wood Products Australia

by

John McGrath, Barrie May and Ian Dumbrell

Publication: A tool to predict fertiliser response and profitability in softwood plantations across Australia. Component 1 South West WA

Project No: VNC476-1819

IMPORTANT NOTICE

This work is supported by funding provided to FWPA by the Department of Agriculture, Fisheries and Forestry (DAFF).

ISBN: 978-1-922718-41-9

Researcher/s:
John McGrath, Ian Dumbrell (McGrath Forest Services), Barrie May (TreeMod).

Forest & Wood Products Australia Limited
Level 11, 10-16 Queen St, Melbourne, Victoria, 3000
T +61 3 9927 3200 F +61 3 9927 3288
E info@fwpa.com.au
W www.fwpa.com.au

Executive Summary

Analysis of the data from WA softwood nutrition and silviculture trials has revealed strong trends in the factors that determine both plantation productivity and responsiveness to fertiliser. The limit to the productivity of plantations in the relatively dry and seasonally variable environment of southern WA is determined by water availability. In order of influence, water availability (measured as the ratio of rainfall to evaporation: R/E), phosphorus supply and then nitrogen supply are the major influences on productivity and responsiveness to fertiliser. Plantation density also has a strong influence on the responsiveness to fertiliser as it influences the availability of water.

The largest responses to fertiliser occurred in situations where there was little restriction on growth due to water supply and the soils were infertile. Plantations on the Blackwood Low Plateau (Donnybrook Sunkland) were the most responsive to fertiliser. Well fertilised plantations in that region, and in other areas with high rainfall, have the potential to grow at more than 30m^3/ha/yr. Current annual increments (CAI) of up to 50 m^3/ha/yr were observed. Where water supply is more restricted the responses to fertiliser are more modest. For example, on the Harvey Coastal Plain the responses to fertiliser were modest despite the fertility of the coastal soils being among the lowest of all the sites on which trials were located. On drier sites plantation density was critical in determining the magnitude of responses to fertiliser with the greater water stress experienced by higher density plantations limiting the response to fertiliser.

There were strong relationships between soil phosphorus and nitrogen concentrations and the response to fertiliser with the response to both nutrients decreasing as the concentrations of these nutrients in the soil increased. The strong relationships between soil nutrient concentrations and growth demonstrated that soil analysis can be used to predict the responses to fertiliser. The Olsen bicarbonate extractable phosphorus provided a useful index of the phosphorus status of the soil. Total soil nitrogen also provided a good estimate of the nitrogen status of the soil.

The duration of the responses to both phosphorus and nitrogen have been estimated from the time course of responses. The longer residual effectiveness of phosphorus contrasts with the relatively short-term responses to applied nitrogen which only lasts between four to six years depending on the application rate.

The interactions between the availability of water and nutrient supply have been defined and used to create three dimensional surfaces that are included in the ProFert model to predict the impact of water supply on the responses to phosphorus and nitrogen. The revised version of ProFert includes the effect of fertilizer rates and the duration of fertilizer responses under WA conditions. The key stand parameters for predicting fertiliser responses in WA plantations include total soil N, soil Olsen P and climate wetness index as well as the amount and type of fertiliser to be applied. These last two factors can be input manually by the user or, alternatively, the model can automatically identify the optimum combinations and amounts of fertilisers to apply at different times throughout a rotation to maximize either profitability or the amount of wood produced at a given site. The recalibrated version of Profert which accommodates the influence of water supply on fertilizer responses has been tested operationally by the Forest Products Commission WA (FPC).

Table of Contents

Contents

Introduction

Fertiliser is an important tool for boosting the growth of softwood plantations after thinning. The economic benefits of appropriate fertiliser use in softwood plantations in Australia and overseas have been well documented (e.g. Campion 2008, May *et al*. 2009). Across Australia, there has been substantial research into nutrient deficiencies in softwood plantations and their correction. This work includes:

- responses to nitrogen (N) and phosphorus (P) fertiliser applied to stands with differing ages, productivities and soil types across different regions of Australia (Neilsen *et al.* 1981, Neilsen 1992, Hopmans *et al.* 1993, Simpson and Grant 1991, 1994, Turner *et al.* 1996, Turner *et al.* 2001, McGrath *et al.* 2003a and 2003b),
- interactions between different nutrients and water availability on growth (Raupach *et al.* 1969, Fife and Nambiar 1999, McGrath *et al.* 2003a and 2003b, Battaglia *et al*. 2004, May and Carlyle 2005, May *et al.* 2009a),
- the effect of different fertiliser forms and times of application on the magnitude and longevity of responses to N and P fertiliser (Raupach *et al.* 1969, Fife and Nambiar 1999, May and Carlyle 2001, May *et al.* 2009a), and
- methods for diagnosing nutrient deficiencies and predicting response to fertiliser (McGrath and Robson 1984, McGrath *et al.* 2003b, Carlyle 1990, May *et al*. 2009).

From this work, various criteria have been identified that can be used to evaluate potential responsiveness of stands to fertiliser. These include soil and foliar nutrients, leaf area index, soil type, stand growth rate and climate. However, identification of responsive sites and accurate prediction of increases in wood production and profitability associated with fertiliser use remains a challenge for growers. This is because relationships between stand and site parameters and response to fertiliser are often not readily transferrable between different regions, species or even age classes. Furthermore, conversion of biological responses to fertiliser to increases in the amount and value of wood products produced can be a complex task.
To improve the capacity of growers to readily predict the profitability of different fertiliser options on different sites FWPA supported the development and parameterisation of a tool, ProFert for Pine (May *et al*. 2017). This tool was designed to integrate existing empirical relationships between stand and site parameters and predicted fertiliser responses in order to calculate long term increases in wood production, log value and profitability. The relationships were obtained from published research (May *et al*. 2009) and data available from collaborating organisations (HVP, Norske Skog and Timberlands Pacific). The most accurate and robust relationships for predicting responses that were available for the regions and growers included in the project were those between the foliar nutrients (N, P, Potassium and Sulphur) and response to N, P and K. As part of the project, these relationships were converted to multi-dimensional surfaces which allowed multiple nutrient limitations to be assessed simultaneously to predict response. The underlying principle used in developing these surfaces was that growth is limited by the most limiting factor so that response to a particular nutrient can be maximised only if:

- no other nutrients are limiting; or
- all limiting nutrients are included in the fertiliser mix.

Other relationships in the model include rate response curves for different fertiliser types and forms and temporal response curves for estimating the duration of growth and nutritional responses to fertiliser. These latter curves were used to model interactions with subsequent fertiliser applications and to estimate the total growth response over the course of a rotation.

The model also included the effects of growth response on both the amount and the value of wood produced by accounting for the effect of increased tree size on yields of different products and the effect of stand age and location on harvesting and transport costs. Increases in wood production can be based on default models or on the outputs of industry growth models such as YTGen to ensure that the predicted increases are consistent with stand inventory and management systems.

By combining empirical results from fertiliser experiments across Victoria, Tasmania and South Australia with growth models used by individual growers, this tool predicts the response, increase in wood production and profitability of fertiliser use in softwood plantations. Estimates of the optimum rates, types, forms and timing of fertiliser strategies to use throughout the rotation to maximize profitability for individual stands were provided. ProFert has been used operationally by several growers across south-eastern Australia.

The wider adoption and use of ProFert is currently restricted due to uncertainty in the applicability of relationships based on results from experiments with *Pinus radiata* in south-eastern Australia to different parts of Australia. The relationships currently used in ProFert were based primarily on foliar nutrient concentrations. Growers have identified the need to develop alternatives to foliar sampling for diagnosing nutrient deficiencies and predicting responses to fertiliser. Foliar sampling at mid-rotation is expensive, requires skilled shooters and is impractical in some situations (e.g. near habitation). Alternatives such as soil sampling and leaf area measurement have been tested in some regions and show promise but require further validation to be operationally useful.

ProFert was designed to include the effect of factors other than foliar nutrients on response. However, no data were available for the regions where ProFert was originally calibrated to assess if responses to fertiliser were limited by rainfall or water availability (May 2009). In contrast, in Western Australia (WA), water availability is a key determinant of growth for softwoods (Butcher 1977, Butcher and Havel 1976, McGrath, Pers. Comm.) and hardwood plantations (White *et al.* 2009, Mendham *et al.* 2011). This difference may be due to the pronounced winter dominance of rainfall and strong rainfall gradients across southern WA which makes water availability more important in determining productivity and the response to fertiliser than in other regions such as the Green Triangle, Victoria, and Tasmania.

Extensive unpublished data from previous trials in WA were used to include the impact of water supply on the response to fertiliser in the ProFert model. This project analysed data from fertiliser trials across WA covering a range of annual rainfalls to determine the interactions between rainfall, nutrient supply, growth, and response to fertiliser. The results were used to develop new predictive relationships that include both rainfall and nutrient status that were incorporated into the model.

Data from the WA experiments was also used to validate and modify the existing P rate response curves in ProFert for WA conditions. The potential for using other diagnostics (e.g. growth rate or soil type in conjunction with rainfall) for predicting response to N and P fertiliser in softwood stands were also assessed.

This project addressed some of the key gaps identified by softwood growers in understanding and predicting fertiliser response and profitability. These include:

- Developing relationships between rainfall and response to fertiliser available from existing WA data to allow for limitations due to differences in water availability.
- Assessing the potential of thinned stands to respond to N and P fertiliser and quantifying the duration of responses to N and P applied at different rates.
- Developing relationships between soil nitrogen and phosphorus and response to fertiliser from a series of trials across southern WA

The resultant updated version of ProFert was then tested for operational use in softwood plantations in WA. This WA specific version was demonstrated to be useful in identifying potentially responsive sites to fertilise as well as optimize fertiliser strategies (i.e. determine the most profitable rate, type and timing for fertiliser application) across FPC's plantations. Subsequent measurements from operational trials in WA can be used to further refine the tool in future providing ongoing improvements to its accuracy and ease of use.

Methodology

Overview of the fertiliser trials used in the WA synthesis.

The data underpinning this project were developed and provided by the Forest Products Commission (FPC) and its predecessor agency the Department of Conservation and Land Management from the 1980's to the early 2000's. Much of this data was unpublished. This includes results from a series of experiments that assessed responses to fertilisation at various thinning intensities in *P. radiata* plantations across sites covering a range of climates and productivities. Initial analyses of this work indicated that stand density, measured as basal area and annual rainfall were important determinants of productivity in both unfertilised and fertilised stands. In addition to trials examining the influence of climate and plantation density on the response to fertilisation there are a range of other trials that have assessed the rates of N and P required to optimise plantation productivity in southern WA. These trials have been carried out in plantations on both low fertility ex-forest sites and higher fertility ex-farming sites.

This synthesis of analysed data from fertiliser trials across WA covering a range of annual rainfalls to determine the interactions between rainfall, nutrient supply, growth and response to fertiliser is presented below in three sections,

1. The influence of climate and plantation density on the response to fertilizer
2. The magnitude and duration of responses to N and P fertiliser in thinned plantations, and
3. Assessing and predicting the responses to fertiliser applications.

The results were used to develop new predictive relationships that include both rainfall and nutrient status that were incorporated into Profert and presented in Section 4.

The trials included in this synthesis were:

Mid rotation thinning x fertiliser trials (four trials):

Four *P. radiata* sites which assessed the mid rotation responses to thinning and fertiliser and were monitored for a minimum of four years and some for as long as 10 years. This allowed the development of relationships between plantation density, fertility, climate and productivity to be defined. Data included:

- tree growth: diameter, height annually (some sites have seasonal diameter growth patterns for specific periods).
- seasonal leaf water potential across multiple years (between three and nine years at individual sites).
- soil water measurements, combined the soil and leaf water data allow the development of relationships between water availability and productivity.

These sites were located to provide sites across the climatic gradients in southern WA but were limited by the availability of plantations and plantings on farmland. These data were combined with data from other fertiliser trials to provide a broad coverage of productivity across the rainfall and evaporation gradients in southern WA.

N x P and N P fertiliser trials (four trials):

There were four main trials, two of which have been published (McGrath 2003 a, 2003b). The sites cover a range of soil (lateritic gravels/loams, duplex sand over clay, deep sands) and climatic conditions, though generally in the >850 mm rainfall zone. In addition to the responses to increasing rates of fertiliser, one trial assessed the impact of split applications and the timing of fertiliser applications.

N rate and P rate trials (three trials):

These trials were established in young plantations and were monitored for up to 21 years. This data provided useful information on the magnitude of responses to N and P fertiliser and were used to develop rate response curves for these elements applied pre-canopy closure.

N x P and potassium trials on ex farmland (five trials):

These consist of four of N x P trials in younger *P. radiata* plantations in the south coast region of WA. These will be used in calibrating the use of soil analysis in defining responses to fertiliser. Initial results indicated that virtually none of these sites responded to P, but there were responses to N and to K on two sites where a potassium rate and N x K interaction trials were installed.

Additional descriptions of methodology are contained in each of the sections below.

Section 1: The influence of climate and plantation density on the response to fertilizer.

Results and Discussion

Summary of climate data

By integrating the data from thinning and fertiliser trials and fertiliser trials across a mean annual rainfall (MAR) range from approximately 300 mm (Wickepin) to 1100 mm (Tallanalla) the interaction between rainfall and responsiveness was assessed. The inter annual variation in rainfall provided an even wider range of climatic conditions with the lowest rainfall at Wickepin of 239 mm and the highest at Tallanalla of 1529 mm (Table 1). These data provide the opportunity to understand the responses to variation in water supply and nutrient status on the productivity of *P. radiata* plantations in south-west WA.

Table 1. Summary climate data for mid-rotation thinning and fertiliser and fertiliser trials in SWWA.

Geological Region	Trial Location	Trial type	Period*	Mean Annual Rain MAR (mm) (Range)	Evap (mm)	CWI (R/E)
Blackwood Low Plateau	Baudin 1	T x F	1976-2019	899	1297	0.69
			1988-2000	**938 (651-1260)**	**1308**	**0.73 (0.46-0.95)**
	Vasse 1	T x F	1976-2019	883	1361	0.65
			1994-2000	**1059 (653-1287)**	**1381**	**0.77 (0.51-0.94)**
	Vasse 9	N Rates	1976-2019	913	1326	0.69
			1993-2001	**1021 (780-1142)**	**1338**	**0.77 (0.55-0.87)**
Darling Scarp	Tallanalla	N x P Rates	1976-2019	1015	1514	0.67
			1985-1995	**1120 (789-1529)**	**1495**	**0.76 (0.47-1.00)**
Swan Coastal Plain (Harvey)	Myalup 132	T x F	1976-2019	791	1637	0.48
			1993-2002	**758 (560-1102)**	**1660**	**0.46 (0.35-0.68)**
	Myalup 131	N x P rates	1976-2019	791	1637	0.48
			1995-1999	**841 (695-1102)**	**1655**	**0.51 (0.42-0.68)**
	Myalup 53/65	N + P Rates	1976-2019	785	1633	0.48
			1978-1984	**884 (751-1024)**	**1600**	**0.64 (0.46-0.62)**
Yilgarn Block	Martins	T x F	1976-2019	345	1722	0.20
			1999-2004	**316 (239-433)**	**1676**	**0.19 (0.14-0.27)**

* Note; The longer period (44 years from 1976-2019) provides a benchmark for the climate in southern WA. Noting that there was a significant decline in rainfall in southern WA in the mid 1970's, hence the use of 1976 as the commencement point of the medium term climatic indices. The second row for each site covers the measurement period for the trials. The range of rainfall and CWI over the trial periods are shown in parentheses.

Climate details and trends.

There were significant variations in the availability and demand for water across the range of trial sites driven by both rainfall and evaporation. The wettest sites located in the Blackwood Low Plateau (BLP aka Donnybrook Sunkland) and the Darling Scarp areas had significantly higher rainfall and lower evaporation than the sites located on the Coastal Plain and Yilgarn Plateau.

Relative to the longer-term climate indices the periods when the trials were undertaken were similar to the longer-term estimates of climate. Small variations from the longer-term values were the ~100 mm higher annual rainfall for the Blackwood Low Plateau and Darling Scarp sites during the monitoring period. Variations in growing season evaporation from the longer-term means were small at all sites. Variations in climate wetness index (CWI=rainfall/evaporation) are largely driven by variation in rainfall as evaporation was relatively constant across years at each site.

Relationship between climate and productivity.

The overall relationship between annual biomass production and climate wetness index (CWI =R/E) (Figure 1) demonstrated that there was a strong upper limit to productivity related to both the supply (rain) and environmentally driven demand (evaporation) for water. In addition to the influence of water supply and demand that is mediated by climate, the influence of factors such as nutrient supply (including the variation in growth due to the time since fertilisation – see section on duration of fertiliser impacts), plantation density and soil factors all influence the productivity achieved. Variation in these factors explain a very large proportion of the differences in the site productivity data.

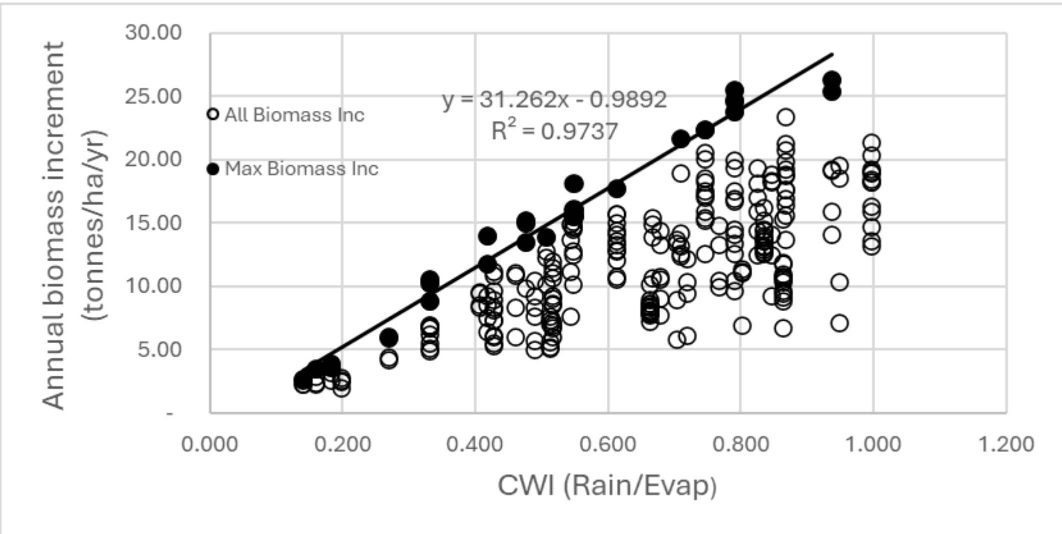


Figure 1(a). Relationship between annual biomass increment (tonnes/ha/yr) and annual climate wetness index (CWI = R/E).

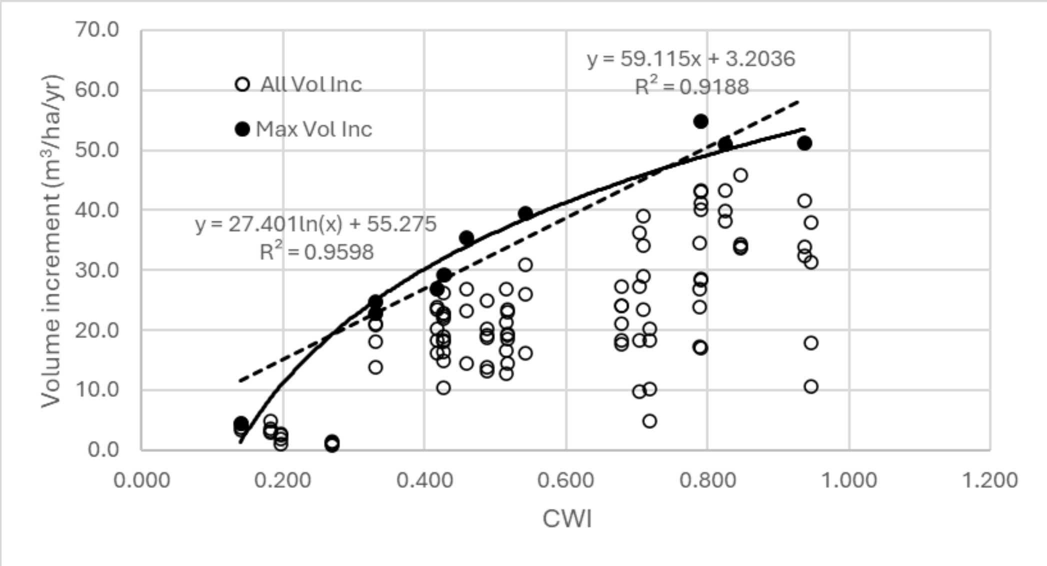


Figure 1b. Relationship between annual volume increment (m^3/ha/yr) and annual climate wetness index (CWI = R/E).

Notes:

1. The data are from plantations in the mid to later part of the rotation.
2. Biomass was calculated using a regression based on diameter only, developed from trees from multiple sites across a variety of ages, sizes and locations. Similarly, volume was estimated using both diameter and height. Fewer volume data were available as height was not measured annually on all sites or over all periods.
3. The data are current annual increment (CAI) for biomass, (tonnes per ha, Figure 1a and volume m^3/ha/yr, Figure 1b). As there were variations (generally small) in the measurement dates the data were adjusted to provide estimates based on a full year.
4. Climate data were derived from the QDAF/BoM Silo/Long Paddock climate data system. The annual climate data were for the period June-May to match the growing season of pines in WA where the minimum growth occurs in late autumn/early winter. Previous versions of this used local estimates of weather data, supplemented by data from Met Access. The annual CWI rather than the site mean data are used to construct the relationship between CWI and productivity.
5. The upper limit to productivity, shown as the boundary regression (identified as solid symbols), was based on the top ~10% of the data (i.e. 29 from 266 data for biomass and 10 from 110 for volume).

The upper limit of the data provides an estimate of the potential productivity of *Pinus radiata* in southern WA when no other limitations such as nutrient supply, soil water storage capacity or plantation density limit growth. For example, as these plantations were largely growing on ex native forest sites the nutrient status of the sites was low and in particular nitrogen availability depended on fertiliser inputs. Without fertiliser application and when soil water storage or plantation density limit growth, the realised productivity on these sites is well below the potential productivity as shown by the data points below the optimum productivity line (open circles). Therefore, variation in the data for each annual series (the vertical spread of data at individual CWI) is due to productivity being limited by low fertility, sub optimal plantation density or the capacity of the soil profile to store all the available water. The details of the response to these factors at the individual sites is provided in more detail in the following section '*Mid rotation fertiliser and thinning by fertiliser trials*'.

Mid rotation fertiliser and thinning by fertiliser trials.

Table 2. Summary of the response fertiliser in older age trials across the climatic and soil fertility gradients in Western Australia.

Geographic unit	**Plantation &Compt.**	**CWI for trial**	**SPH**	**Soil N%**	**Soil P HCO_3 (ppm)**	***Actual response (m3/ha/yr)**	*** % response**	**Period of response**	**Comments**
Blackwood Low Plateau	Baudin 1	0.74	300-700	0.08	5.0	11.1-12.6	44-85	1988-2000 (age 9-21)	Response to combined N and P Beyond age 17 no fertiliser applied.
	Vasse 1	0.77	375-750	0.06	31.0	4.0-6.6	13-33	1994-2000 (age 11-17)	Response to N only and increases with N rate. Response at mid-rotation limited by high early N applications.
	Vasse 9	0.77	412	0.06	31.0	2.8-9.8	10-30	1993-2001 (age 13-21)	Response to N only as adequate P applied. Response increased with increasing N application.
Darling Scarp	Tallanalla	0.76	380	0.10	1.4	7.5-11.5	85	1987-1997 (age 17-27)	Response to N and P in factorial trial Response to N declined after six years.
Swan Coastal Plain	Myalup 53/65	0.55	220	0.03	0.5	**[#]6.9**	47	(1978-1984 Age 21-27)	Response to N and P but overall response limited by water supply at higher densities with total response constant across densities, % response decreased with increasing density.
	Myalup 132	0.46	250-750	0.04	0.6	5.6-6.0	27-41	1993-00 (age 14-21)	
	Myalup 131	0.51	357	0.04	0.5	5.3	27	1995-1999 (age 16-20)	
Yilgarn Plateau	Wickepin	0.19	250-500	0.04	2.0	*[##]0.7*	*[##]Nil*	2000-2004 (age 12-16)	No response to fertilizer as growth was limited by water availability.

Notes:
* This is based on the volume response. Volume estimates were based on the cone formula and from local volume equations. However, any changes to % responses likely small and % responses are used to drive ProFert.

[#] Estimated from data in published paper (McGrath *et al.* 2003)

[##] This response was not statistically significant

Impact of thinning and fertilisation on productivity and water stress across the climate gradient in southern WA.

Responses at high rainfall.

Blackwood Low Plateau (Baudin 1) (Mean Rain = 942 mm CWI = 0.72)
Fertilising a 9-year-old stand with N (270 kg/ha) and P (90 kg/ha) at four-year intervals (age 9, 13, 17; 1988, 1992, 1996) (Figure 2) resulted in a 140 m^3/ha increase in volume increment at 300 sph (an 84% increase) and a 126 m^3/ha increase in volume increment at 700 sph (a 44% increase) to age 21. No further fertiliser was applied after age 17 (1996) and the decline in the slope of the growth curve at age 21 (2000), four years after the third fertiliser application, suggests that growth beyond this point was limited by a reduction in the nutrient status of the plantation. This decline in growth four years after the final nitrogen application is consistent with the decline in growth observed in other fertiliser trials both in WA (McGrath *et al*. 2003) and other regions (May *et al*. 2009b). The 12-year PAI (age 9 – 21) for the fertilised 300 sph and 700 sph treatments were 26 and 34 m^3/ha/yr respectively. Beyond age 21 the PAIs declined to 14.1 and 13.8 m^3/ha/yr for the 300 and 700 sph fertilised treatments (Table 3).
In this region, the period 2000 - 2010 was drier than average, and based on the overall relationship between CWI and productivity (Figure 1) the contribution of the drier years to the decline in productivity when CWI declined from 0.73 to 0.62 would have been approximately 17%. However, the decline in productivity from 2001 to 2010 was much larger than this and varied between 43% and 60% (Table 2). This suggests that in addition to a decline in growth related to the lower rainfall during this period that a decline in nitrogen supply or an age-related decline in productivity contributed to this larger decline in growth rates. The application of 90 kg at each of the three fertiliser applications between 9 and 17 years likely eliminated any deficiency in phosphorus.
While it was apparent that there was a significant decline in productivity between age 21 and 30 years, the response to fertiliser achieved in the previous 12 years was either sustained at 700 sph or increased at 300 sph so that at the end to the rotation the additional volume from fertilisation was 130 m^3/ha at 700 sph and 198 m^3/ha at 300 sph.

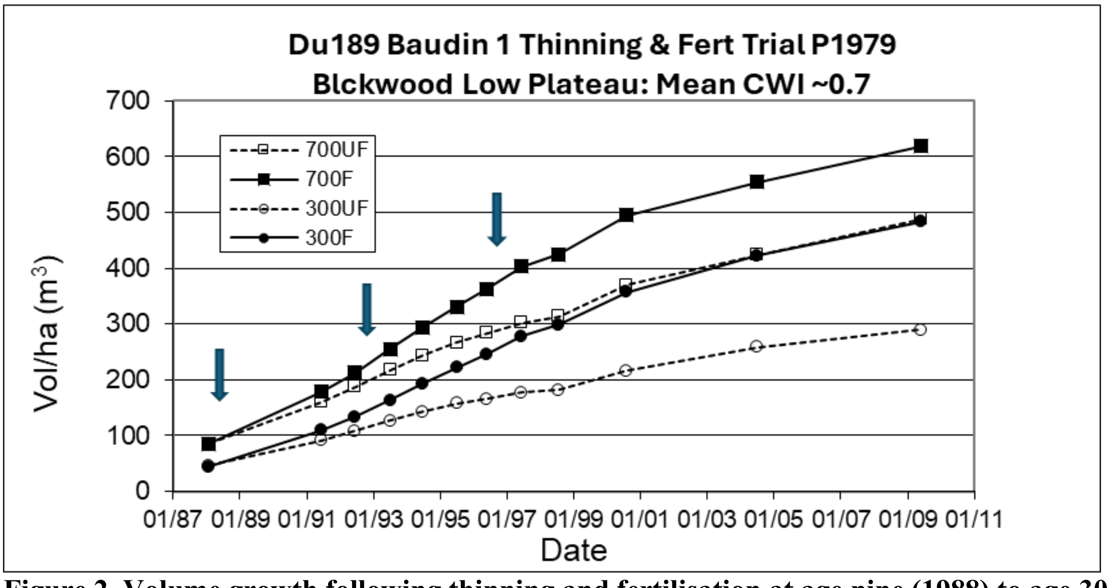


Figure 2. Volume growth following thinning and fertilisation at age nine (1988) to age 30 years (2009). Fertilised with N (270 kg/ha) and P (90 kg/ha) at four-year intervals (age 9, 13, 17; 1988, 1992, 1996). Fertiliser applications indicated by arrows. From age 9 to 30 years.

Table 3. Periodic annual increments following thinning and fertilisation (Baudin 1).

Density and fertiliser treatments	PAI (m^3/ha/yr)		
	9-21 years (1988-2000)	21–30 years (2001-2011)	% 2001-2010/ 1988-2000
Growing season rain (mm)	938	806	85
CWI	0.73	0.62	
300 sph, nil fertiliser	14.3	8.2	57
300 sph, 3 x (270 N + 90 kg P)	26.0	14.1	54
700 sph, nil fertiliser	23.7	13.2	56
700 sph, 3 x (270 N + 90 kg P)	34.1	13.8	40

Pinus radiata ceases growing at a pre-dawn leaf water potential (PDLWP) of -1.5 MPa. Thus, with the exception of 93/94 (723 mm) and 94/95 (651 mm) years when rainfall was significantly lower than the mean over the 9-year period from 9 - 18 years when PDLWP was monitored, the growth of unfertilised trees at this plantation would have been continuous as PDLWP remained above this critical level, albeit slower as the seasonal water stress progressed. There was a very large difference in the level of water stress between the fertilised and unfertilised treatments with the trees in fertilised plots experiencing higher levels of water stress (Figure 3). The additional water used by the faster growing fertilised treatments (see Figure 4 below) led to lower water potentials (higher levels of water stress) in the fertilised treatments relative to the unfertilised treatments culminating in PDLWP falling below the critical minimum in autumn in 1994 and 1995 in the fertilised plots.

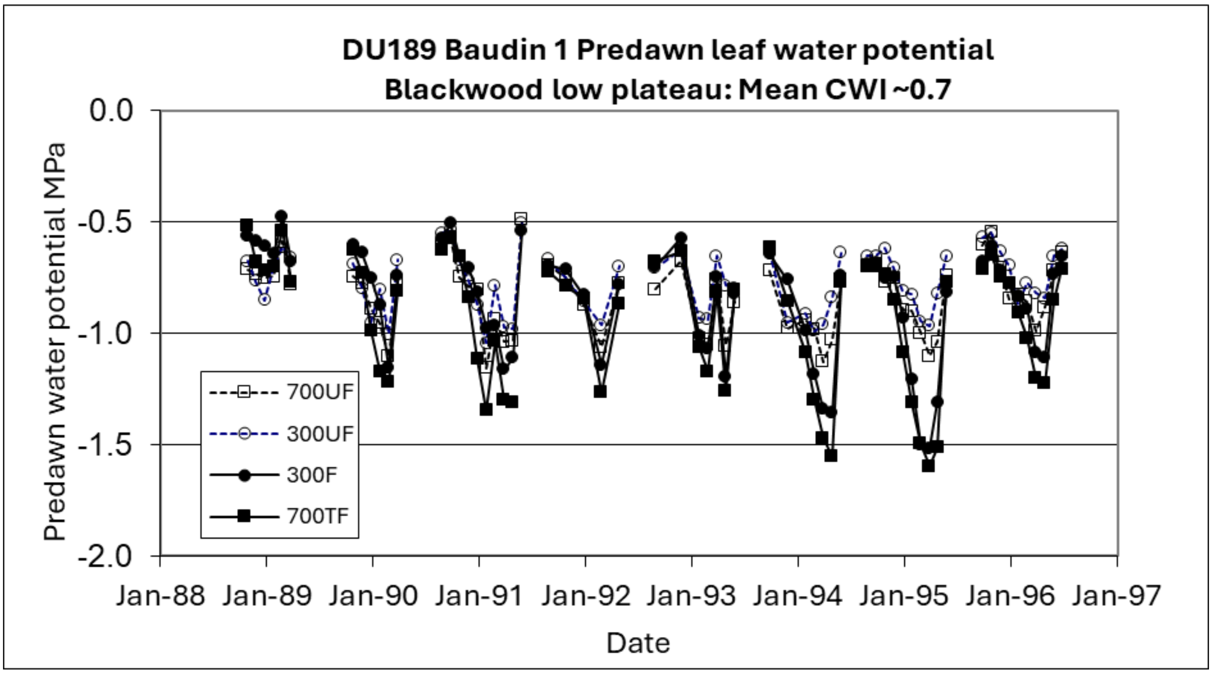


Figure 3. Influence of plantation density and fertiliser application on pre-dawn leaf water potential from November 1988 to July 1996, from age 9.4 to 17 years. (Baudin 1 thin x fert trial).

Soil water was measured to 4 m at the Baudin 1 site. Despite the high rainfall (mean rainfall during the monitoring period of 938 mm) the annual recharge in the surface 4 m appears to be ~400 mm (Figure 4). This was the same or less than for the drier site at Myalup on the Swan Coastal Plain (Figure 7) and indicated that water was lost from these soil profiles either through runoff or drainage.

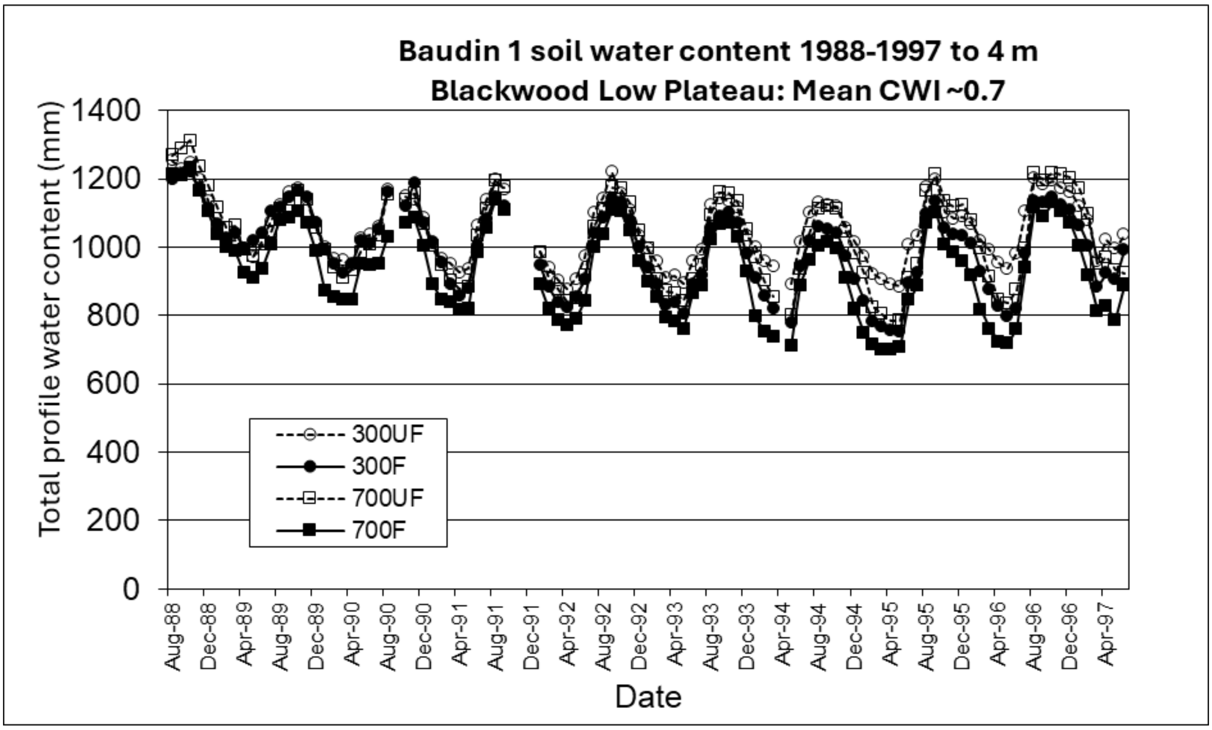


Figure 4. The impact of plantation density and fertiliser application on the annual variation in total soil water content to 4.1 m at Baudin 1, from age 9.25 to 17 years.

Responses at medium rainfall: Swan Coastal Plain.

(Myalup 132) (Mean Rain = 742 mm CWI = 0.46)

The response to fertilisation of a 14-year-old stand on the Swan Coastal Plain (Harvey) fertilised twice with N (270 kg/ha) and P (90 kg/ha) at a four-year interval (age 14, 18; 1993, 1997) was influenced by the density of the plantation (Figure 5). The response to fertiliser in the seven years from 14 to 21 years, estimated as volume increment, was 39, 31 and 14 m^3/ha across the density range 250, 500, 750 sph. As the overall growth was lower in the lower density stands the percentage increase in volume growth was consequently higher in the lower stocking 250 sph stand at ~38% and declined to 31% at 500 sph and 11% at 750 sph.

The fertiliser response was sustained to age 25 (2004) in all treatments. Beyond age 25 the response to fertiliser declined in the 500 and 750 sph treatments with no significant difference in volume production between the fertilised or unfertilised 500 and 750 sph treatments at age 32 years (Figure 5). The initial response to fertiliser in the 250 sph treatment was sustained through to 32 years.

No further fertiliser was applied after age 18 (1997) and the change in the slope of the growth curve beyond age 21 (2000) suggests that the reduction in nutrient supply contributed to the decline in growth beyond this point. The percentage reduction in PAI after age 21 was greatest in the 250 fertilised stand which initially had the greatest response to fertiliser (Table 4). The 7-year PAIs (age 14 – 21) for the fertilised stands were 20.3, 24.6, 19.7 m^3/ha/yr for the 250, 500 and 750 sph treatments respectively and for the unfertilised stands the PAIs were 14.8, 20.1, 17.0 m^3/ha/yr respectively (Table 4). Beyond age 21 the PAIs declined in all treatments, with the greatest decline in the fertilised treatments. By age 32 years the earlier fertiliser responses at the 500 and 750 sph had been offset by the slower growth in the fertilised treatments between age 21 and 32 years. In contrast the initial gain in growth from fertiliser in the lower density 250 sph treatment was sustained. While in general the first decade in the 2000's was drier than average across southern WA, the CWIs were similar for the period 1993-2000 (CWI: 0.47) and 2000-2011 (CWI 0.45) (Table 4) at the Myalup site. This indicates that the decline in growth post 21 years at this site was not related to declining rainfall.

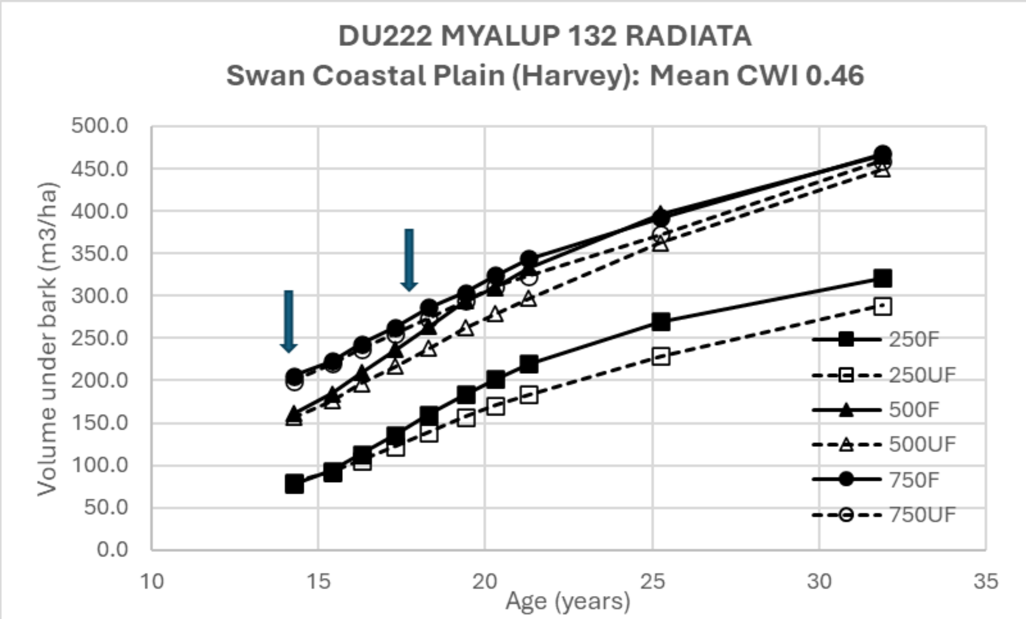


Figure 5. Volume growth following thinning and fertilisation at age 14 (1993) to age 32 years (2011). F: fertilised with N (270 kg/ha) and P (90 kg/ha) at a four-year interval (age 14, 18; 1993, 1997), UF: unfertilised. Values in legend indicate the post-thinning stocking in stems/ha. Fertiliser application indicated by arrows.

Table 4. Periodic annual increments following thinning and fertilisation (Myalup 132).

Density and fertiliser treatments	**PAI (m^3/ha/yr)**		
	14-21 years (1993-2000)	**21 – 32 years (2000-2011**	**% 2000-2011/ 1993-2000**
Mean growing season rain (mm)	782	722	92
CWI (R/E)	0.47	0.45	
250 sph, nil fertiliser	14.8	9.5	64
250 sph 2 x (270 N + 90 kg P)	20.3	9.2	45
500 sph, nil fertiliser	20.1	13.8	68
500 sph 2 x (270 N + 90 kg P)	24.6	12.0	48
750 sph, nil fertiliser	17.0	12.3	72
750 sph 2 x (270 N + 90 kg P)	19.7	11.3	57

Soil water and leaf water potential were only measured at this site for three growing seasons, from age 15 – 18 years (Figure 6). There was a very strong difference in the level of water stress between treatments with the density of the plantation having a much greater impact on the level of water stress than on the higher rainfall Baudin 1 site. Applying fertiliser at each density increased the level of water stress (Figure 6), though the impact of fertiliser was modest compared with the impact of increasing plantation density.

The level of water stress at this Swan Coastal Plain site was greater than in the higher rainfall site on the Blackwood Low Plateau with the denser treatments and the 750 sph treatment had lower PDLWP for much of the year and in two of the three years of monitoring growth in the denser treatments was below the point (-1.5 MPa) at which growth ceased for four months. This likely accounts for the lower percentage increase in the growth of the fertilised treatments in the high-density treatments on this site.

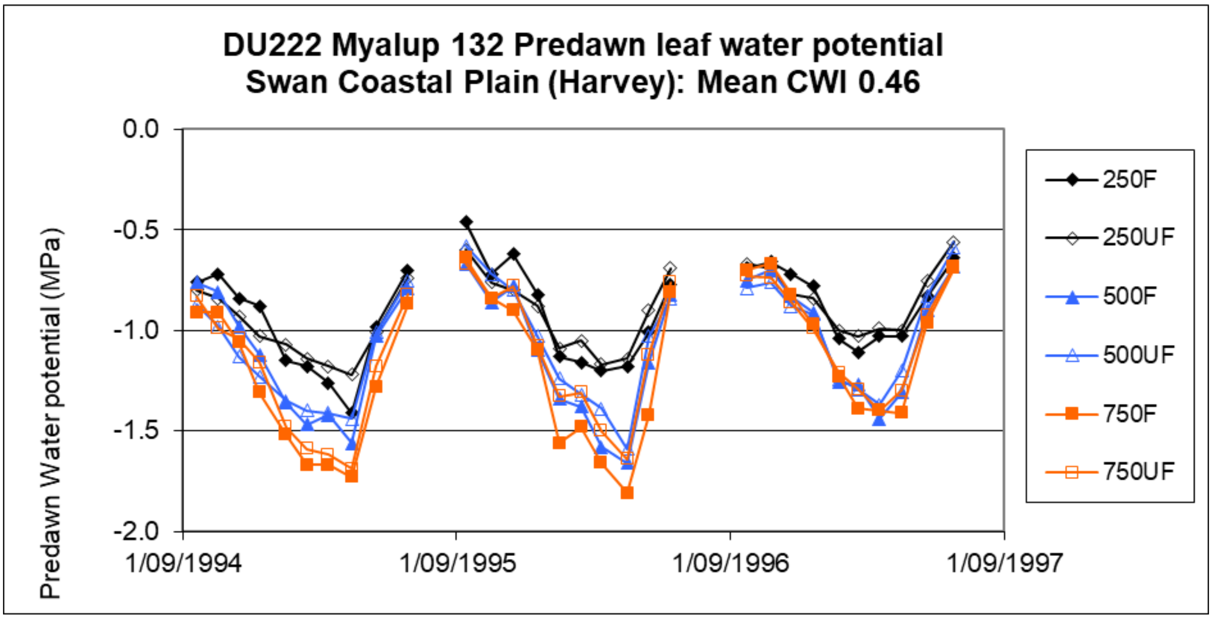


Figure 6. Influence of plantation density and fertiliser application on pre-dawn leaf water potential from September 1994 to June 1997, age 15 to 17 years. (Myalup 132 Thin x fert trial).

There was a strong variation in rainfall and hence CWI across the three monitoring seasons with rainfall of 611, 724 and 1102 mm in successive growing seasons from 1994/95 to 1996/7. CWI followed a similar pattern varying with values of 0.33, 0.42 and 0.68 across this period. Which is reflected in the level of water stress over this period.

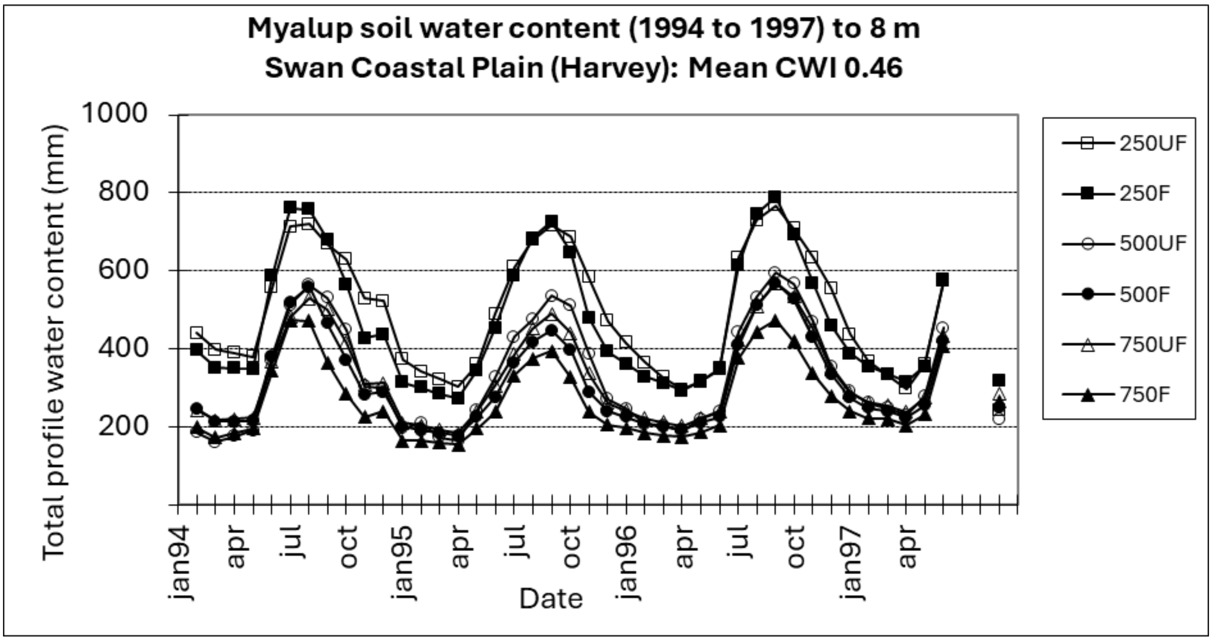


Figure 7. The impact of plantation density and fertiliser application on the annual variation in total soil water content to 8.0 m at Myalup 132. This covers the period from age 15 to 17 years.

Annual recharge from the driest to the wettest part of the recharge/usage cycle varied strongly between the plantation densities with a minimum level of recharge of ~230 mm in the 750 Fertilised treatment in the 1995/96 year (Figure 7). Even in the wettest year (1102 mm) the recharge in this treatment was only 300 mm. In contrast, the recharge under the 250 treatments was between 410- and 500-mm. Soil water was measured to 8 m on this coarse sandy site and water moved below this depth under the 250 sph treatments. Thus, the recharge was underestimated in the lower density treatments.

Summary: It is clear that growth on this site is limited primarily by water availability. Fertilising unthinned stands resulted in only small and transitory responses to fertiliser. Responses of ~40% can be obtained in low density plantation (250 sph).

Low rainfall site: Yilgarn Block.

(Martins Wickepin) (Mean Rain = 316 mm CWI = 0.19)
Due to the restricted site available on a private property, the design of this trial was restricted to two densities (250, 500 sph) in an 11-year-old stand in 1999. Diameter only was measured in 1999 while both diameter and height were measured from 2000 to 2004 and the responses are reported as volume for the period 2000 -2004 (age 12 to age 16). There was no significant difference in growth between any of the fertiliser or density treatments across the four years that the site was monitored and the annual increment over this period was ~2.6 m^3/ha/yr in both the 250 and 500 sph stands (Figure 8).

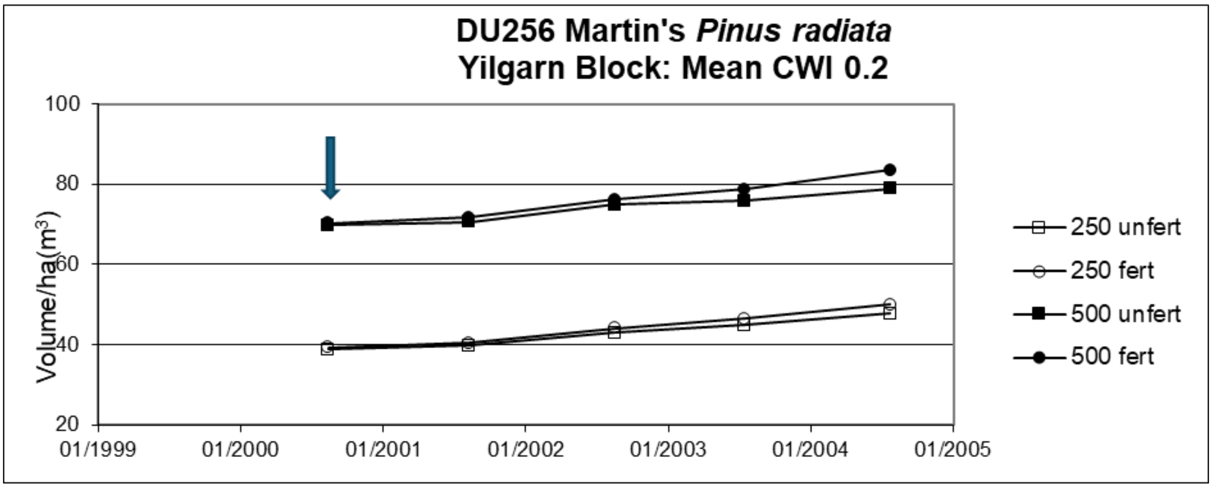


Figure 8. Volume growth following thinning and fertilisation at age 12-year-old (2000) to age 16 years (2004). Fertilised with a single application of N (270 kg/ha) and P (90 kg/ha) in July 2000 Fertiliser application indicated by arrows.

The low water availability for plantations in this rainfall zone on the Yilgarn Block is demonstrated by the low predawn leaf water potentials for much of the year with low PDLWP at both densities (Figure 9). Except for the 1999-2000 season PDLWP was below -1.5 MPa for between three and six months. The PDLWP declined to levels considerably below that experienced on the wetter sites on the Blackwood Low Plateau (Baudin 1) and the Swan Coastal Plain (Myalup 132). PDLWP appeared to stabilise at -2.0 MPa. Such behaviour has been described as isohydric behaviour where plants maintain PDLWP above lethal levels. The similarity of the water potentials in all treatments irrespective of density or fertiliser application is consistent with the low growth and absence of a fertiliser response at this site. The low water availability provided the limit to productivity.

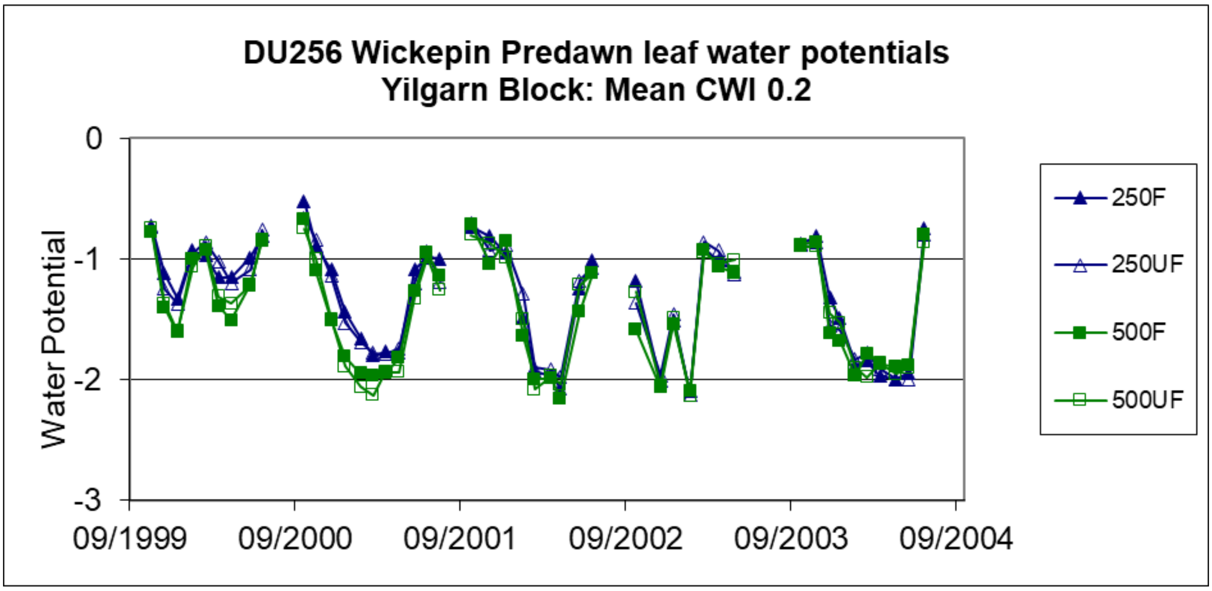


Figure 9. Influence of plantation density and fertiliser application on pre-dawn leaf water potential from October 1999 to June 2004 age 11. 3 to age 16 . (Martins Wickepin Thin x fert trial).

At this low rainfall site annual recharge was limited. The initial differences between the treatments largely remained across the monitoring period suggesting that these are differences in the storage component of soil water that the trees did not access (Figure 10). Annual recharge was as low as 50 mm in some years and up to 250 mm in wetter years for the low-density treatments. Thus, limited water storage is required to accommodate the water storage requirement at this low rainfall site.

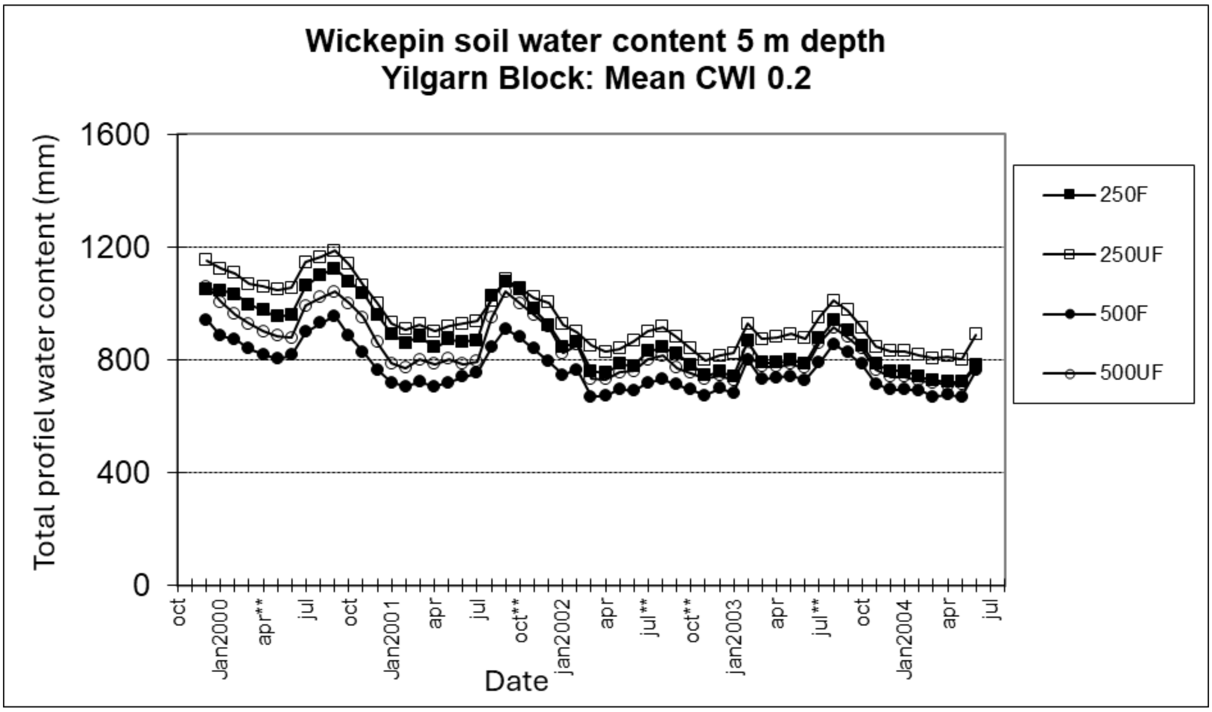


Figure 10. The impact of plantation density and fertiliser application on the annual variation in total soil water content at Martin's Wickepin Thinning by fertiliser trial December 1999 to June 2004. Age 11.4 to 16 years.

Summary. The low growth rates, absence of a response to fertiliser and low leaf water potential and soil water storage clearly demonstrate that the productivity of plantations in the low rainfall zone is limited by water supply. Applying fertiliser did not increase growth significantly and 250 sph produced the same overall volume as 500 sph.

Water use efficiency.

While water use efficiency (WUE) was not measured directly in these trials, the similar recharge and use of soil water at the Myalup site for the fertilised and unfertilised treatments at each density (Figure 7) and similar leaf water potential between the fertilised and unfertilised treatments (Figure 6) indicated that a significant component of the increase in growth following fertilisation was due to an increase in water use efficiency, i.e. there was no additional water used but there was an increase in growth. The decline in growth across all densities to a common low level in the second part of the trial also indicated that water use efficiency was increased by fertiliser application in the earlier part of the trial.

The increase in WUE appeared to be related to the level of water stress experienced both within and between the sites. At the wetter Baudin 1 site the increase in growth due to fertiliser at 300 sph was 82% and 44% at 700 sph (Figure 2). In the low density (250 sph) treatment at Myalup there was a 47% increase in growth, and this declined to 22% at 500 sph and 16% at 750 sph (Figure 5). While at the driest site (Wickepin) there was no increase in growth at either 250 or 500 sph (Figure 8). The absence of a response to fertiliser at the driest site (Wickepin) demonstrated that where water supply is severely limited there was no increase in the efficiency of water use.

Integrating the effects of climate, stocking and nutrient status on plantation productivity.

By segregating (selecting) the densities that provide the highest productivity from each site and partitioning the data into plus and minus fertiliser applications there was a clear separation between the fertilised and unfertilised treatments and a strong interaction between the response to fertiliser and water availability as measured by climate wetness index (CWI) (Figure 11a).

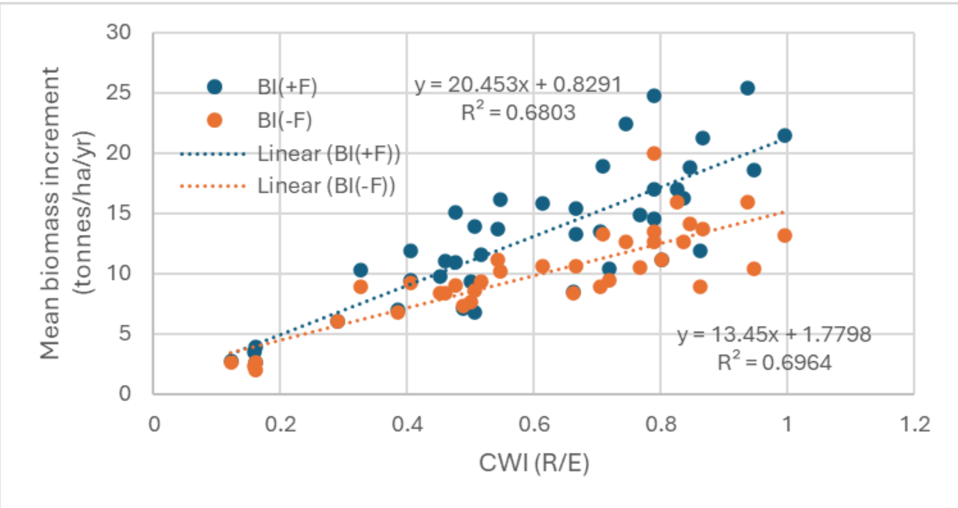


Figure 11a. The influence of fertiliser application on the relationship between Climate Wetness Index (CWI) and productivity.

Linear regressions between annual increments and CWI explain over two thirds of the variance in the data. Thus, partitioning the data based on fertility explains a significant proportion of the variance in the data (Figure 11a).

The impact of climate on the response to fertiliser was also estimated by assessing the response both in volume (Figure 11b) and as a percentage response (Figure 11c) at the post thinning trial sites across the south-west of WA. Both the absolute response (Figure 11b) and percentage responses (Figure 11c) increased linearly as the CWI increased.

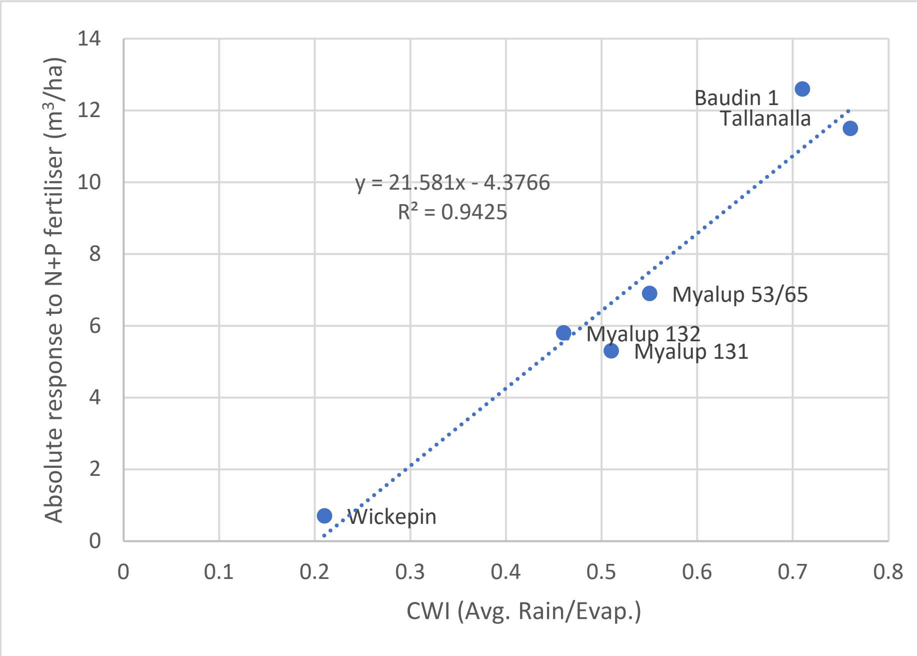


Figure 11b: Relationship between CWI during the measurement period and absolute response to maximum rates of fertiliser (difference between growth on the fertilised treatment compared with the control applied) at sites at Wickepin, Myalup, Baudin and Tallanalla.

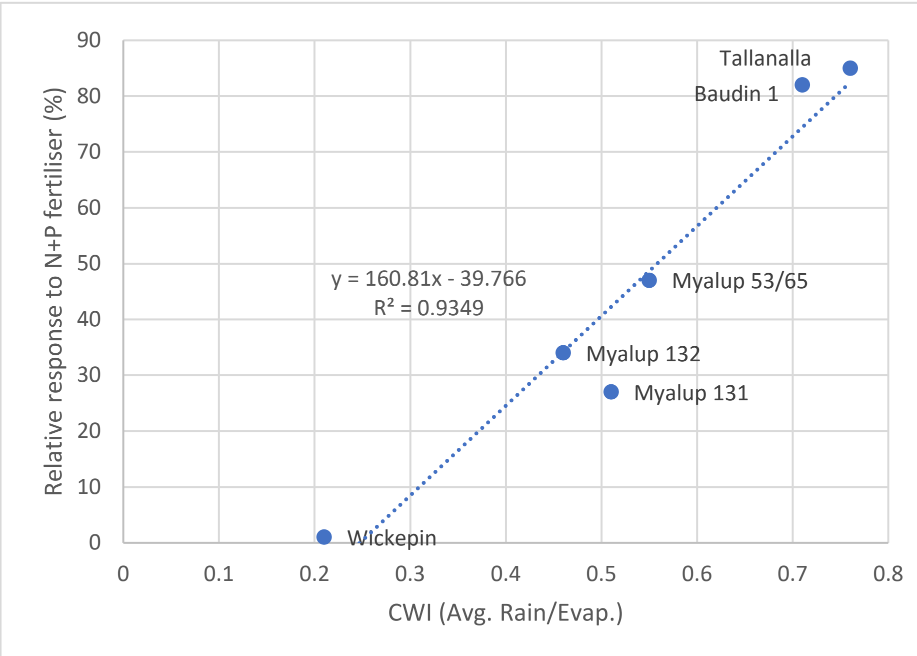


Figure 11c: Relationship between CWI and relative response (compared with the control) to maximum rates of fertiliser applied at sites at Wickepin, Myalup, Baudin and Tallanalla.

Water availability drives potential productivity and determines growth responses.

The response to increasing water availability (CWI) and fertiliser application measured as the annual increment (Figure 1) demonstrated a strong influence of water availability on growth. Although CWI provides a clear indication of the response to fertiliser across the climatic gradients of southern WA there remained considerable unexplained variation in the annual increment data (Figures 11a). As outlined above this was likely due to factors such as the time since fertiliser application and variations in plantation density.

To address these issues the responses to fertiliser were evaluated over the 4-year period since fertilisation (Figure 12). Four years was chosen as most or all of the response to nitrogen has been achieved by that time (Figures 16 a and b, 17 b,) and in trials with multiple fertiliser applications fertiliser was applied at 4-year intervals (T x FF trials, N rate and frequency trials) (Figures 18 and 19) so, to be able to include these data, increments over four years are provided. Noting also that the existing version of ProFert also uses the period 4-year post fertilisation to assess fertiliser responses. Similar to the data for annual growth, the impact of water availability on the overall response to fertiliser over four years post fertilisation increases as the availability of water increases (Figure 12).

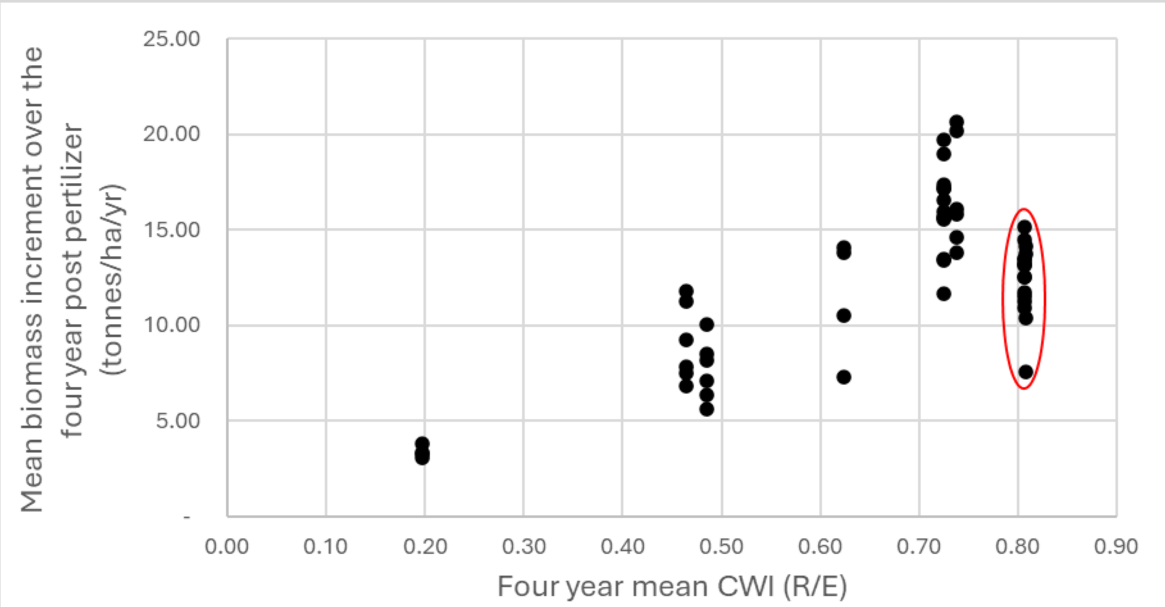


Figure 12. The mean annual increment in the four years post fertilisation for both adequate fertiliser and control treatments from mid-rotation trials at Wickepin, Myalup, Baudin and Tallanalla in southern WA.

The circled data in Figure 12 were excluded from the subsequent analysis as there appeared to be an additional limitation to productivity on two of the high rainfall sites (located on the Blackwood Low Plateau). The most likely limitation to growth on these sites is the capacity of the trees to access the full soil profile due to heavy and possibly waterlogged clays at depth. Consequently, under consistently wet periods not all the rainfall was available to the trees due either to deep drainage or runoff. This was explored through an analysis of the soil water storage capacity at sites across the rainfall gradient (above).

Impact of plantation density on the response to fertiliser

By partitioning the data into three density groups plus and minus fertiliser six treatment categories were defined:

- Low density: 250-300 sph, minus fertiliser
- Low density: 250-300 sph, plus fertiliser
- Medium density: 375-500 sph, minus fertiliser
- Medium density: 375-500 sph, plus fertiliser
- High density: 600-750 sph, minus fertiliser
- High density: 600-750 sph, plus fertiliser

Using the 4-year post fertilisation increment period the upper limit to growth demonstrated a linear response in relation to CWI (Figure 13) in a similar manner to the annual data (Figure 1). The upper limits using the 4-year increment data were slightly lower than that defined using annual growth and climate data (Figure 1) as the four-year period includes the variation due to the decline in the response to nitrogen over time (see Section 2, Figures 27, 28). Using this treatment segregation, the individual linear regressions for the four-year increment data explain between 83% and 96% of the variation (Figure 13). The response to fertiliser was strongly related to CWI in each of the density comparisons. For each density comparison the response to increasing CWI was greater for the fertilised treatments (Figure 13).

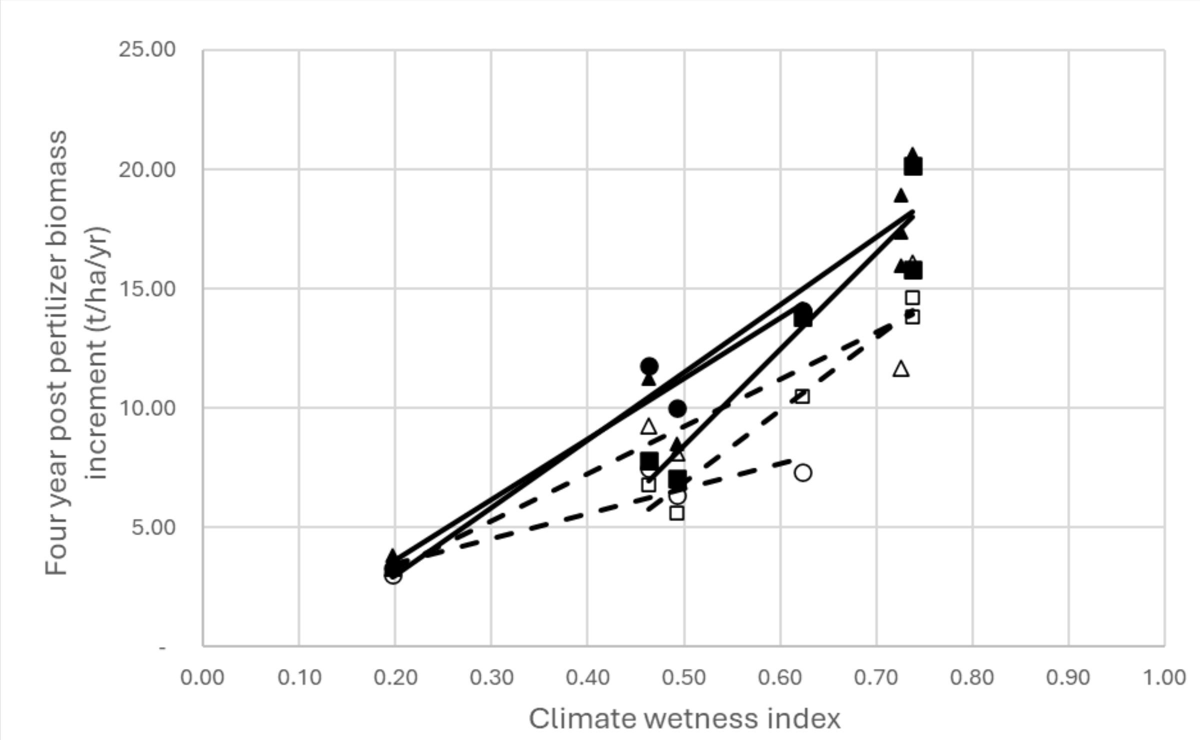


Figure 13. The mean annual increment in the four years post fertilisation for adequate fertiliser and control treatments at low (250-300 sph ○) medium (375-500 sph △) and high (600-750 sph □) density from trials in southern WA. Fertilised treatments have solid symbols and solid regression lines, unfertilised treatments open symbols and broken regression lines).

Symbols	Density (sph)	Fertiliser	Regression equation	R^2
● ——	250-300	Optimum	y = 25.32x – 1.44	0.95
▲ ——	375-500	Optimum	y = 28.26x – 2.63	0.91
■ ——	600-750	Optimum	y = 40.23x – 11.64	0.91
○ -----	250-300	Nil	y = 10.49x + 1.39	0.83
△ -----	375-500	Nil	y = 19.84x – 0.69	0.88
□ -----	600-750	Nil	Y = 30.27x – 8.23	0.96

There was a strong interaction between plantation density and the response to fertiliser. The response to fertiliser was highest in both actual and percentage terms for the lower density treatments (Figures 12, 13). This was due to the lower level of water stress that the thinned plantations experienced (Figures 3, 6). The smaller response in the medium density (MD) and high density (HD) stands relative to the low density (LD) stands was due to the higher level of water stress experienced by medium density (MD) and high stands (Figures 3, 6). The upper boundary to productivity was similar for both low and medium density treatments (Figure 13). At the higher level of water availability (CWI > 0.7) the productivity of the medium and high density stands was similar (Figure 13). The response pattern in the higher density (HD) stands to increasing CWI and fertiliser application was different to that in the lower and medium density stands with a steeper decline in biomass production as CWI declined and a lower response to fertiliser at the mid-range of CWI (Figure 13). Again, this is due to the higher level of water stress experienced by high density stands at mid-range CWI (Figure 6). Fertilising high density (unthinned) stands at sites with CWI in the region of 0.4-0.5 will not

lead to increased growth and may result in the promotion of water stress (Figure 6) and drought related mortality. There were no high density stands (600 – 750 sph) at the lower rainfall site (Wickepin).
The predicted response to adequate fertiliser applications in the 4-year period post fertilisation indicates that, for low density (250-300 sph) stands, an additional 12 tonnes of biomass could be produced annually when water supply was high (CWI =1.0) (Figure 14). However, in the Blackwood Low Plateau region the long-term CWI is ~ 0.7 indicating that the maximum response to fertiliser would be ~8.0 tonnes/ha/yr.

Conclusions:

- The availability of water limits the response to fertiliser in pine plantations across southern WA. The intensity of this limit to response is determined by both the climate and the density of the plantation.
- On infertile high rainfall sites responses in the order of 85-90 % can be achieved with optimum fertiliser
- Under very dry conditions where the CWI (R/E) is around 0.2 there was no fertiliser response at any density this confirmed that as water becomes more limiting responses to fertiliser decline.
- At medium CWI (0.4-0.5) there was a response across the density range, however the response declined in both volume and as a % response as plantation density increased.
- Under wetter conditions (CWI >0.7) low-density and high-density plantations responded to fertiliser. However, the response was lower in high density stands.
- The extensive data available allowed the description of the potential response to fertiliser based on plantation density and climate. However, responses in a range of plantation densities have not been modelled in ProFert as we have focussed on responses in thinned stands only.

Section 2 The magnitude and duration of responses to N and P fertiliser in thinned plantations

Results and Discussion

Responses to phosphorus application

The soils of southern WA are inherently deficient in phosphorus and agriculture in WA has relied on substantial inputs of P to sustain the productivity of these systems. The impact of phosphorus application has been assessed across a range of environments and plantation ages. Both responses in young and older plantations have provided useful insights into the role of P fertilisation in optimising plantation productivity in WA. The responses observed have ranged from no response to more than doubling of growth with adequate applications of P. While not providing information on the response to P supply, trials where there was no response to applied P have provided understanding of the conditions under which responses to P will not occur (Table 5). Plantations in WA growing on previously forested sites generally respond to fertilisation with P. In contrast plantations growing on previous farmland which have received significant P applications generally don't respond to P fertilisation.

Table 5. Summary response to phosphorus fertiliser across the climatic and soil fertility gradients in WA.

Geographic unit	Plantation/ Trial	CWI for trial	Prior land use	SPH	Soil N% (OC% for S. Coast*)	Soil P HCO_3 (ppm)	Response to P %	Actual response (m^3/ha/yr)	Period of response	Comments
Darling Scarp	Tallanalla	0.76	Forest	380	0.10	1.4	70 (85% to N+P)	7.5 - 11.5	1987-1997 (17-27 yrs)	Response to P at various rates of N Response to P increased with increasing N supply
Blackwood Low Plateau	Baudin 20	0.74	Forest	1300	0.05	2.0	134	8.5	1985-1992 (0-7 years)	Response to P with other nutrients unlimited on a high rainfall site
	Jarrahwood 7	0.74	Forest	750 & 375	0.06	3.5	40	***0.8 m2/ha/yr***	1982-1989 (0-7 yrs)	Response to P, limited by the low supply of nitrogen, high rainfall site
	Vasse 9	0.77	Forest	412	0.06	**31.0**	Nil P response	Nil	1993-1995 (13-15 yrs)	No response to P after two years N x P trial converted to N rates/frequency after two years
Swan Coastal Plain	Myalup 131	0.51	Forest	357	0.04	0.5	27	5.3	1995-1999 (16-20 yrs)	Response to P with adequate N Response limited by the availability of water
South Coast	Thorps	0.52	Farm	1300	**2.49**	6.0	Nil	Nil	1991-1996 3-8 (16?)	NxPxK interaction, no P response N and K responses
	Wise	0.50	Farm	1300	**2.46**	18.0	Nil	Nil	1991-1995 3-7	P rate trial, No P response
	Milgraums	0.51	Farm	1300	**3.32**	11.0	Nil	Nil	1991-1995 4-8	P rate trial, No P response
	WAWA	0.63	Farm	1300	**3.14**	63.0	Nil	Nil	1991-1995 3-7	P rate trial, No P response

* Based on a mean C/N ratio of 12.9 for 137 farm plantation sites in southern WA. The soil N for the south coast sites would be between 0.19 and 0.26% N.

Details of responses to phosphorus application

Baudin 20 P rate trial.

Phosphorus was applied annually at (0, 7, 14, 27, 55, 109, 164, 218 kgP/ha) from planting in 1985 until 1992 (age 7-years). There was no strict zero P application in the trial as the seedlings were provided with a starter application of P which contributed 32kg P per ha and an unplanned/inadvertent operational application of 200 kg/ha Agras No1 in July 1986 (at ~ age one) applied an additional 15 kg P/ha. The combined total of these 'background' applications was 47 kgP/ha and was included in the cumulative P applications for each treatment. The highly P deficient nature of the leached lateritic soils of the Blackwood Low Plateau meant that these applications of phosphorus, which were equivalent to half a tonne of superphosphate, did not eliminate the response to subsequent applications of phosphate at this site.

As the objective of this trial was to define the response to phosphorus application on this phosphorus deficient site, the influence of other nutrient deficiencies on the response to P were eliminated by annual applications of N (200 kgN/ha as Agran), K (100 kgK/ha as muriate of potash) and applications of Zn (10kg/ha ZnSO4) and Cu (5kg/ha CuSO4) at planting.

The annual increments increased from age 3-4 to age 6-7 with the 'plateau' increment for the 6-7 year of ~46 m^3/ha/yr (Figure 14). While the measurements at this site were not continued, these increments and the standing volume at age 7 of ~ 165 m^3/ha demonstrate that the heavy early fertiliser applications promoted rapid early growth of the plantations.

The plateau of the growth curve extended to 1600 kg/ha total P applied (Figures 14, 15). The relative response as basal area (Figure 16) was truncated at 800 kg/ha to make the data easily comparable with the data from the Jarrahwood 7 site (Figure 17) where the range of P applications was up to ~800 kgP/ha. The response relationships were analysed using all data. The maximum growth occurs when a cumulative total of approximately 400 kg of P is applied, while 90% of maximum growth occurred at approximately 200-250 kg of applied P (Figures 16, 17).

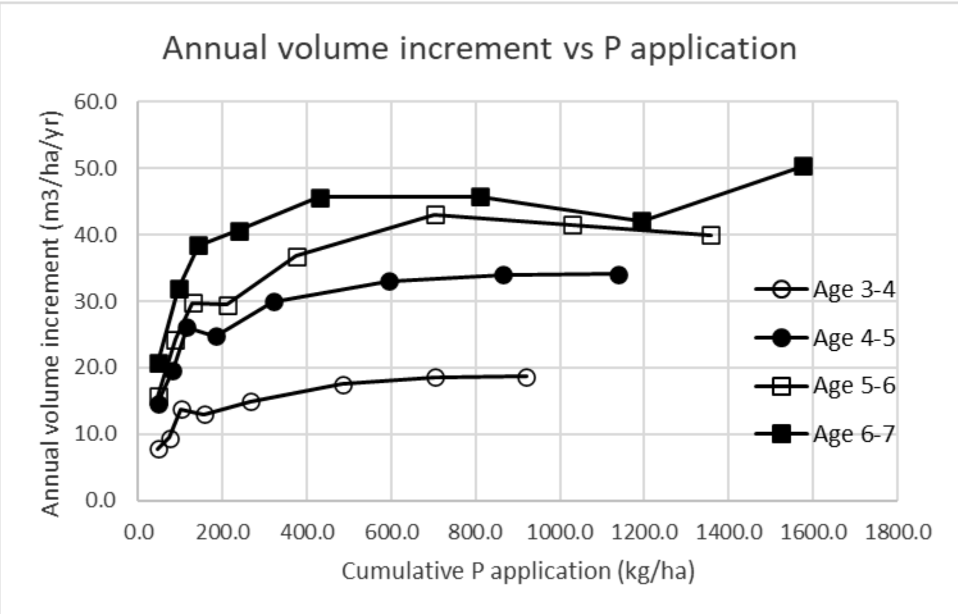


Figure 14. Impact of P application on annual volume increment between 3 and 7 years in the Baudin 20 P rates trial.

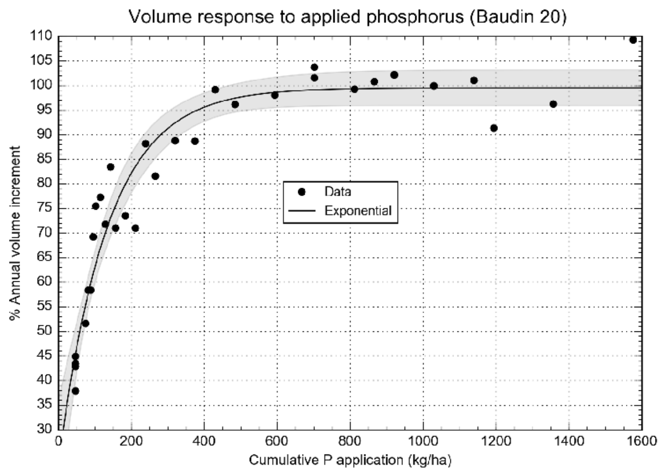


Figure 15. Annual volume response to applied P calculated as a % of the maximum volume increment for each year at Baudin 20, where the supply of all other nutrients was not limiting. Note this is the combined analysis of the data in Figure 14.

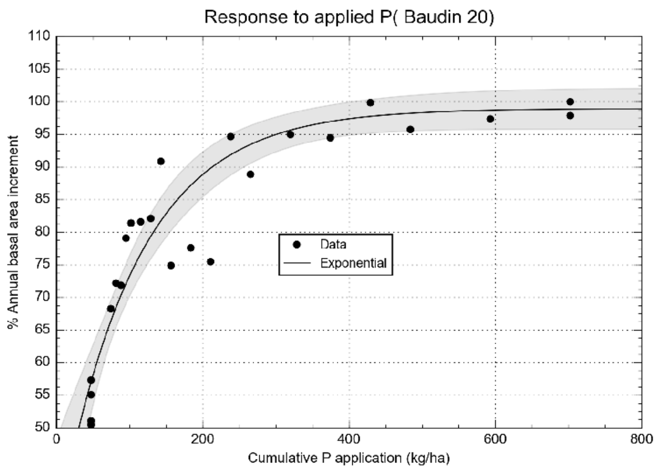


Figure 16. Annual basal area response to applied P calculated as a % of the maximum annual basal area increment. The supply of all other nutrients was non limiting. This shows the response up to 800 kg/ha applied P to make comparisons with the data from Jarrahwood 7 (below) easier.

Jarrahwood 7 P rates trial.

This trial was initially designed to test the rates of phosphorus required to optimise the production of a clover pasture planted at establishment and tree growth of a *P. radiata* plantation. The initial objective was to determine if the subterranean clover pasture could supply sufficient nitrogen for the plantation during the establishment phase. Clover production was estimated at ~4 tonnes/ha/year in the second and third year after establishment. By age four the clover pasture was severely dominated by the trees as they closed canopy with less than 0.5 tonnes/ha of clover produced and clover had virtually disappeared by age six. Thus, little nitrogen fixed by the pasture would have been available to the trees. Consequently, the plantation was grown without significant input of nitrogen. The trial provided a phosphorus rate trial with a low supply of nitrogen.

At establishment in 1982, 500 kg/ha of Superphosphate Cu Zn Mo (8.9% P) was broadcast and in addition the seedlings received 150 gm per tree Superphosphate Cu Zn fertiliser (8.9%P). The base level of superphosphate was designed to provide sufficient P to establish a subterranean clover pasture and provided 45 kg/ha P. The initial application to the seedlings supplied a further 18 kg/ha P (63 kg/ha P in total). Due to these initial P applications (and similar to the Baudin 20 P rates trial) there was no zero P treatment in this trial. Six annual applications of superphosphate at 0, 50, 100, 200, 400, 800, 1600 kg per year provided annual applications of 0, 4.5, 9.1, 18.2, 36.4, 72.8, 145.6 kg P/ha from 1983- 1988. As with the Baudin 20 trial, the highly P deficient nature of the leached lateritic soils of the Blackwood Low Plateau meant that the initial applications of phosphorus, which were equivalent to ~700 kg/ha of superphosphate, did not eliminate the phosphate response at this site.

Unlike the Baudin 20 trial where both annual diameter at breast height over bark (DBHOB) and height data were collected only DBHOB was measured in the Jarrahwood 7 trial and in some cases the interval between measurements was two years. Consequently, the responses are presented as basal area increments and derivatives of that. The response to phosphorus by the trees is shown as a percentage of the maximum annual basal area increment for each year from age three to age seven years (1985-1989). The low phosphorus treatment produced 65% of the maximum for this site (Figure 17).

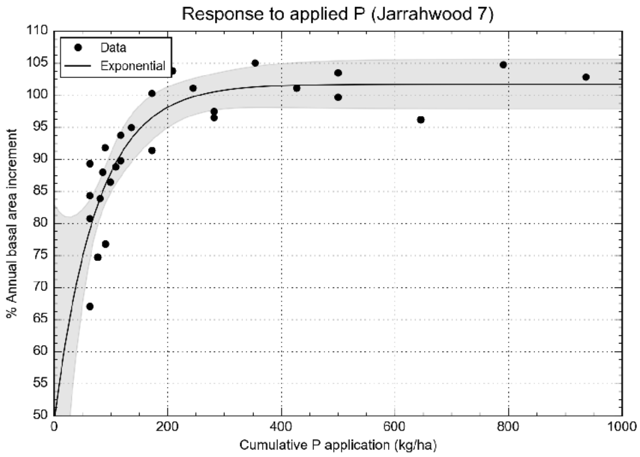


Figure 17. Jarrahwood 7 P rates trial. Annual basal area response to applied P calculated as a percentage of the maximum annual basal area increment, where the supply of nitrogen was inadequate to sustain growth at the site potential.

Comparison of responses to phosphorus between the Baudin 20 and Jarrahwood 7 trials.

For this comparison the growth achieved in the Baudin 20 trial, where all known nutrient requirements on these soils were provided, was defined as the maximum growth in young plantations in the Blackwood Low Plateau (BLP).

The growth at Baudin 20 was virtually double that achieved at Jarrahwood 7. By age seven at Baudin 20 the basal area of trees growing with an adequate supply of P was ~39 m^2/ha (Figure 18a). In contrast the peak basal area achieved at the same age at Jarrahwood 7 was ~19 m^2/ha (Figure 18b). The Jarrahwood 7 trial was grown without the addition of mineral nitrogen.

Importantly the application of P required to maximise growth was >400 kg/ha at Baudin 20 or more than twice the application of ~170 kg/ha required to maximise basal area production at Jarrahwood 7 (Figures 20 a, b). The data are presented as percentages of the maximum growth that can be achieved in young plantations on the Blackwood Low Plateau by using the growth at Baudin 20 as the maximum achievable under the climatic conditions in this region (Figure 18(b)).

The response to applied P at Baudin 20 was strongly curvilinear with ~90% of the maximum achieved with 200 kg/ha applied P but requiring a further 200 kg/ha to maximise growth.

Using the basal area data at ages seven the compressed nature of the response at Jarrahwood 7 made it difficult to determine if the response was similarly curvilinear. However, the more detailed analysis of this response (Figure 17) also demonstrated that the response was curvilinear and 90% of maximum growth was achieved at ~100 kg/ha P, or half that required at Baudin 20.

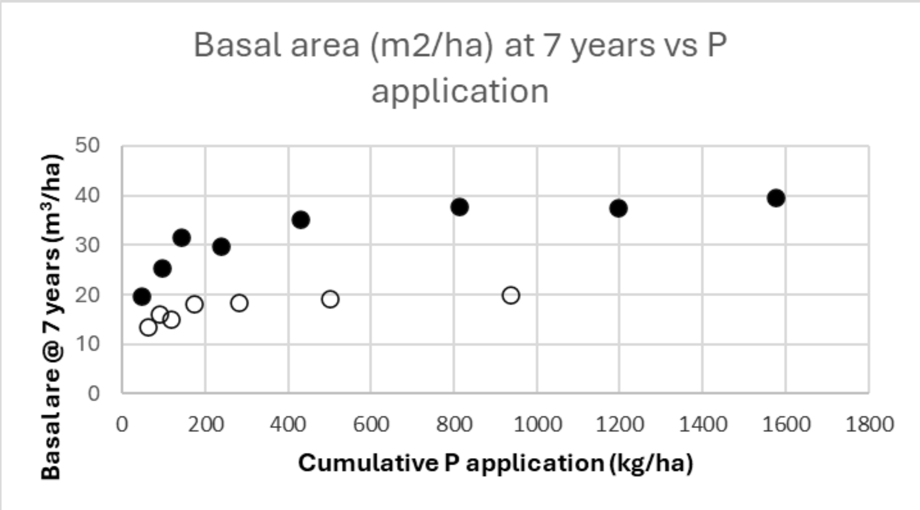


Figure 18(a). Comparison of the response to applied P measured as the basal area response (m^2/ha) to applied P (kg/ha). ● Baudin 20 where the supply of N was adequate to sustain growth at the site potential, ○ Jarrahwood 7 where the supply of N was low as no fertiliser N was applied.

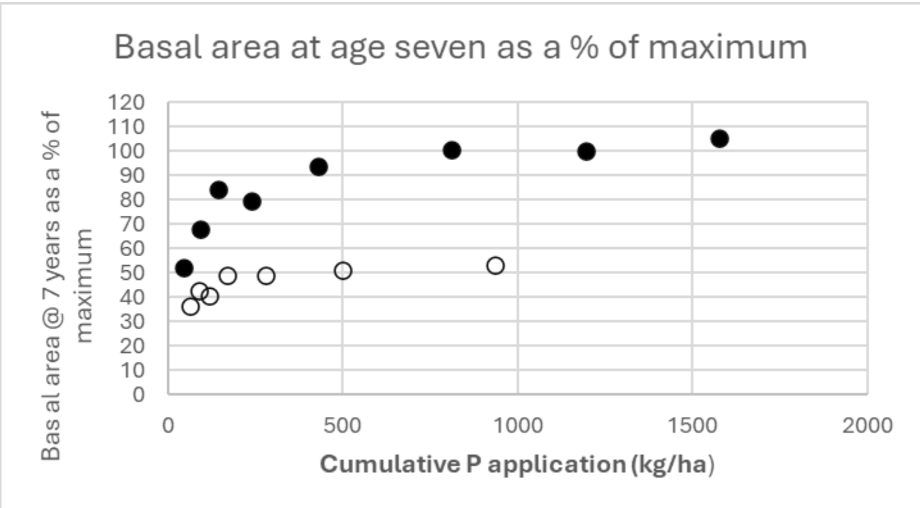


Figure 18(b). Comparison of the response to applied P measured as the basal area response (m2/ha) to applied P (kg/ha) calculated as a % of the maximum annual basal area increment. ● Baudin 20 where the supply of N was adequate to sustain growth at the site potential, ○ Jarrahwood 7 where the supply of N was low as no fertiliser N was applied.

Tallanalla N x P trial.

This trial differed from the Baudin 20 and Jarrahwood 7 trials in that it was a post thinning trial rather than an early rotation trial. The fertiliser was a single application to a 17 y.o. thinned plantation rather than multiple applications of fertiliser at the beginning of the rotation. The trial tested the response to both phosphorus and nitrogen and the interaction between these in a full 5 x 5 factorial design. The rates of N were: 0, 68, 135 270 540 kg/ha and P were: 0, 45, 90, 180, 360 kg/ha. The response to nitrogen was short lived with even the highest N applications increasing growth for a maximum of five growing seasons post fertilisation (Figures 26 and 28).

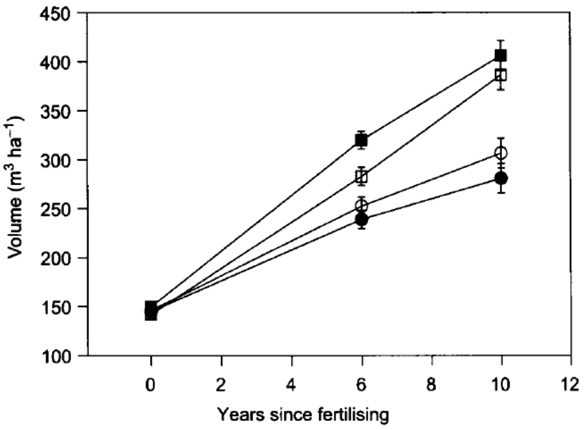


Figure19. Volume response (m^3/ha) over ten years after application of phosphorus and nitrogen separately and in combination (P0N0 = ○, P0N540 = ●, P360N0 □, P360N540 = ■).

The response to phosphorus lasted for at least 10 years post fertilisation (Figure 19) and the scale of the response to P depended on the availability of nitrogen (Figure 20). In the first four years post fertilisation the response to phosphorus without added nitrogen was ~38% and that was achieved with 45 kg P/ha. The response to P increased when the application of N increased and with an N application of 270 kgN/ha and above the response from fertilisation with P was 85%. This was achieved at 180 kg/ha P, with 95 % of the maximum response being achieved at 90 kg/ha P (1 tonne superphosphate) (Figure 20).

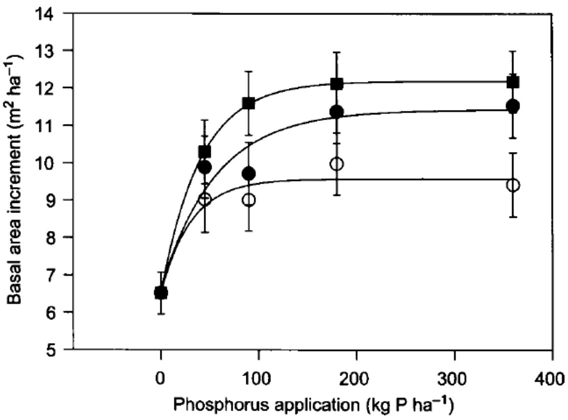


Figure 20. Response of basal area increment (m^2/ha) in the first four years after application of phosphorus (0, 45, 90, 180, 360 kg/ha) and different rates of nitrogen N0 = ○, N135 = ●,N 270, 540 combined = ■).

It is clear from the comparison of the two early rotation trials on the Blackwood Low Plateau (Figures 17, 18 a and b) and the mid-rotation trial at Tallanalla (Figure 20) that the supply of nitrogen has a major impact on the response to phosphorus. When the nitrogen supply is low the response to phosphorus is limited and the apparent requirement for P is lower than when the supply of nitrogen is adequate.

The apparent lower rate of P required to achieve maximum growth at Tallanalla (Figure 21) and Jarrahwood 7 (Figure 18 a, b) relative to the rate required to maximise growth at Baudin 20 was likely due to the difference in nitrogen supply and hence the growth rate at these sites. The N application at Tallanalla was a single application, while nitrogen was applied annually at Baudin 20 and in the first 7 years 1400 kg of N was applied. The response to phosphorus at Baudin 20 was likely not limited by other nutrients, whereas the response to N at Tallanalla declined in the period post fertilisation (Figure 19) and after 6 years no impact of the single N application at Tallanalla remained (Figures 19 and 20). At Jarrahwood 7 the only nitrogen would have come from the nitrogen fixed by the ephemeral subterranean clover understory which had virtually disappeared by age 6. Consequently, the responses to phosphorus at both Tallanalla and Jarrahwood 7 were limited by low nitrogen supply.

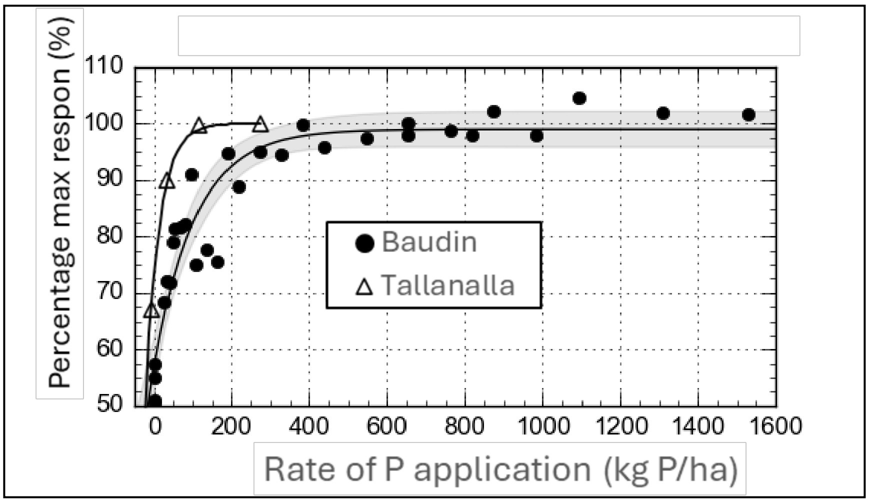


Figure 21. Comparison of response to phosphorus application between the Tallanalla and Baudin 20 sites.

Responses to nitrogen application.

The mid rotation response to nitrogen alone was assessed at four separate locations with varying climatic and soil conditions.

Table 6. Summary of responses to nitrogen fertiliser across the climatic and soil fertility gradients in WA.

Geographic unit	Plantation/Trial	CWI for trial	Prior land use	SPH	Soil N% (OC% for S. Coast*)	Soil P HCO₃ (ppm)	Response to N %	Actual response (m³/ha/yr)	Period of response	Comments
Darling Scarp	Tallanalla	0.76	Forest	380	0.10	1.4 (0P) 10-30 when P applied	25% to 4 yrs	7.5 - 11.5	1987-1997 (17-27 yrs)	Response to N at various rates of P. Response to N increased with increasing P supply. N response restricted to five years post fertiliser even at higher N applications.
Blackwood Low Plateau	Vasse 1	0.65 (83-09) 0.77 (94-00) 0.58 (01-09)	Forest	Planted 1300 Various denisty	0.06	31.0	25	*NA*	Rotation	Rates of N response from establishment to age 20. Mid rotation response reduced due to high initial N rates.
	Vasse 9	0.77	Forest	412	0.06	31.0	34	8.9	1993-1999 (13-19 yrs)	No response to P after two years N x P trial converted to N rates/frequency after two years. Response to N sustained with multiple applications.
Swan Coastal Plain	Myalup 131	0.51	Forest	357	0.04	0.5	25	4.7	1995-1999 (16-20 yrs)	Response to N with adequate P. Response limited by the availability of water.

While the Vasse 1 N rates trial is useful in understanding the responses to nitrogen over a full rotation the data from this trial do not contribute to the understanding of mid rotation fertilisation in situations where modest rates of fertiliser have been applied early in the rotation. The high applications of nitrogen and other nutrients (P, K, Zn, Cu, Mn) to this plantation produced high basal areas even in plantations thinned to 375 sph at age nine. The high early growth rates mean that even on this site with a relatively high water supply there was little opportunity for the growth rate of the plantation to be increased further from the mid rotation onwards. While this provides an important understanding of the options to optimise productivity across a full rotation it is not the focus of this project and has not been explored further here.

The Tallanalla, Vasse 1, Vasse 9 plantations were located in regions with high rainfall and during the trial periods the CWI for these sites was ~ 0.77, while the CWI was 0.51 at the Myalup 131 site on the Coastal Plain at Harvey (Table 6).

N responses on water limited sites.

N x P trial Myalup 131, Myalup 53/65.

A full factorial trial of four rates of P and four rates of N was established in a commercially thinned stand at age 16 with a mean stocking of 357 sph. The stocking ranged from 279-493 sph and the initial basal area ranged from 11.2 to 19.7. This initial variation imposed significant variation on the results.

Table 7. Volume increments (m^3/ha) in the four years post thinning and fertilisation in the N x P trial at Myalup Cpt 131.

	Nitrogen rates (kg/ha)			
P rates (kg/ha)	0	100	200	400
0	16.2	*MV	16.4	16.7
75	14.8	19.9	21.2	16.4
150	14.3	18.5	20.8	19.3
300	15.1	20.9	17.4	20.3

* = Missing value.

The shaded area of the treatment matrix defines a plateau for growth with a mean PAI in the four years after fertilisation of 19.4 m^3/ha/yr (Table 7). There appeared to be no response to N application without P and likewise no response to P without N. If the mean of these treatments (15.6 m^3/ha/yr) is used as the control treatment value, then the response is optimised by the application of 75 kg P/ha and 100 kg N/ha. On this site the response to applied fertiliser was limited by both N and P but the response to fertiliser is modest.

The individual responses to P and N are shown in Figures 22 a, b. The data from both the earlier trial which assessed the response to a combined NP fertiliser (Figure 23 a) and the later trial indicate that both N and P are required to achieve a response on this site/soil, which is likely due to the low fertility on this soil with surface soil HCO_3 P of 0.5 ppm and nitrogen of 0.04%.

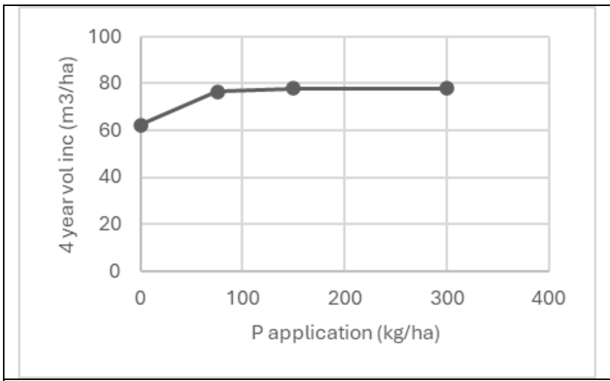


Figure 22a. Response to Applied P on the Coastal Plain at Myalup. N at adequate rates.

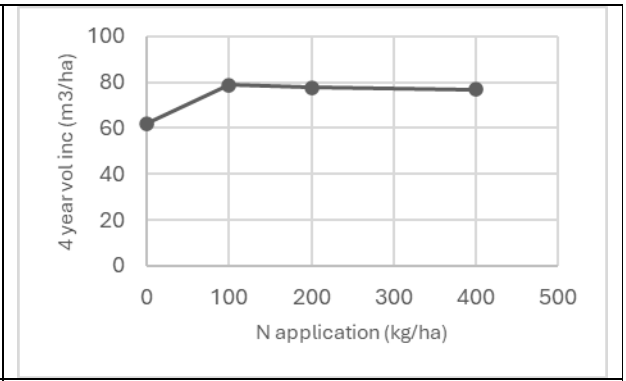


Figure 22b. Response to applied N on the Coastal Plain at Myalup. P at adequate rates.

The response to combined N and P in the earlier trial (Myalup 53/65 Figures 23 a, b) demonstrated a strong response to low rates of N and P (Figure 23a) and the short-lived response to the combined application of N and P even at 75 kg P/ha and 175 kg N/ha (Figure 23b) strongly suggests that N was the most limiting nutrient on these infertile coastal sands in that without N there was no continuing response to P.

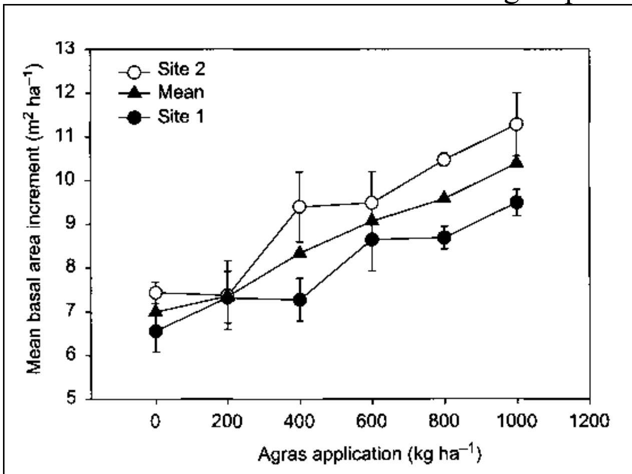


Figure 23a. The effect of Agras No1 (17.5%N and 7.6% P) on basal area increment of *Pinus radiata* in the six years after application to a second thinned stand (May 1978 to January 1984). Standard errors are shown as vertical bars on the data for each site (bars are 2 SE).

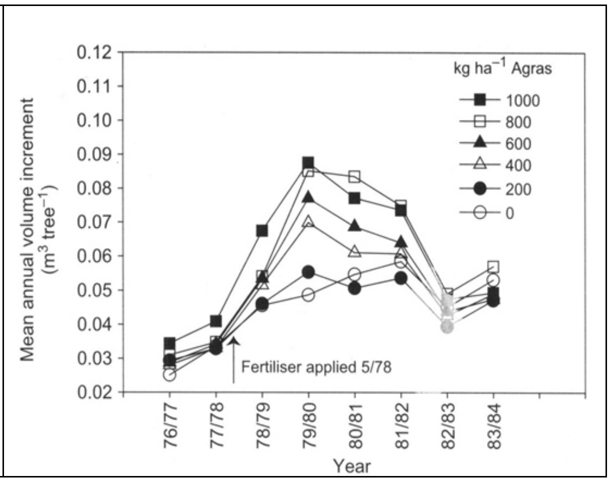


Figure 23b. The effect of Agras No1 (17.5%N and 7.6% P) on annual volume increment of *Pinus radiata* for six years after application. The coefficient of variation for the individual data varied between 4% and 15% (mean CV = 8%).

Response to nitrogen on higher rainfall sites.

The Vasse 9 nitrogen rates and frequency of application and the Tallanalla NxP trials provide data on mid rotation responses to nitrogen in higher rainfall areas.

Vasse 9 nitrogen rates and frequency of application trial.

The trial area had received 177 kg of elemental P (equivalent to ~2.0 tonnes of superphosphate) in a series of fertiliser applications from establishment to age 10 and as a result had an adequate supply of P with the HCO_3 P concentration of 31 ppm (Table 6). Rates of 0, 100, 200, 400 kg N/ha were applied once at age 13 and twice at either two or four year intervals (age 15 or 17 years) and three times at two-year intervals (13, 15, 17 years). This provided a range of total N application from 100 to 1200 kg N/ha plus an unfertilised control. The response was measured over six years from age 13-19 years. There did not appear to be a significant influence on the timing of N application on the response. There was a linear response up to a rate of 400 kg N/ha with the PAI increasing from 26.2 to 34.7 m^3/ha/yr (Figure 24). The variation in stocking and soil type across the trial meant there was considerable variation in the data. However, there was a strong relationship between N application and PAI up to 400 kg N/ha (R^2 = 0.71, Figure 24).

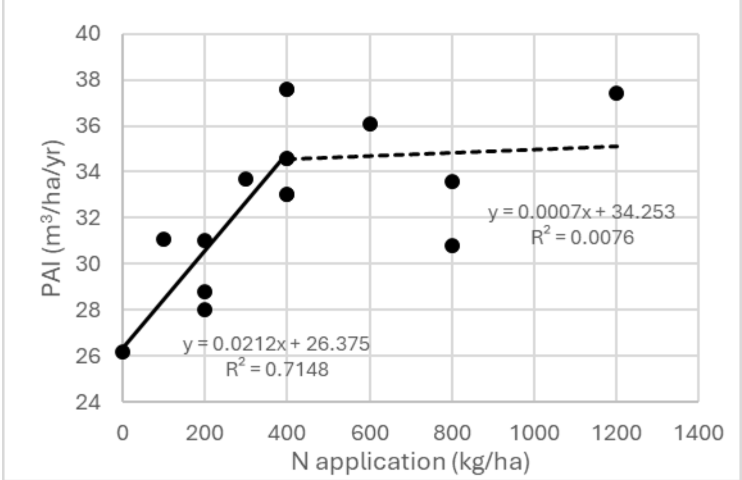


Figure 24. Response to applied nitrogen on a high rainfall site on the BLP (Vasse 9).

Tallanalla N x P rates trial.

Note the data provided in Figure 25 have been extracted from the published work from that trial. Locating the primary data has proved elusive at this point. A curvilinear model fitted to the data explained much of the data. This is primarily due to the estimates from the published data being means of the treatments which masks the variation in the data. However, it provides a useful response equation for the modelling process.

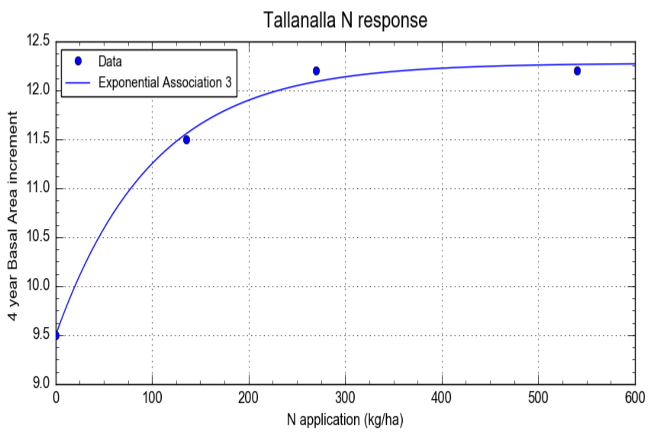


Figure 25. Response to applied N with an adequate P supply in the four years post thinning and fertilisation (age 17-21 yrs) at Tallanalla.

Model
y = a*(b-exp(-c*x))
a = 2.78382665719444E+00
b = 4.41018815207572E+00
c = 9.97660104094678E-03
Standard Error =0.14
R2 = 0.996

Duration of fertiliser responses.

Under the conditions experienced in WA, responses to single applications of nitrogen last between three and five years (Myalup 53/64 Figure 23b, Tallanalla Figures 26a, 26b). The duration of the response depends on the rate of application with longer term responses occurring with higher rates of application (Figure 26a vs 26b). There was a strong cycle in the response to nitrogen application with very little response occurring in the first-year post application and the response lasting a maximum of five years at very high rates of N application and as short three years with low applications. Most of the growth response to nitrogen occurred in the period between two and four years post fertilisation (Figures 23b, 26a, 26b).

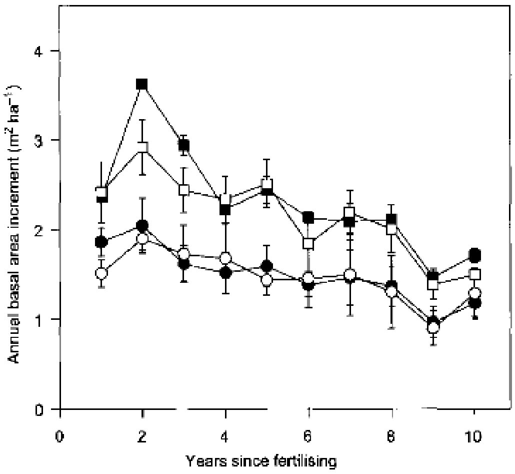


Figure 26a. Effect of low rates of nitrogen and phosphorus applied separately and in combination on the annual basal area increment for 10 years after fertilisation. (P0N0 = ○ , P0N135 = ●, P90N0 = □, P90N135 = ■).

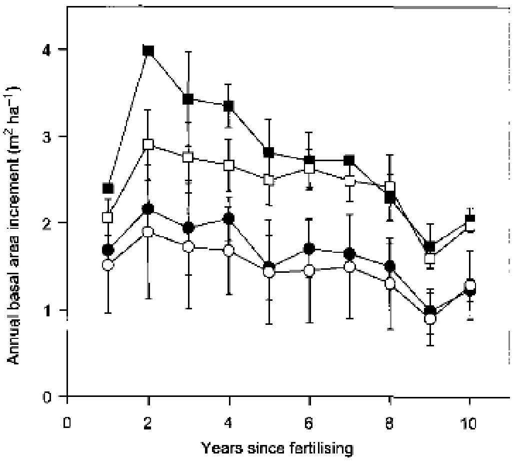


Figure 26b. Effect of high rates of nitrogen and phosphorus applied separately and in combination on the annual basal area increment for 10 years after fertilisation. (P0N0 = ○, P0N540 = ●, P360N0 □, P360N540 = ■).

The impact of multiple fertiliser applications was investigated in thinning by fertiliser trials on the Blackwood Low Plateau (BLP) and the Swan Coastal Plain (SCP). On the BLP (Baudin 1) three separate applications of phosphorus and nitrogen (90 kg P and 270 kg N) were applied at age nine, 13 and 17 to stands at 300 and 700 sph. The plantation was a low productivity area with a pre-treatment standing volume of 80-84 m^3/ha at age 9 (700 sph) (PAI ~9m^3/ha/yr). The responses to the treatments were measured from age nine (1989) until clearfell at age 30 years (2009). Periodic volume increments (PAI's as annual increments during the intensive phase of the trial and as PAI's for the periods when the interval between measurements was greater than one year) were plotted against the midpoint of the measurement interval for the periods 9-12, 18-21, 21-25 and 25-30 years e.g. while the trial commenced in 1988 (age nine) the next height measurement was in 1991 (age 12) so the mean volume increment was plotted against age 10.5 (Figure 27).

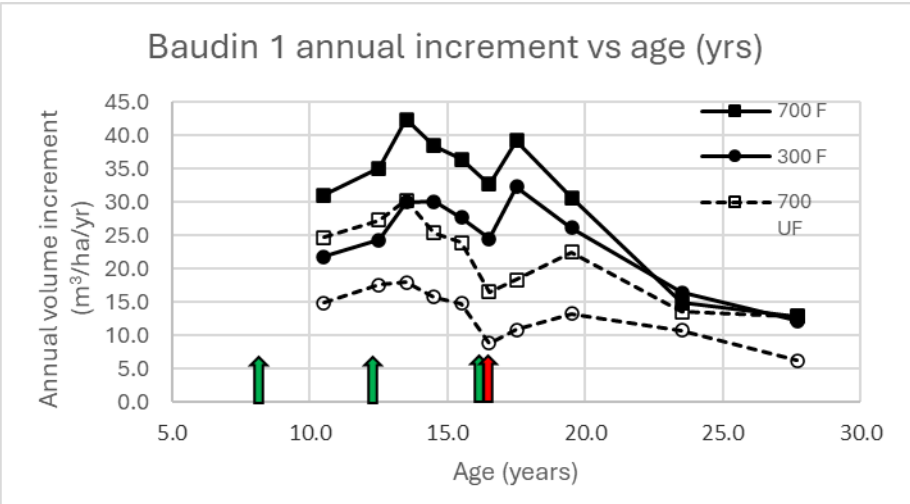


Figure 27. Impact of thinning and multiple fertiliser applications (90kg P and 270 kg N) at 4-year intervals on annual volume increment (Baudin 1, BLP).
Note: Green arrows indicate fertiliser applications, red arrow indicates a survival P application of 18.5 kg P to the low nutrient treatments in 1996 as the phosphorus deficiency had reached the point where tip death was observed.

The fertilised high density stands (700 sph) maintained the periodic annual increments (PAI) at ~ 35 m^3/ha/yr for the period from 9 – 21 years during which fertiliser was applied at four-year intervals. Fertilised low density stands (300 sph) maintained PAI at > ~28 m^3/ha/yr over the same period. While variable, the PAI for the unfertilised treatments were ~24 and 14 m^3/ha/yr for the 700 and 300 sph stands during the same period (Figure 27). The fertiliser response was greater in the 300 sph stand than for the 700 sph stand with the mean difference between the unfertilised and fertilised treatments of 14 m^3/ha/yr during the 'fertiliser period' (Figure 27). Maintaining the plantation at a higher density contributed 10 m^3/ha/yr and fertilising added a similar 10 m^3/ha/yr.

Following the thinning at age nine the PAI's for all treatments increased and this increase was larger for both the fertilised treatments. Following the second and third fertiliser applications the increment increased further and then declined. Following the third fertiliser application at age 17 years there was an initial increase in increment followed by declining increments. By seven years after the last application (age 24 years) the PAI's had declined to the same level as the low fertiliser treatments. In the subsequent five years (to age 30) the increments in all except the 300 sph unfertilised treatment were similar at ~12 m^3/ha/yr (Figure 27).

The decline in growth in the last decade of the trial was likely due to a combination of the declining nitrogen status of the plantation in the absence of fertiliser, lower rainfall during that period which resulted in a CWI of 0.61 relative to a CWI of 0.71 in the earlier part of the trial and an age-related decline in growth. The decline in rainfall/CWI would have accounted for an ~ 17% decline in growth based on the data in Figure 1. It appears that part of the decline in growth was due to the inevitable decline in growth as trees age.

The apparent small increase in volume increment following the 'survival' P application did not appear to provide a long-term benefit, though without a control it's impossible to define the magnitude of this effect.

On the Swan Coastal Plain (Myalup 132) two separate applications of phosphorus and nitrogen (90 kg P and 270 kg N) were applied at age 14 and 18 to stands at 250, 500 and 750 sph. The plantation was a moderate productivity area with the standing volume of the 750 sph stands of 200-205 m^3/ha at age 14 (PAI ~14 m^3/ha/yr). The responses to the treatments were measured from age 14 (1993) until clearfell at age 32 years (2011). Periodic volume increments (PAI's as annual increments during the intensive phase of the trial and as PAI's from age 14 to age 21 and for the periods 21-25, 25-32 years) were plotted against the midpoint of the measurement interval (Figure 28).

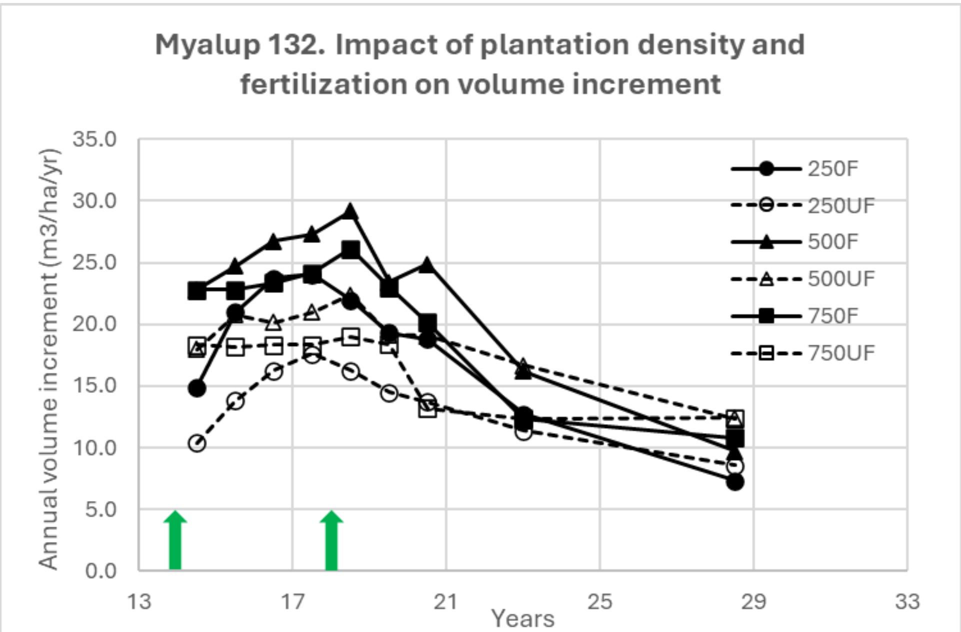


Figure 28. Impact of thinning and multiple fertiliser application (90kg P and 270 kg N) at four-year intervals on annual volume increment (Myalup 132 SCP). Note: Green arrows indicate fertiliser applications.

The fertilised stands (250, 500 and 750 sph) maintained annual increments at ~ 20-25 m^3/ha/yr for the period from 14 – 21 years during which fertiliser was applied at four-year intervals (Figures 5 and 28). The mean increments for the unfertilised treatments were ~15, 20 and 18m^3/ha/yr for the 250, 500 and 750 sph stands during the same period (Figure 28). Over the intensive management period the cumulative fertiliser response was highest in the lower density (250 sph) stand at 38 m^3/ha and decreased to 31 m^3/ha at 500 sph and to 14 m^3/ha in the 750 sph stand (Figures 5 and 30). Maintaining the plantation at a higher density in this water limited stand limited the response to fertiliser as water availability provided a strong limit to productivity of this site.
For the increment period 25-32 years the increments (plotted against 28.5 years in Figure 28) for the fertilised treatments were lower than the unfertilised treatment for each density. This effect was most pronounced for the higher density 500 and 750 sph stands and resulted in the initial impact of the fertiliser diminishing such that by age 32 years there was no significant annual response to fertiliser in the stands at 500 and 750 sph (refer Figure 5). This contrasts with the maintenance of fertiliser responses at higher plantation densities at the wetter sites (Figure 2).

Following thinning at age 14 the PAI's for both the fertilised and unfertilised 250 treatments increased. In contrast the increments for the unfertilised 500 and 750 stands were relatively similar across this period. Following the second fertiliser application at age 17 the increments declined so that by the age 21–25-year increment period there was no difference between the fertilised or unfertilised treatments at each density. By the 25-32 period the increments ranged from 7.3- ~12.5 m^3/ha/yr.
The decline in growth in the last decade of the trial was likely due to the declining nutrient status of the plantation in the absence of fertiliser as the rainfall at this site was relatively similar between the early and latter stages of the trial with the CWI of 0.47 vs 0.45 (Table 4). The overall limitation on this site was water availability and that maintaining the stands at 750 sph led to significant water stress (Figure 6). This impact likely increased as the stand basal area (and leaf area) increased with age. As leaf water potentials were only measured during the first phase of the trial it was not possible to describe the longer-term effects of the silvicultural treatments on the level of water stress experienced.

The residual effect of applied phosphorus.

While phosphorus is retained in the soil much longer than more soluble nutrients such as nitrogen and potassium the availability of P declines over time. This is shown for the loam soil at Tallanalla as both the HCl P (Figure 29) and HCO_3 P (Figure 30a) declined over time.

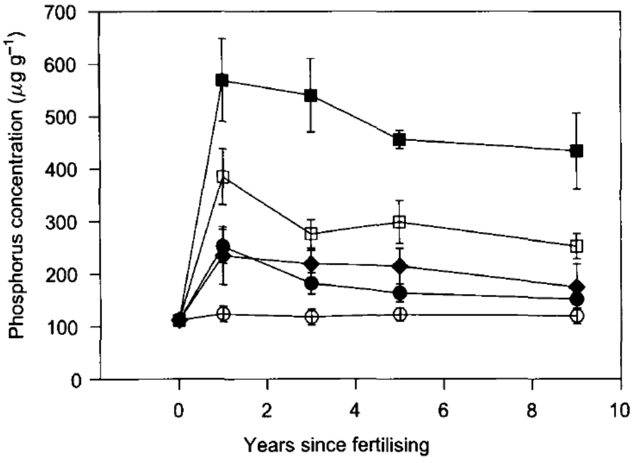


Figure 29. Effect of the application of phosphorus (P0 = ○, P45 = ●, P90 = ◆, P180 = ■, P360 = □) on the acid extractable (HCl) phosphorus in the surface soil (0-10 am) for nine years after application.

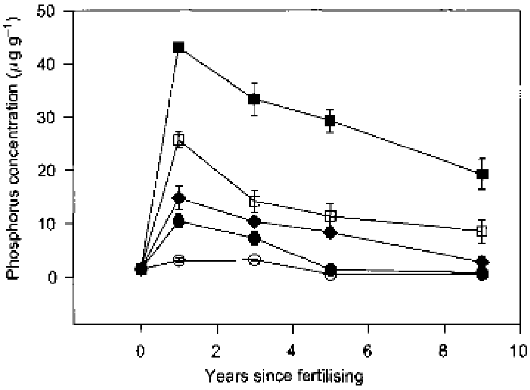


Figure 30a Effect of the application of phosphorus (P0 = ○, P45 = ●, P90 = ◆, P180 = □, P360 =■) on the bicarbonate extractable (HCO_3) phosphorus in the surface soil (0-10 cm) at one, three, five and nine years after application.

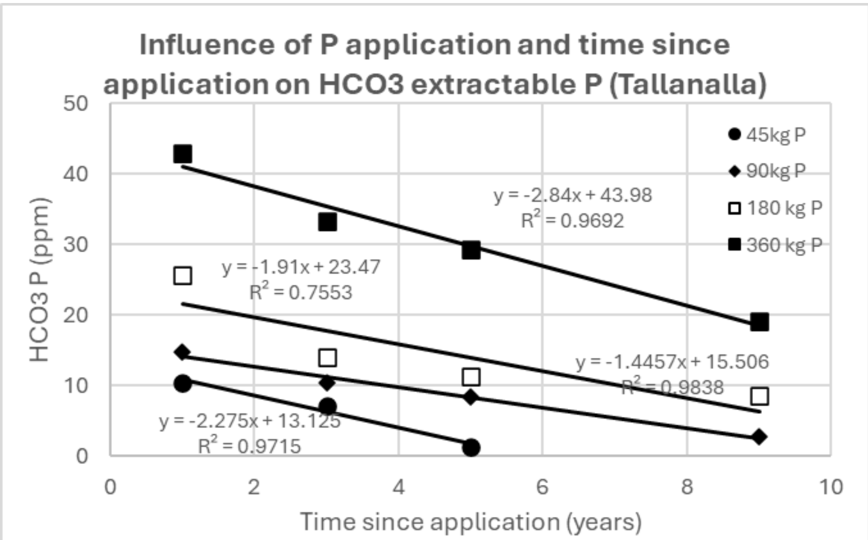


Figure 30 41b. Effect of time since application and the rate of phosphorus application (P45 = ●, P90 = ◆, P180 =□, P360 =■) on the bicarbonate extractable (HCO_3) phosphorus in the surface soil (0-10 cm) for nine years after application.

Based on the regressions fitted to the decline in P availability HCO_3 P would decline to the pre-treatment concentrations approximately six, 11, 12.5, and 15.5 years after application for the 45, 90 180 and 360 kg P/ha applications respectively (Figure 30b). While the residual effect of P is considerable, it does decline with time. The 90 kg P application is equivalent to a 1.0 tonne of superphosphate and that lasts a maximum of 10 years on this soil type which has a high PBI.

An alternative way of examining the residual activity of P is to examine the relationship between the extractable P concentrations and the application of P at successive times (Figure 31) which demonstrated that the P availability declined over time.

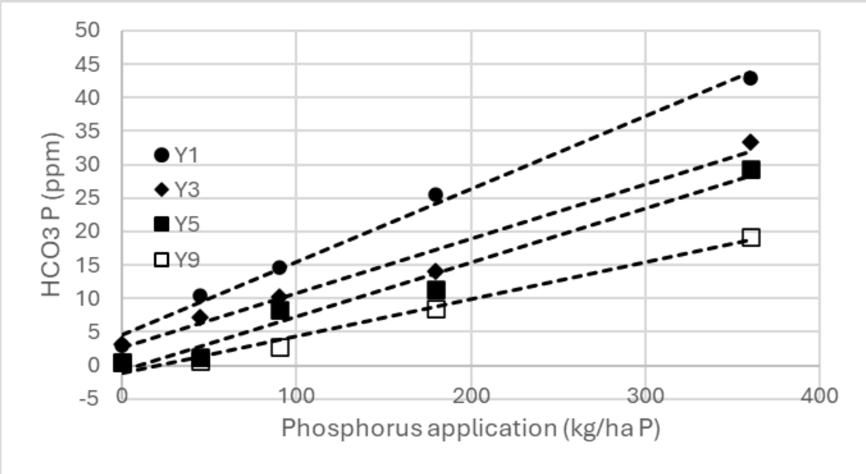


Figure 31. Effect of time since application (Yr 1 = ●, Yr 2 = ◆, Yr 3 = ■, Yr 4 = □) and the rate of phosphorus application on the bicarbonate extractable (HCO_3) phosphorus in the surface soil (0-10 cm) at Tallanalla. Linear relationships:
Year 1: $y = 0.1089x + 4.6325$, $R^2 = 0.99$; 3 year: $y = 0.0814x + 2.605$, $R^2 = 0.98$,
Year 5: $y = 0.0809x - 0.8075$, $R^2 = 0.97$; 7 year: $y = 0.0551x - 1.14$, $R^2 = 0.9826$.

The annual applications of P at the Jarrahwood 7 and Baudin 20 trials made it more difficult to estimate the residual effect of P at these sites as at each successive sampling the phosphorus in the soil had been in the soil from one to seven years (by the sampling at age seven). Despite the 'mix' of ages of application at each time the same trend that was apparent in the Tallanalla soil data of decreasing effectiveness of applied P over time is apparent with a decline in both HCl and HCO_3 extractable P over time (Figures 32 a, b). A difference between the trends between HCl P and HCO_3 P was that there appeared to be a difference between the HCL extracted fraction between ages two and three (Figure 32a) while this difference was not apparent for the HCO_3 P fraction (Figure 32b). When the overall relationship between total P (HCl P) and HCO_3 extractable P was examined, this difference did not impact the overall relationships between HCl and HCO_3 P (Figure 33).

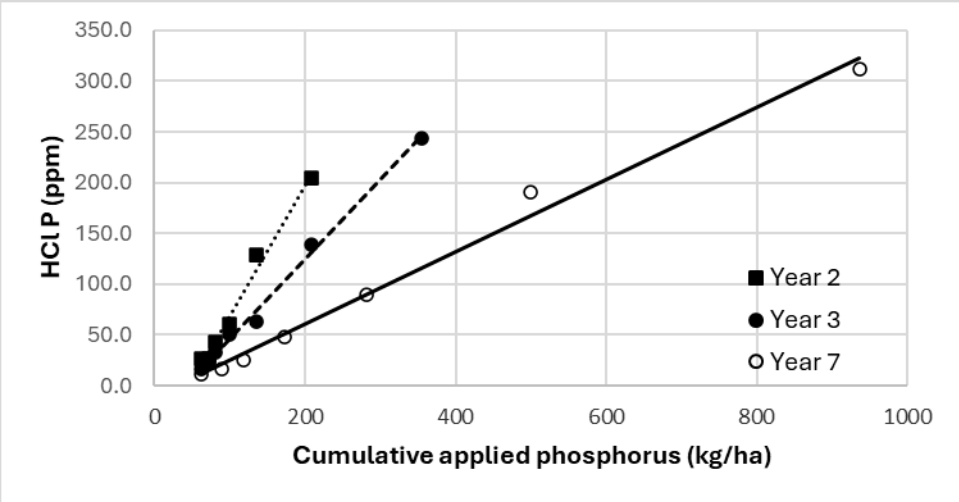


Figure 32a. Relationship between applied phosphorus and HCl extractable P at Jarrahwood 7 at two (■), three (●) and seven (○) years after application. Linear relationships:
Year 2: y = 1.3003x – 61.669, R^2 = 0.9878,
Year 3: y = 0.7847x – 31.949, R^2 = 0.9944,
Year 7: y = 0.3566x – 11.065, R^2 = 0.9906.

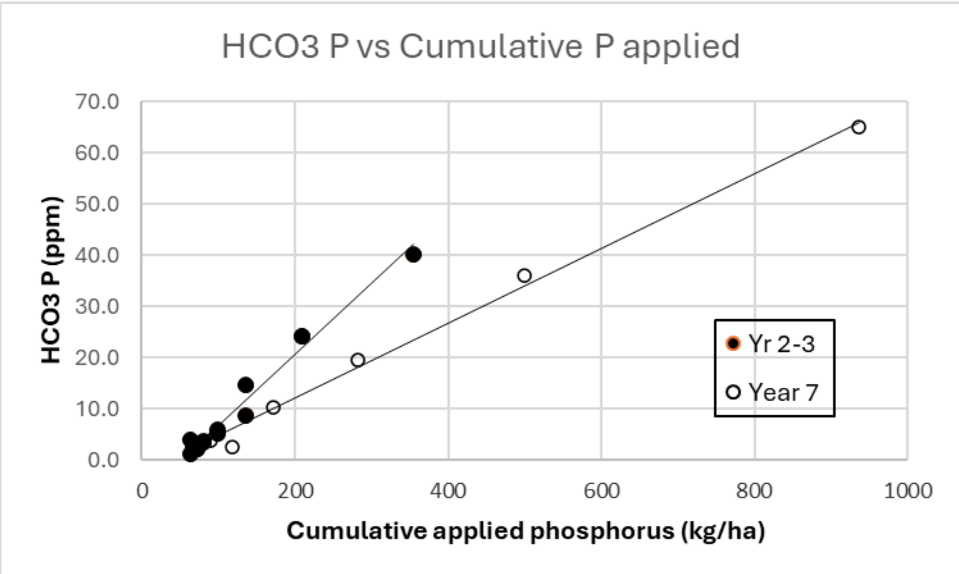


Figure 32b. Relationship between applied phosphorus (kg/ha) and HCO_3 extractable P (ppm) at Jarrahwood 7 at 2-3 and 7 years after application. Linear relationships:
Year 2-3: y = 0.1388x - 7.0517, R^2 = 0.9756,
Year 7: y = 0.073x - 2.2972, R^2 = 0.9924.

Conclusions of duration and magnitude of fertiliser impacts.

- Both phosphorus and nitrogen are required to optimise the productivity of plantations on previous native forest sites with increases in growth up to 85%.
- Large response to phosphorus were evident following thinning and in the establishment phase of the plantations.
- The responses to mid-rotation nitrogen application varied between 25 and 35%. The lower percentage response occurred at drier sites and the increase in growth from N application, measured as the four year PAI following fertilisation, was approximately half that at the wetter sites (4 vs 8 m^3/ha/yr). This was despite the low soil N concentration at the driest site. The application of N that achieved the optimum growth was also lower on the dry site than on the wetter sites.
- Responses to nitrogen depend on the adequate supply of phosphorus and water.
- From a range of trials over multiple sites it is clear that impact of nitrogen fertilisers is limited to four or five growing seasons post fertilisation.
- Responses to phosphorus applications last longer due to the residual nature of P in the soil. However, where N is a primary limitation to growth, as occurs on most of the ex-forest sites the response to fertiliser is limited by the duration of the response to N.
- The duration of impact of phosphorus increased with increasing rates of phosphorus application.
- By 7-8 years after the second fertiliser application on the Coastal Plain (Figure 28) and third application on the Blackwood Low Plateau (Figure 27) the response to fertiliser had disappeared.

Section 3: Assessing and predicting the responses to fertiliser applications.

Results and Discussion

Using soil phosphorus as a diagnostic tool for plantation P status.

The availability of soil phosphorus to plants varies between soils with plant available P being lower on soils that have a high phosphate adsorption capacity. Sands generally have a low P adsorption capacity while heavier textured soils, and soils with high iron and aluminium content have a high capacity to adsorb P. Soil phosphorus availability has been used with a wide range of agricultural crops to assess the phosphorus status of the soil and to determine the fertiliser requirements for crops. A variety of extraction methods have been used to assess the plant available phosphorus status of soils.

Bicarbonate (HCO_3) extractable P is the most commonly used extractant for assessing soil P status in Australia and there are two common extraction methods used. The primary difference between the two methods is the time that the soil is in contact with the extraction solution. The Colwell extraction method uses a longer (16 hr) extraction period and extracts the easily adsorbed fraction and some of the more strongly bound P that are not available to plants (Moody 2007). The Olsen extraction method uses a shorter extraction period (30 mins) which is thought to limit the proportion of extracted P that is strongly bound in the soil (Rayment and Lyons 2011).

Two P extractants were used to assess the soil P status for these trials. Soil P was extracted with 6N HCl and 0.5 N HCO_3 (Olsen Bicarbonate method). The 6N HCl extraction provides an estimate of total soil P as organic and strongly bound inorganic pools of phosphorus are extracted. The Olsen HCO_3 P provided an estimate of plant available P (Gourley *et al.* 2019). When the pine nutrition trials summarised here were undertaken the Phosphorus Buffering Index (PBI) was not assessed. Olsen soil P values are not affected by the capacity of the soil to adsorb P and consequently the Phosphorus Buffering index (PBI) is not required to assess the soil P status (Gourley *et al*. 2019). The PBI can be useful in determining the amount of fertiliser P required to increase soil P (Anon, Vic Dairy soils and Fertiliser Manual 2013) (Table 8).

The relationship between the total P (HCl P) and available P (HCO_3) for three key soil types/land units on which pine plantations are grown in WA are shown in Figure 33. These soil/landscape units are the loams of the Darling Scarp (DS), lateritic derived duplex soils of the Blackwood Low Plateau (BLP - aka Donnybrook Sunkland) and the deep sands on the Swan Coastal Plain (SCP). While these relationships are not directly an estimate of the phosphate adsorption capacity of the soils, the slopes of relationships (Figure 33) indicates that the P in the sandy coastal plain soils is more easily extracted than in the heavier textured soils found in the Blackwood Low Plateau and the Darling Scarp. The heavier loam soil from the Darling Scarp appeared to have lower P availability that the soils on the BLP (Figure 33). This is consistent with the increasing PBI values SC<BLP<DS (Table 9).

The relationship between HCO_3 P and HCl P for the two sites on the BLP (Baudin 20, Jarrahwood 7) were further examined (Figure 34) as the PBI was higher at the Baudin 20 site. The relationship between the two P extractants was very similar and indicated that the phosphorus availability would have been very similar at these sites.

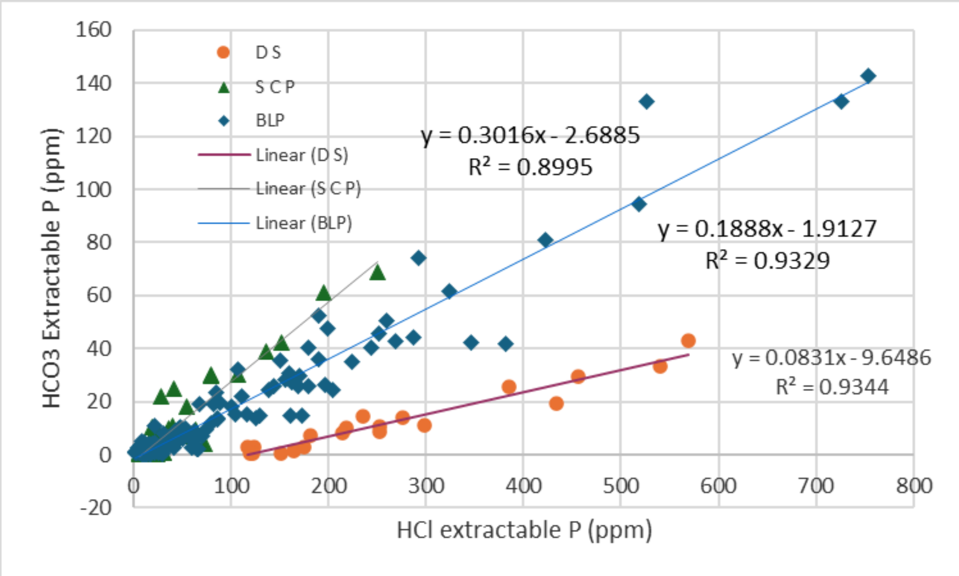


Figure 33. Relationship between HCl and HCO_3 extractable soil phosphorus for soils from the Darling Scarp (DS), the Blackwood Low Plateau (BLP) and the Swan Coastal Plain (SCP).

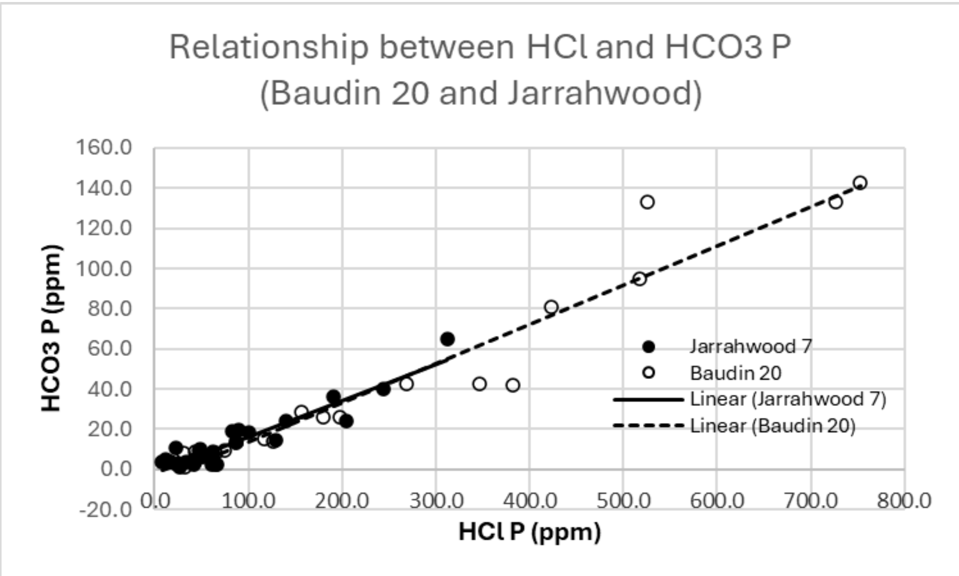


Figure 34. Relationship between HCO_3 extractable P (ppm) and HCL P (ppm) (Total P) at Jarrahwood 7 (●) and Baudin 20 (○). Linear relationships:
Jarrahwood 7: y = 0.1796x – 1.5376, R^2 = 0.8901;
Baudin 20: y = 0.1954x – 5.7362, R^2 = 0.9394

The soils at the core fertiliser trial sites were resampled in March 2022 (Table 9) to assess the Phosphorus Buffering Index (PBI) at the trial sites. The PBI values ranged from extremely low values for the coarse coastal sands in the Myalup trials (9-16) to very low to low at the trials on the Blackwood Low Plateau (42-132) to high values on the Darling Scarp site (292). The PBI values are consistent with the analysis of the relationships between Olsen P (HCO_3 P) and total (HCL) P, where low PBI values are associated with a higher relative availability of P on the Coastal Sands and a low availability of P was associated with the high PBI values on the Darling Scarp loams.

Table 8. Phosphorus buffering index (PBI) categories for common WA soils.

Classification of P-Sorbing Properties of WA soils based on PBI		
PBI	**Classification**	**Soil Types**
<15	Extremely low	Grey sands, Bassendean sands, Badgingarra sands, Wilbray sands
15-35	Very very low	
36-70	Very low	Grey brown sands, deep duplex soils Lancelin sands, Jerramungup sands, Coolup sands, Esperance sands
71-140	Low	
141-280	Moderate	Grey loamy sands, yellow-brown sands, Coolup loamy sands, Spearwood sands, Dandaragan red earths, Dongara black wattle, Wongan Hills, Merredin sandy loams
281-840	High	Lateritic gravels, sandy loams, Kununurra clays, Darling Range loams
>840	Very high	Lateritic loams, iron rich peat, karri loams podzol hardpans

From: Summit fertilizers Phosphorus Buffering Index, also see Bolland *et al.* 2010.

Table 9. Phosphate buffering index (PBI) and soil description for fertiliser trial sites in the south west of WA. The PBI class is based on the categorisation provided in Table 8.

Geographic Unit	Site	Surface soil	PBI	PBI class
Darling Scarp	Tallanalla	Red brown loam (Darling Range loam)	293	High
Blackwood Low Plateau	Baudin 20	Gravelly yellow sandy	132	Low
	Jarrahwood 7	Yellow sands	73	Low
	Vasse 1	Yellow sand	64	Very low
	Baudin 1	Grey sands	42	Very low
	Vasse 9	Grey sands	47	Very low
Harvey Coast	Myalup 131	Coarse grey brown sand	16.3	Very very low
	Myalup 132	Coarse grey brown sand	9.2	Extremely low

The relationships between soil P and response to fertiliser in WA pine plantations.

The trial at Tallanalla (1985-1995) defined relationships between both HCO_3 P and HCl P with critical concentrations (defined as the point at which growth declined from the maximum growth) of ~ 17 ppm for HCO_3 P (Figure 35) and 330 ppm for HCl P (Figure 36). The approach used was to describe the responsive part of the growth curve as a linear relationship. Often the critical concentration is defined as the concentration at which 90% of maximum growth occurs. If this criterion was used, then the critical HCO_3 P value would be ~13 ppm and P275 ppm for HCL. The 90% criterion is often used as the relationships are strongly curvilinear which means that little additional growth is achieved for large increases in P concentrations.

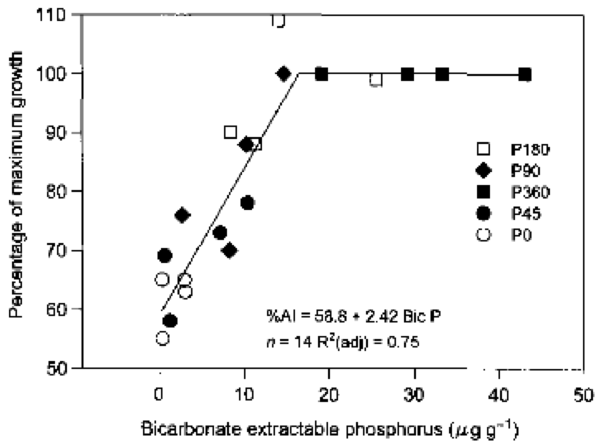


Figure 35. Relationship between the concentration of bicarbonate extractable P (HCO_3 P) in the surface soil and the annual basal area increment expressed as a percentage of the maximum increment each year. Relationships are based on sampling and measurements one, three, five and nine years after application of fertiliser (P0 = ○, P45 = ●, P90 = ◆, P180 = ■, P360 = □). (From McGrath *et al.* 2003b).

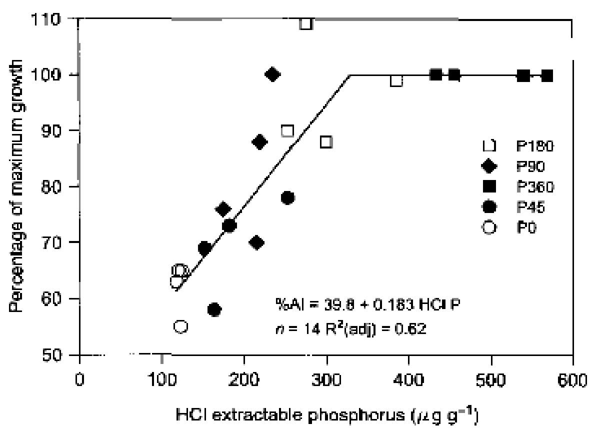


Figure 36. Relationship between the concentration of HCl extractable P (HCl-P) in the surface soil and the annual basal area increment expressed as a percentage of the maximum increment each year. Relationships are based on sampling and measurements one, three, five and nine years after application of fertiliser (P0 = ○, P45 = ●, P90 = ◆, P180 = ■, P360 = □). (From McGrath *et al.* 2003b).

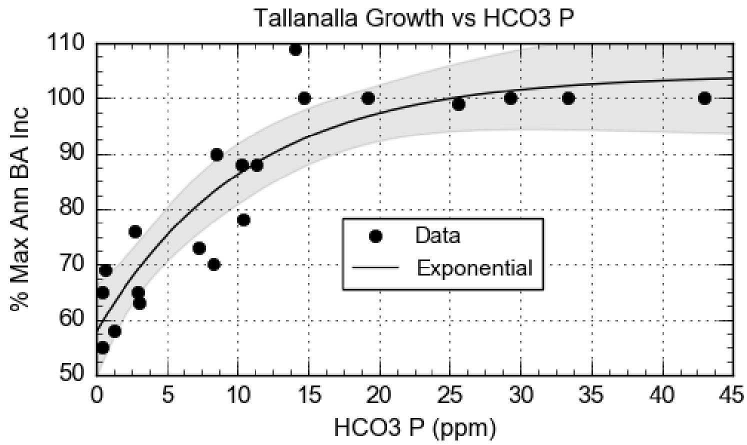


Figure 37. Relationship between the concentration of bicarbonate extractable P (HCO_3 P) in the surface soil and the annual basal area increment expressed as a percentage of the maximum increment each year. Relationships are based on sampling and measurements 1,3,5 and 9 years after application of fertiliser.
Exponential model: a*(b-exp(-c*x)), a = 46.73, b = 2.23, c = 0.0949, R^2 = 0.8182, s.e. = 7.64.

Using an exponential relationship (Figure 37) to describe the relationship between HCO_3 P and the response to P for the Tallanalla data increased the estimate of the HCO_3 P concentration required for maximum growth from ~17 to 25 ppm, but importantly did not alter the estimate for a critical concentration based on 90% of maximum growth which remains at 12-13ppm HCO_3 P.
Relationships between growth and HCO_3 P were developed for the two phosphorus rate trials in young plantations located on the Blackwood Low Plateau. The individual exponential relations explain a large proportion of the variation for both the Baudin 20 (Figure 38) and Jarrahwood 7 (Figure 39) trials. The shape of the relationships varied between the two sites with maximum growth occurring at 40 ppm HCO_3 P at the Baudin 20 site (Figure 38) and at 10 HCO_3 P at the Jarrahwood 7 site (Figure 39). Similarly, the point at which 90% of maximum growth was achieved was 20 ppm at Baudin 20 and 5ppm at Jarrahwood 7 (Figures 38, 39).

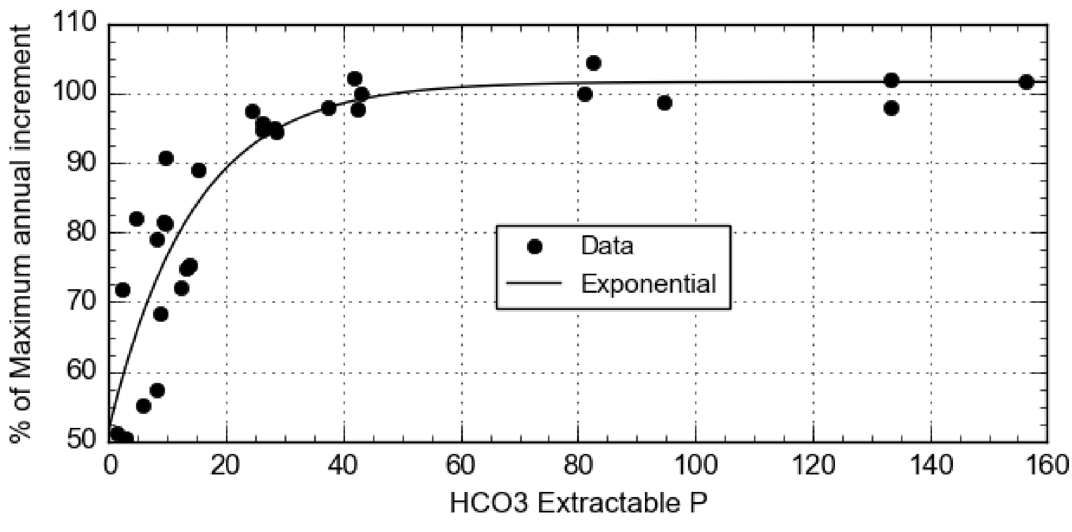


Figure 38. Relationship between HCO_3 extractable P and annual basal area growth as a percentage of the maximum growth (Baudin 20) Increment data from 3 to 8 years.
Exponential model: a*(b-exp(-c*x)), a = 49.94, b = 2.035, c = 0.06965, R^2 = 0.79, s.e. = 7.8.

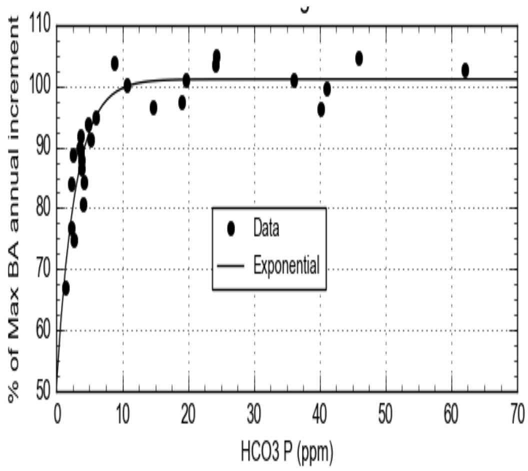


Figure 39. Relationship between HCO_3 extractable P and annual basal area growth as a percentage of the maximum growth (Jarrahwood 7) Increment data from three to seven years. Exponential model: a*(b-exp(-c*x)), a = 49.84, b = 2.03, c = 0.3524, R^2 = 0.84, s.e. = 4.2.

Note: the scale of the X axis in Figure 39 has been adjusted to approximate the scale of the x axis in Figure 38 to make the comparison between the shape of the curves easier.

Cross site analysis.

The similar relationships between the plant available P (Olsen HCO_3 P) and total P (HCl P) at the Jarrahwood 7 and Baudin 20 sites (Figures 33, 34) indicated that the availability of soil phosphorus would be similar at these sites. While there was some variability in the Phosphate Buffering Index (PBI) for these sites all the values for the Blackwood Low Plateau sites were classified as low or very low indicating a similar availability of P on these soils (Table 9). The growth at Baudin 20 was double that at Jarrahwood 7, largely due to the optimal supply of other nutrients (in particular nitrogen) and required a higher phosphorus application to achieve the optimum growth (Figures 18 a, b). This suggests that the supply of phosphorus required to optimise growth under a particular set of conditions is determined by the growth rate that is determined by other conditions such as the supply of water and other nutrients. The HCO_3 P concentration provides a measure of the capacity of the soil to provide phosphorus to the trees. Rapidly growing trees require more phosphorus.

By combining the cumulative growth to age seven years for the Baudin 20 and Jarrahwood trials (Figures 40 a, b), which provided a common measurement point, and defining the maximum growth as that achieved in the optimally fertilised Baudin 20 site, similar relationships to the individual site relationships (Figures 38, 39) were developed from the combined relationships (Figures 49 a, b). The optimum growth at Baudin 20 occurred at ~ 40 ppm and 10 ppm for Jarrahwood 7, which were similar to the concentrations defined using annual growth data (Figures 38, 39). When all other nutrient limitations ware eliminated (Baudin 20) the phosphorus requirement to achieve the maximum growth rate increased relative to the lower productivity site (Jarrahwood 7). This was evident in both the critical soil P concentration (Figure 40a) and the amount of phosphorus that needs to be applied (Figure 40b) to achieve optimal growth.

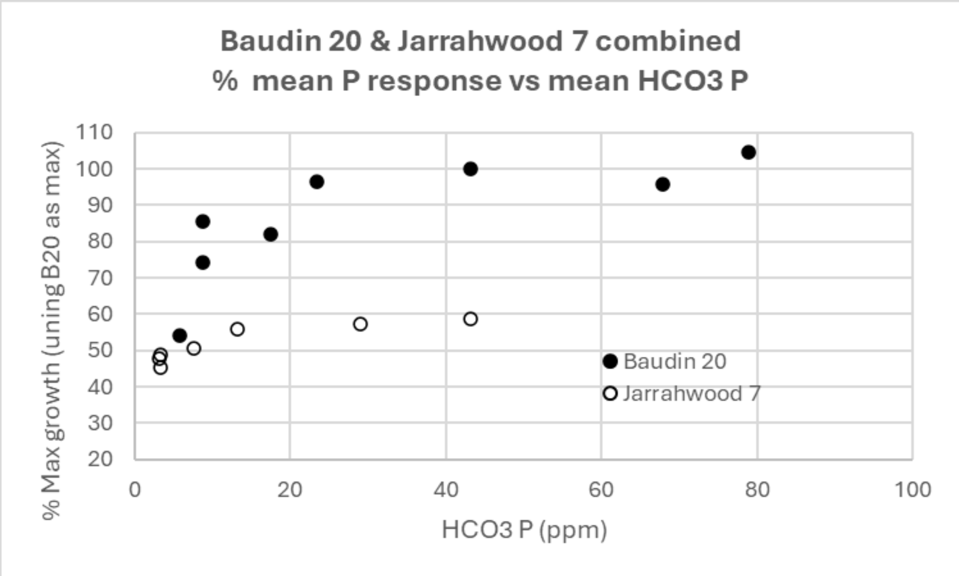


Figure 40(a). Relationship between the % of the maximum BA at age seven years for the BLP (based on Baudin 20 BA growth as the maximum for this region) for Baudin 20 (●) and Jarrahwood 7 (○) vs mean Olsen HCO_3 extractable P to age seven years.

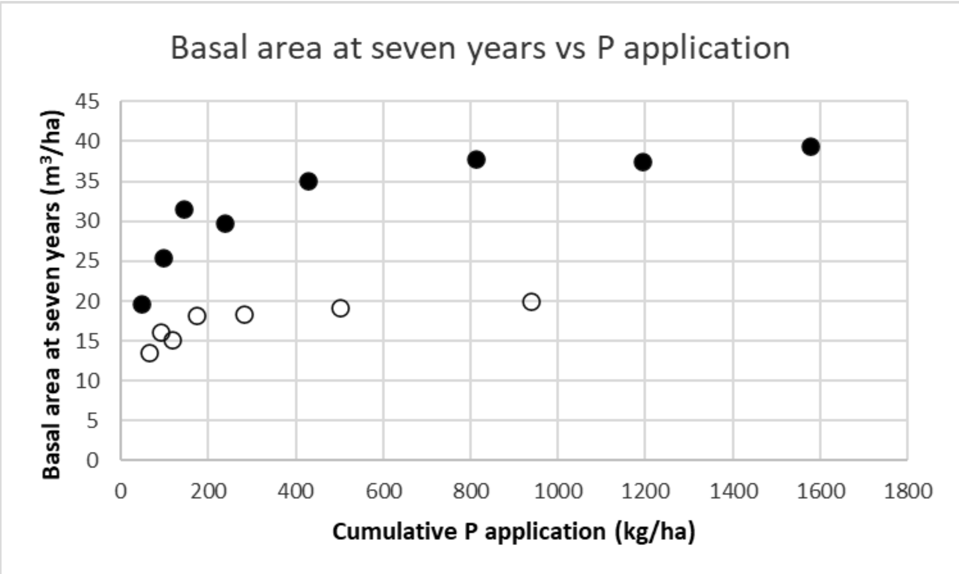


Figure 40(b). Response to applied phosphorus as BA increases at age seven years for the BLP at Baudin 20 (●) and Jarrahwood 7 (○) vs cumulative applied P (kg/ha).

The use of the Baudin 20 data as the maximum productivity for the BLP appears reasonable as the growth at age seven was similar (slightly higher) than the basal area achieved in a similar trial which tested the impact of N rates at Vasse 1 where again all other nutrient limitations were eliminated. Whether this estimate of the maximum productivity is relevant to the Jarrahwood 7 site was not tested as none of the treatments at Jarrahwood 7 provided adequate supplies of all other nutrients. The similarity in soil nutrient characteristics and climate between these sites on the Blackwood low Plateau (Table 5) suggests that this is a reasonable assumption.

Comparing the Darling Scarp and Blackwood Low Plateau sites.

While it is not possible to directly compare the basal area growth between the young plantations on the BLP and the Tallanalla site on the Darling Scarp we have combined the relative annual growth vs HCO_3 P data from Baudin 20 and Tallanalla for growth in relation to HCO_3 P (Figure 41) and HCl P (Figure 42).

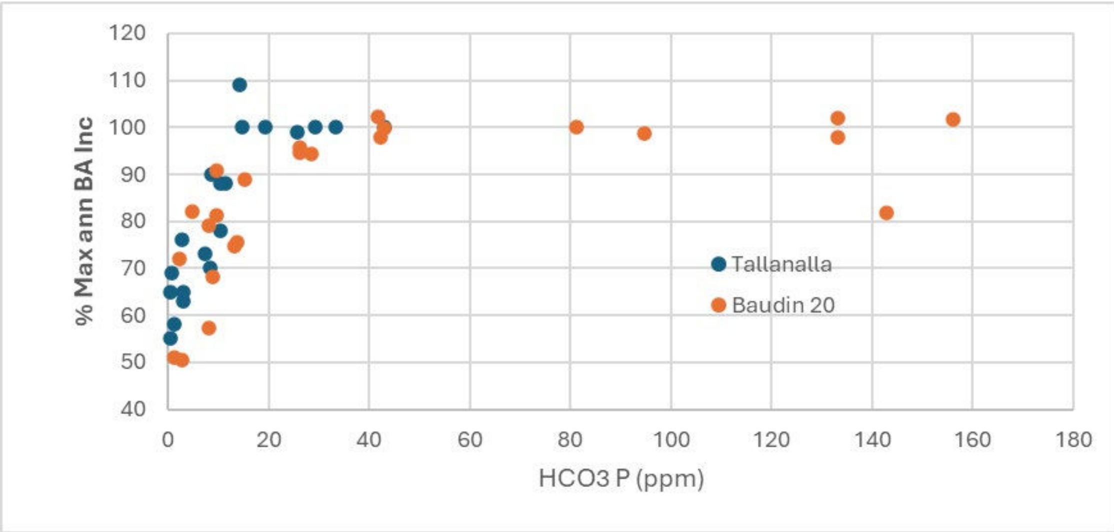


Figure 41(a). Combined relationship between HCO_3 extractable P and annual basal area growth as a percentage of the maximum growth for each of Baudin 20 and Tallanalla. This shows the individual site data.

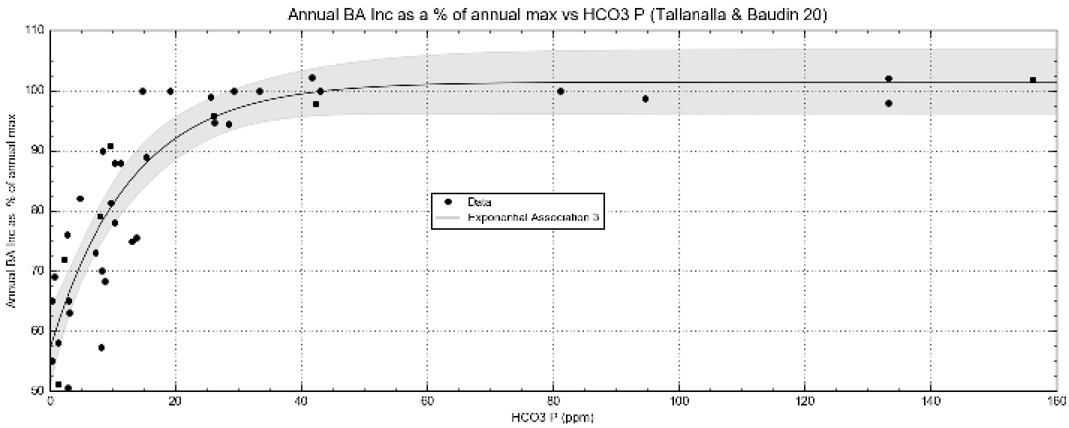


Figure 41(b). Combined relationship between HCO_3 extractable P and annual basal area growth as a percentage of the maximum growth for each of Baudin 20 and Tallanalla. Note to get the exponential model to fit it was necessary to remove the outliers at ~14 and 142 ppm HCO_3 P. R^2 =0.79. s.e.7.7). Exponential model: a*(b-exp(-c*x)), a = 44.44, b = 2.28 c = 0.0778.

By combining the increment and soil phosphorus data from Baudin 20 and Tallanalla there was a reasonably consistent relationship between HCO_3 P and annual basal area increment. The statistics for the relationship are provided in Fig 39(b). The exponential relationship did not fit the data when the outliers at 14 and 142 ppm HCO_3 P are included. Removing the outliers allowed the relationship to converge. However, even without those data the relationship appears sufficiently strong to provide a useful index of response to P on medium to heavy textured soils. An alternative assessment/hypothesis is provided below.

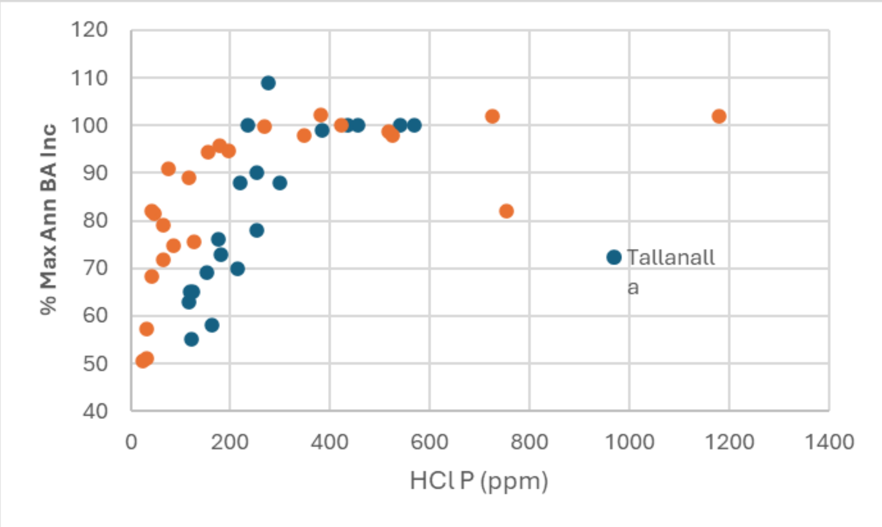


Figure 42. Combined relationship between HCl extractable P (Total P) and annual basal area growth as a percentage of the maximum growth for each of Baudin 20 and Tallanalla. This shows the individual site data.

There appeared to be distinctly different relationships between responsiveness to HCl extractable P between sites (Figure 42), with higher concentrations of HCl P required to maximise growth on the Tallanalla site than at Baudin 20. This indicated that the phosphorus in the Tallanalla soils was more strongly adsorbed than at Baudin 20 so higher concentrations are required to optimise growth. This was consistent with the relationships between the available P fraction (HCO_3 P) and total P (HCL P) where for a given HCL P concentration the HCO_3 P was lower on the Tallanalla soil than on the soils from the Blackwood Low Plateau (Figure 33). The higher phosphate buffering index (PBI) values for the Tallanalla soil (Table 9) were also consistent with the heavier Tallanalla soil requiring a greater amount of phosphorus to meet plant requirements.

An alternative hypothesis to why the apparent HCO_3 P requirement varies between the sites is that the level of P required increases as the growth rate increases.

The only apparent limitation to growth at the Baudin 20 site was water availability with all known nutrient requirements being met by the basal nutrient applications. In the final year of the intensive management of the trial the annual volume increment was ~45 m^3/ha/yr. This is comparable to the growth at the nearby Vasse 1 nitrogen rates trial where annual increments at a similar age were between 45 and 50 m^3/ha/yr. This suggest that the Baudin 20 site was growing near the maximum for this region/climatic zone.

The Tallanalla site is in a similar rainfall zone with a CWI 0.76 which is comparable to the CWI values at Baudin 20 (CWI 0.74) and Vasse 1 (CWI 0.76) (Table 2). Whatever the cause, the volume increments at Tallanalla were lower than observed in the younger stands on the BLP at ~28 m^3/ha/yr (Figure 19). Based on this, the productivity at Tallanalla was 62% of that at Baudin 20. Similarly, the basal area growth over seven years at Baudin 20 was 38.3 m^2/ha and at Jarrahwood 7 at the same age 19.0 m^2/ha (Figure 18a) thus the productivity at Jarrahwood 7 was half that at Baudin 20. By scaling the annual productivity at each site relative to the productivity at Baudin 20 an interesting picture emerges with the HCO_3 P requirement for maximum growth increasing as the productivity increases (Figure 43). At Jarrahwood 7, with half the productivity at Baudin 20, growth plateaued at ~ 7.5 ppm HCO_3 P, at Tallanalla with productivity at 62% of the Baudin 20 site this value was 15 ppm HCO_3 P and at the higher productivity Baudin 20 site the value was between 25 and 40 ppm (Figure 43). If this hypothesis is correct, then soil HCO_3 P provides an estimate of the capacity of the site to provide phosphorus to the plantation but the demand for phosphorus varies depending on the growth rate. Consequently, as the demand for nutrients increases then the capacity to supply the nutrients needs to be higher to meet this higher demand.

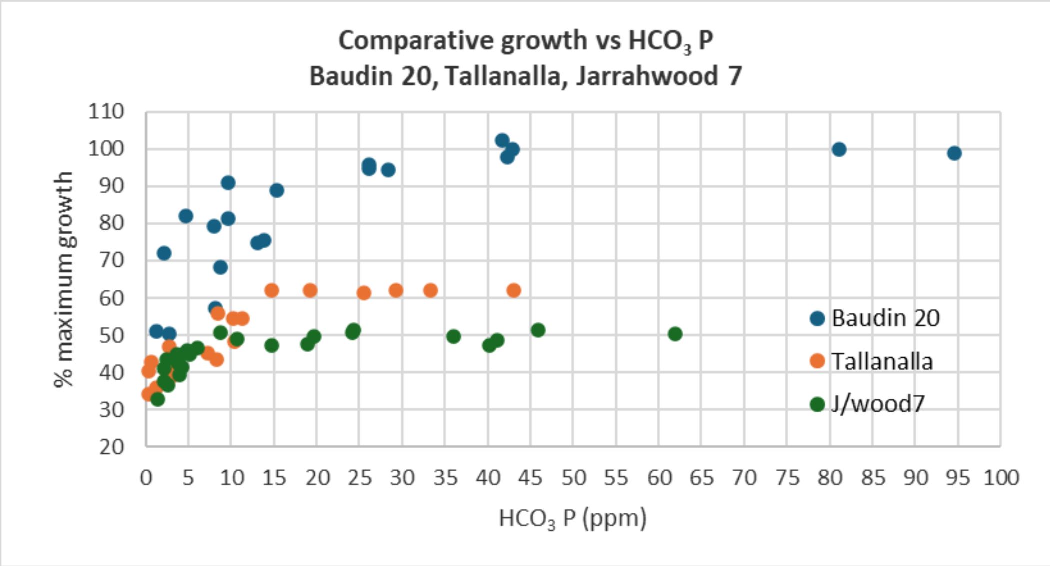


Figure 43. Scaled relationship between HCO_3 extractable P and annual basal area growth as a percentage of the maximum growth for each of relative to that at Baudin 20. This shows the individual site data.

The increase in phosphorus requirement with increasing productivity has been observed for pasture systems with the soil phosphorus requirement increasing with increasing levels of production (Bolland *et al.* 2010). It is possible that this concept is relevant to other site related limitations, for example if growth is limited by water availability, then the requirement for nutrients would be lower than when water supply is higher.

Response to nitrogen.

Four-year responses to N fertilizer alone have been measured across eight experiments in WA. Nitrogen was applied at rates ranging from 0.2– 1.2 t N/ha. Applications above 300-400 kg N/ha (See Figure 24) were more than adequate for the tree's requirements on sites with high rainfall. The application that optimises growth is lower on drier sites (Figure 22). The responses ranged from 3% at the WAWA trial in young P. radiata on a fertile ex-pasture site located on the south coast, to 33% at Vasse 9. In the absence of limitations due to rainfall or P, responses to N fertiliser are commonly related to foliar N or total soil N concentrations (May et al. 2016, Turner et al. 2001). Foliar N was not measured across the eight experiments in WA and soil N was measured at only four sites. However, soil organic carbon(C) was measured across seven of the sites (including the four sites where soil N was not measured). Since soil organic C is closely related to total soil N this can be used as a surrogate to predict soil N. Previous studies of plantations soils on ex agricultural land across southern WA had average C:N ratio of 12.9 (R. Harper pers comm).

The four-year responses to N fertiliser were strongly related to soil organic C across the sites as shown in Figure 44 (R^2 = 0.78). Soil total N was estimated for four sites at which it was not measured using the C:N ratio of 12.9. Using these estimated values for soil N with the measured values a relationship explaining 81% of variation in response to N across the eight sites was developed (Figure 45). The one major outlier point (WAWA) may be an anomaly as soil total concentrations were estimated from soil carbon concentrations at this site.

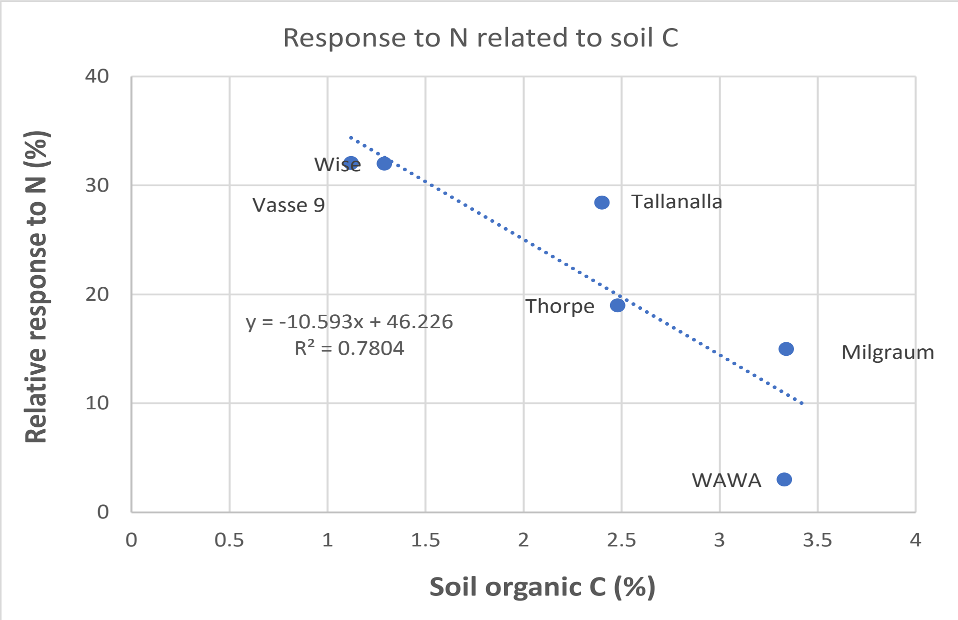


Figure 44. Relationship between percentage growth response to N fertiliser and soil organic C.

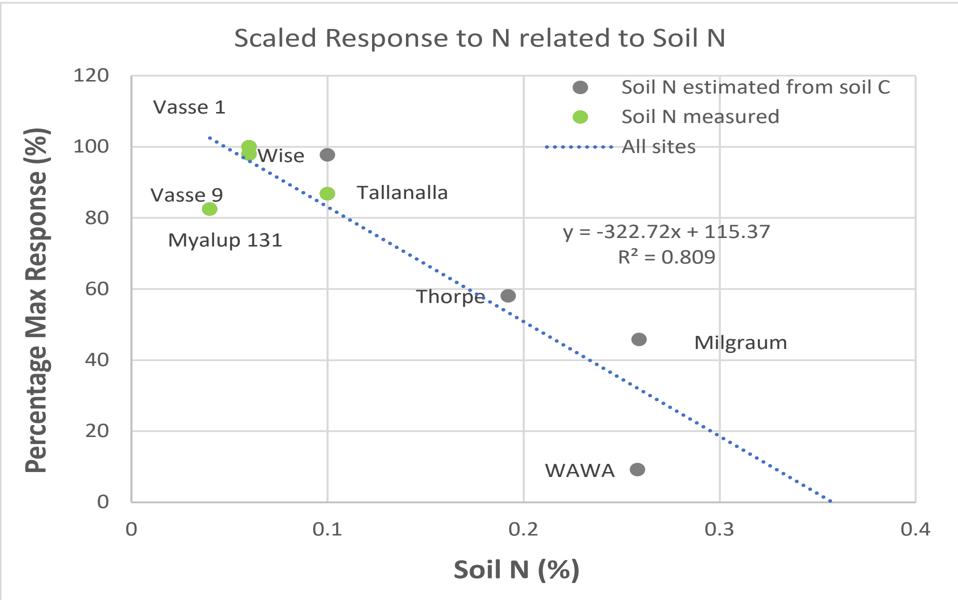


Figure 45. Relationship between percentage growth response to N fertiliser and total soil N either measured directly or estimated from soil organic C.

Conclusions

- The strong relationships between soil P and growth have allowed the definition of a reliable Olsen bicarbonate P critical concentration and the responsiveness to soil P below this critical concentration.
- There are also strong relationships between the response to nitrogen application and soil N, however a critical upper concentration of soil N above which there was no response was not well defined.

Section 4: Incorporation of results from existing experiments into Profert (and provide to growers for final testing).

Results and Discussion

The initial relationships developed from the analysis of WA data have been incorporated into the model and define the responses to water availability, nitrogen and phosphorus (as described in earlier data analysis for the project - MS4 and MS5). The relationships were refined to match the requirements of ProFert. The model also includes a time course of the response to both N and P, with N having a relatively short-lived impact while the response to P is maintained for longer periods.

The model was debugged and provided to FPC in a working form (15/12/2021)

The Western Australian version of ProFert is driven by productivity responses to:

- Water availability defined as Climate Wetness Index (CWI = Rain/Evaporation)
- Phosphorus supply
- Nitrogen supply

This version of ProFert uses soil fertility assessments to drive the model, unlike the earlier (Eastern) versions which used foliar nutrient status to drive the model. The WA version has been calibrated to soil P and N availability as soil nutrient data were available and the assessment of soil nutrient status is easier than sampling the foliage of large trees. Additionally, the seasonal variation in foliar nutrient concentrations means that sampling timing is critical if foliar sampling is to be used effectively. This is possibly even more important in the very strongly seasonal climate in WA. Therefore, soil sampling potentially provides a more robust assessment method for WA conditions.

Incorporating the response relationships previously described for WA has required:

- The presentation of the responses as relative % responses to match the existing model architecture,
- The development of interactive response surfaces between water availability (CWI) and nitrogen and phosphorus, respectively.

These responses to water availability, phosphorus and nitrogen are shown below. The equations that drive the model have been incorporated into ProFert and this version of the model has been provided to FPC for testing.

Response to water availability.

The data in Figures 46 and 47 define the relationship between the response to fertiliser and water availability. These data are based on the absolute (Figure 46) and relative (Figure 47) cumulative four year responses to maximum rates of N+P fertiliser applied across a range of sites that were deficient in either or both these nutrients and therefore show the maximum potential response across these stands given limitations in other factors (i.e. water, temperature or other nutrients). The strong relationships between response to N+P fertiliser and CWI indicate that water supply is the main remaining limitation to growth (i.e. after N and P limitations have been addressed). At low CWI the responses to fertiliser are largely limited by water supply while as water availability increases the scope to achieve fertiliser responses increases. This relationship underpins the way ProFert operates for WA *P. radiata* plantations.

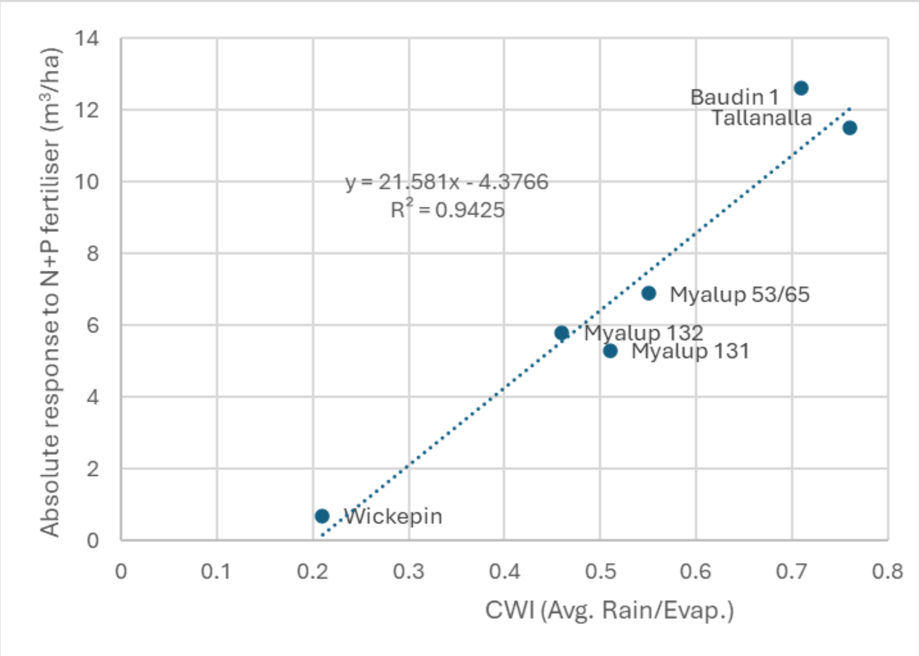


Figure 46. Response to adequate application of N+P fertiliser in relation to climate wetness index. These data are from sites across the climatic gradient in southern WA.

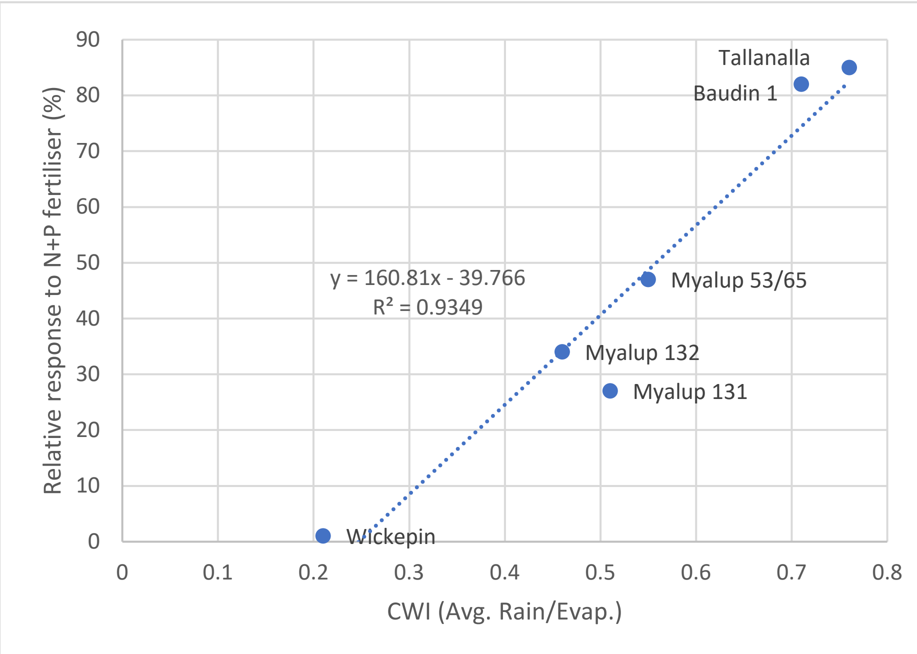


Figure 47. Response to adequate application of N+P fertiliser in relation to climate wetness index expressed as a % increase relative to the unfertilised reference treatments. These data are from sites across the climatic gradient in southern WA.

Response to phosphorus.

The relationship between soil P availability (measured as bicarbonate extractable P) and four-year response to P fertiliser was derived from results from three experiments (Baudin, Tallanalla and Jarrahwood) in which different rates of P were applied over time. All sites were very deficient in P. Changes in soil P availability and growth of trees after each of these applications over time allowed the responses to P given different initial soil P conditions to be calculated. The resultant data showed strong relationships between soil P and subsequent response to P fertiliser across each of these sites (R^2 ranging from 0.70 to 0.80). The results across the three sites were standardized by expressing the responses relative to the maximum response at each site. This allowed a single curve based on the pooled results from the three sites to be derived.

Figure 48 shows the increase in basal area growth at each of the three sites expressed relative to maximum growth for the highest rate of P application. In Figure 49 the results were inverted to show the relationship between response to P fertiliser (expressed relative to the maximum response measured at each site) and initial soil P availability. This relationship (Figure 49) was used as the key driver (in conjunction with that between response to fertiliser and CWI) with the response to P fertiliser (applied at "luxury rates" of over 300 kg P/ha) in the absence of other nutrient limitations in the ProFert model.

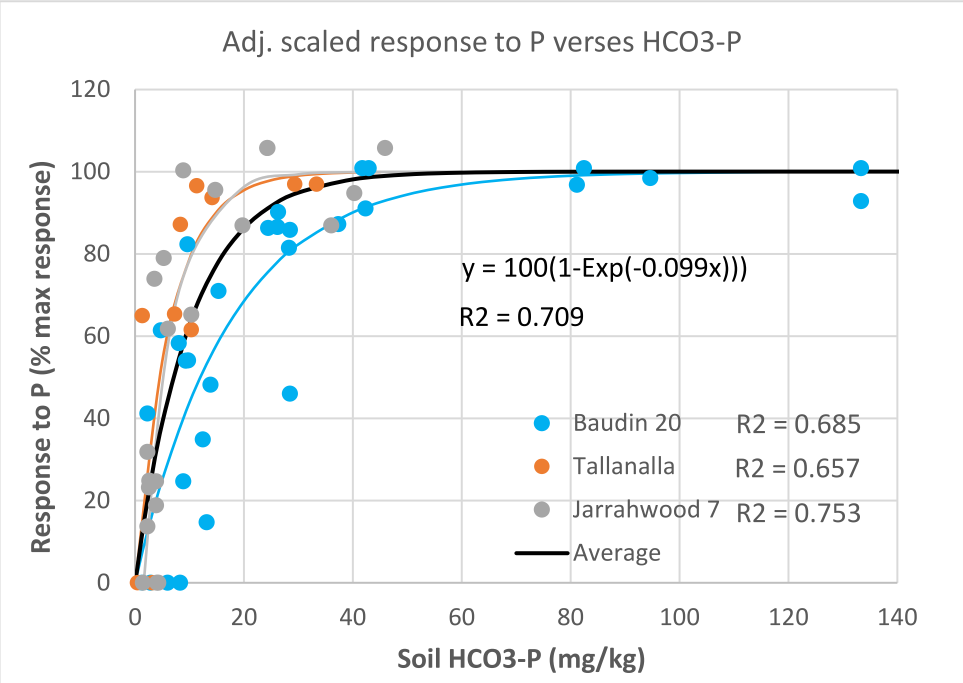


Figure 48. Scaled growth response relative to soil bicarbonate P.

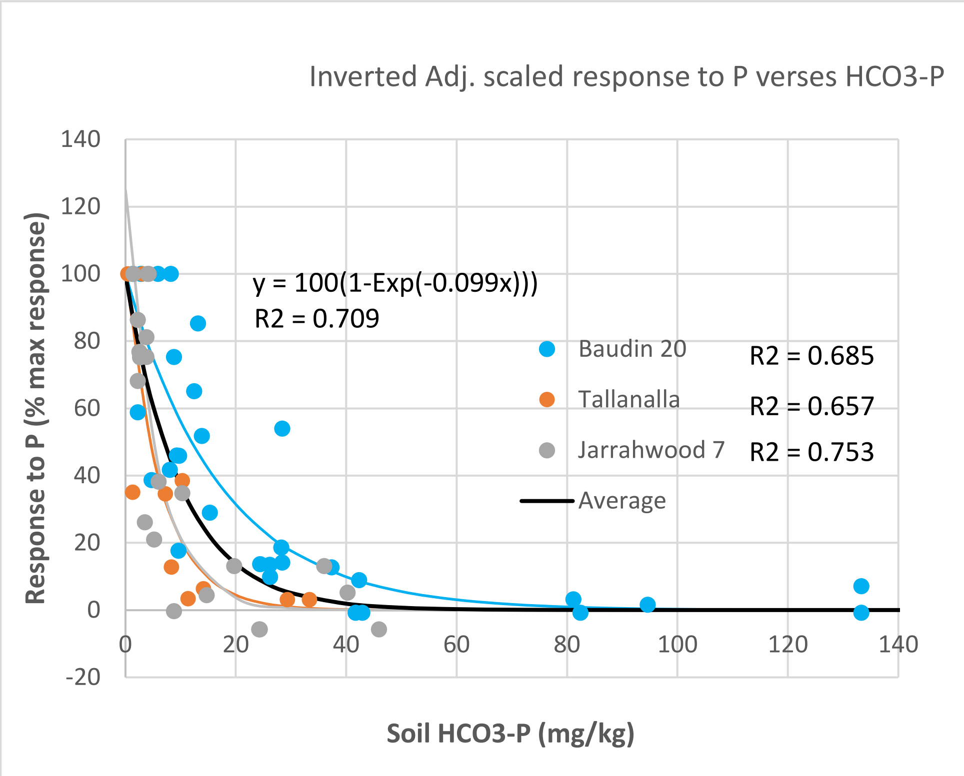


Figure 49. Inverted scaled growth response relative to soil bicarbonate P. Note this is how Profert works, i.e. large response at low soil P concentrations.

The effect of rate of P application and response to P fertiliser was calculated from results from Tallanalla where the responses to single applications of different rates of P were measured over time. These results (again scaled relative to the response to the maximum rate applied) indicated that there was a strong curvilinear relationship between rate of P applied and response to P (Figure 50). The relationship appears to plateau for rates around 300 kg P/ha. However, approximately half of that (150 kg P/ha) was required to achieve 90% of the maximum growth (Figure 50).

This relationship was used in ProFert to determine the effect of different rates of P application on response (after calculating the underlying response to CWI, P and other nutrient limitations assuming the maximum rate of P was applied).

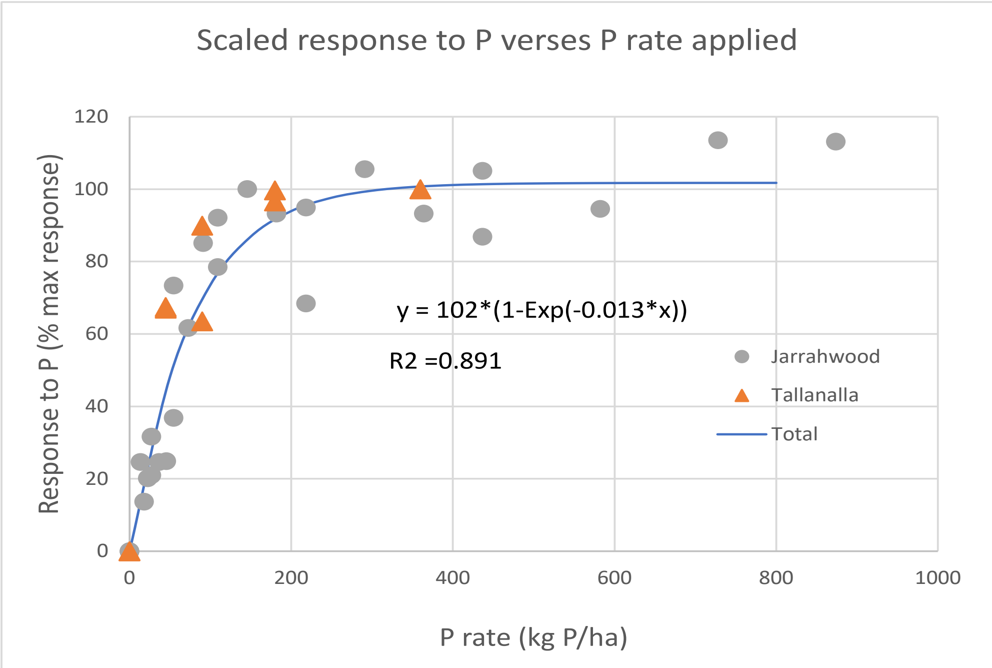


Figure 50. Scaled response to applied phosphorus.

Combined response to P given limitations in water availability.

The combined effect of CWI and soil P availability (as indicated by bicarbonate extractable P) on relative (%) four-year response to P fertiliser are calculated in ProFert by combining the relationships shown in Figures 47 and 49 above. The resultant relationship is illustrated in the surface shown in Figure 51.

This relationship shows the predicted response to P fertiliser for any site given limitations in water availability (as indicated by CWI) and soil P availability. The maximum response is for sites with adequate water (as indicated by a CWI > 0.8) and very low soil P availability (bicarb P < 5 mg/kg). As water availability decreases the response to P falls to zero (i.e. CWI < 0.2) and similarly, as soil P availability increases response decreases (steeply at first and gradually tapering off) until soil P availability reaches 25 mg/kg where the expected response falls below 10%. The curvilinear (exponential) nature of the relationship reflects the exponential relationship between phosphorus availability and growth shown in Figures 48, 49, 50.

The limits to the available climate data mean that the response is limited to between CWI 0.2 (dry) and 0.8 (wet). The practical application of this is that the best responses to fertiliser will occur in wetter areas with low availability of phosphorus. While this in not revolutionary, it is likely the first time in Australia that this interaction has been properly quantified and hence can be integrated into fertiliser decision making.

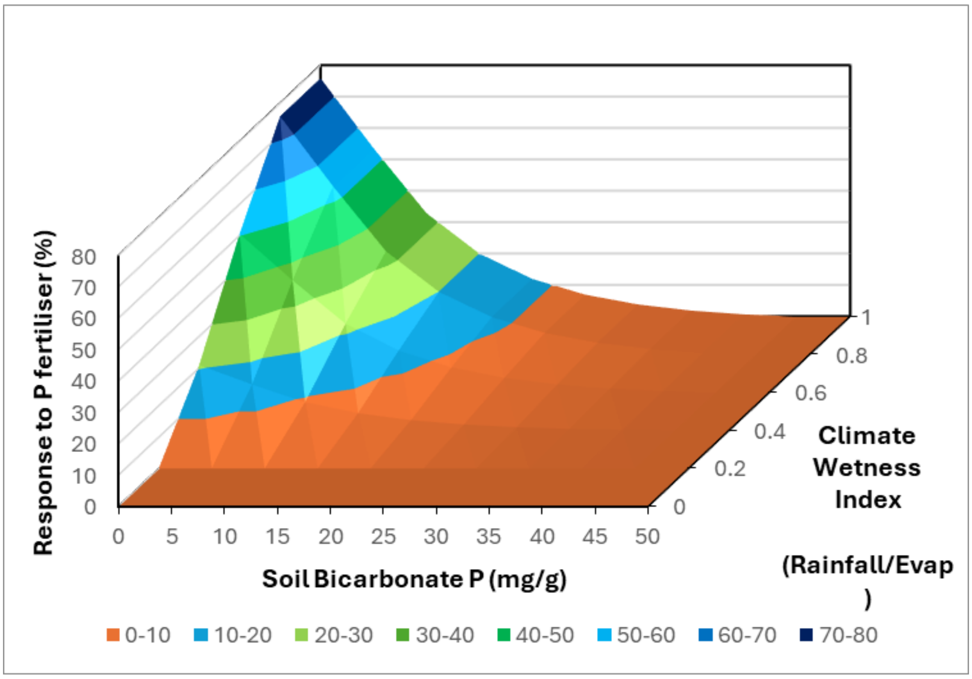


Figure 51. Integrated response to water availability (CWI) and soil phosphorus status (measured as soil HCO_3 P).

Response to Nitrogen.

The relationship between four-year responses to N fertiliser and measured and derived soil total N concentrations from the across the eight fertiliser trial sites with N treatments as shown in Figure 45 was used to estimate the maximum potential response to N fertiliser at sites not limited by rainfall or other nutrients (i.e. P). This relationship explained 81% of variation in N response and so was considered suitable to incorporate into ProFert (Figure 53). In addition, the relationship based on soil organic carbon (R2 = 0.78) was included as an alternative where soil N has not been measured (Figure 44).
The effect of N limitation on growth is illustrated by the increase in response to applied N as soil N declines (Figure 52). The upper and lower limits of this relationship were assumed to be 100% and 0% respectively and were based on the minimum and maximum recorded values for soil total N.

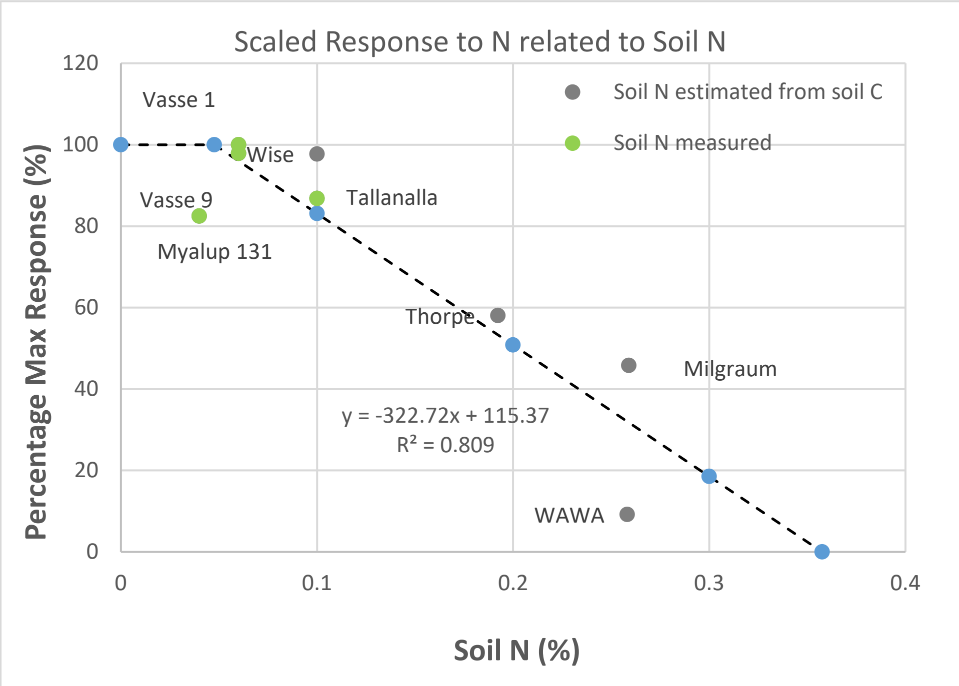


Figure 52. Relative limitation imposed on the response to N fertiliser due to soil nitrogen status measured as total N concentration.

Effect of N rate on response to N fertiliser

The effect of rate of N applied on response was calculated from the measured responses to N at experiments where N was applied in conjunction with P (Tallanalla and Vasse 9 sites) or where no P limitation was evident . There was a relatively strong (R2 = 0.66) curvilinear relationship between rate of N application and response across both sites (Figure 53). This relationship appeared to approach an asymptote for rates above 600 kg N/ha, indicating that this may be the maximum effective rate of N that can be applied in a single application. However, there were also indications in the data (not shown) that this maximum rate may vary depending on other nutrient limitations, with the rate tending to increase as the rate of P applied together with N increased. This result is consistent with that from other studies (e.g. May *et al*. 2009) in which N application was found to induce P limitations at some sites (as indicated by foliar P concentrations decreasing to critical values).

As with the other relationships, the rate response relationship for N was scaled so that the response was equal to 100% at a notional maximum rate of N application. However, unlike the other relationships, this maximum was set for 400 kg N/ha (the average rate of N applied across the eight sites for the results used in Figures 53 and 54). This approach assumes that where N is applied at a rate of 400 kg/ha the response to N will follow that shown in the relationship shown in Figure 45. Where higher or lower rates of N are applied the response is scaled up or down according to the relationship shown in Figure 54.

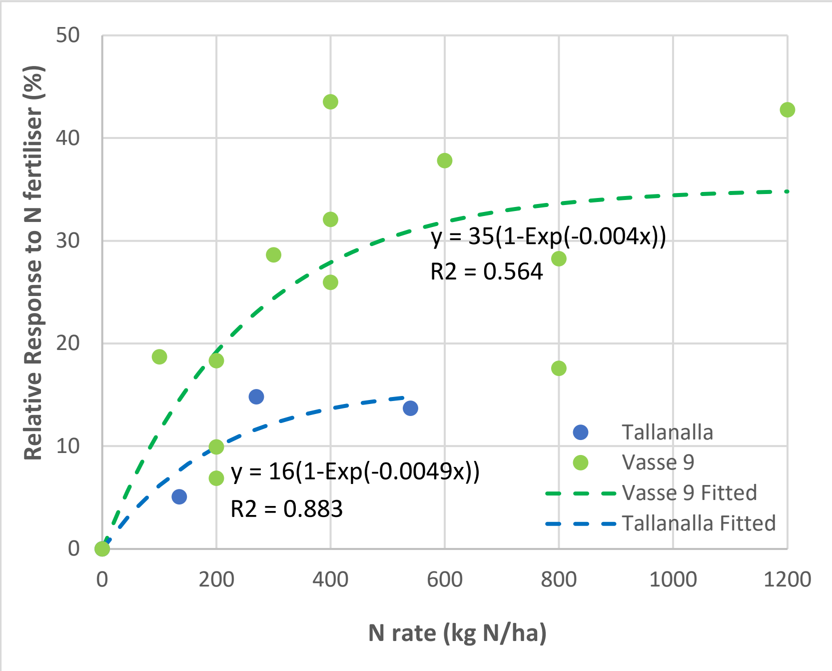


Figure 53. Effect of rate of N application on the response to N at Tallanalla and Vasse 9.

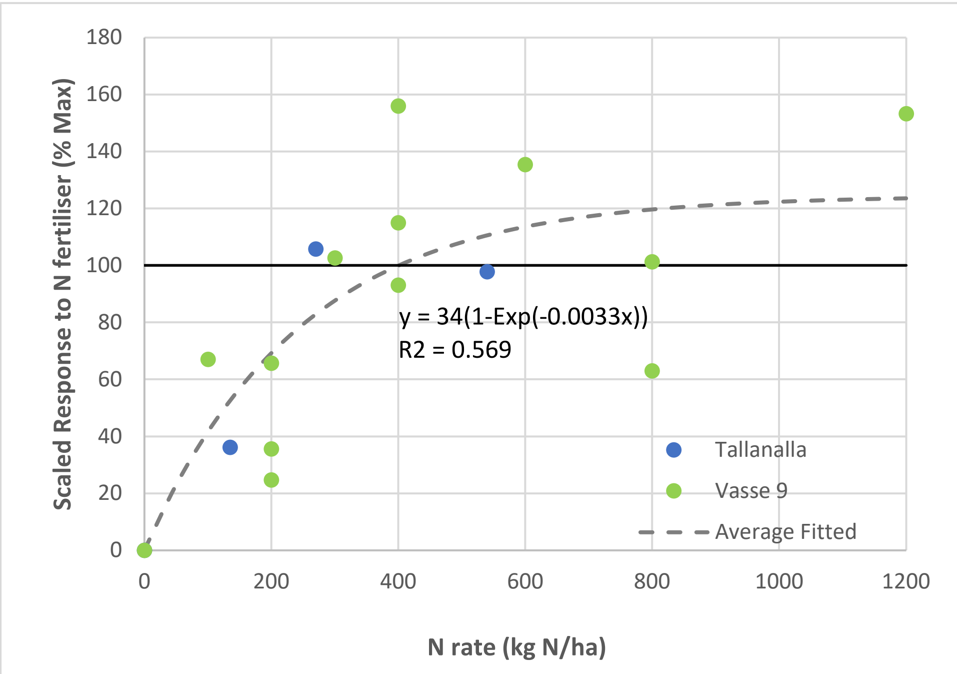


Figure 54. Response to applied nitrogen, scaled to 100% for a rate of 400 kg N/ha.

Combined effects of soil N and water availability on response to nitrogen.

The integrated effects of water availability (as indicated by CWI) and soil N availability (as indicated by soil total N concentrations) on response are presented as a response surface in Figure 55. As with the phosphorus version, the limits to the range in climate across the sites mean that the response is limited to between CWI 0.2 (dry) and 0.8 (wet). The linear nature of the relationship reflects the linear relationship between nitrogen availability and growth shown in Figures 44 and 45. Again, the practical application of this response surface is that the best responses to fertiliser will occur in wetter areas with low availability of nitrogen.

A similar approach is used, where the response to N fertiliser is limited by other factors (e.g. soil P). The predicted response to N is scaled back by ProFert depending on the degree of

limitation due to soil P availability (as shown in Figure 48). Where N, P and CWI all limiting growth ProFert selects the most limiting factor and applies that relationship before adjusting the response by the degree of limitation due to the next most limiting factor and then adjusting the final response by the limitation due to the third factor.
Where soil P concentrations are at a level where a response to P fertiliser could be expected (i.e. less than 50 mg/g based on the relationship shown in Figure 49), it is assumed that the response to N fertiliser will be reduced by the same % as the scaled response to P (e.g. where the soil HCO_3-P concentration is 10 mg/g the response to N is assumed to be reduced by about 35%. However, if P fertiliser is applied together with N, this limitation is assumed to be reduced according to the amount of P applied (and the initial soil HCO_3-P concentration). The effect of P fertiliser on soil P is assumed to follow the slope of the relationship between rate of P application and soil P shown in Figure 42 (i.e. for the 1st year after application). Therefore, applying 100 kg P/ha to a site where soil HCO3-P was initially 10 mg/g could be expected to increase it by around 11 mg/g resulting in a concentration of 21 mg/g (in the 1st year after application). Based on the relationship in Figure 49, this rate of P applied is assumed to reduce the relative limitation of the N response from 35% to around 13%.
This effect is assumed to gradually wear off in line with the change in soil P over time after application (as shown in the decreasing slopes for relationships in Figure 31 for years 1-9). So, the estimated effect of P fertiliser on the annual response to N (as well as subsequent applications of N fertiliser) is assumed to gradually wear off over the time course of the N response.

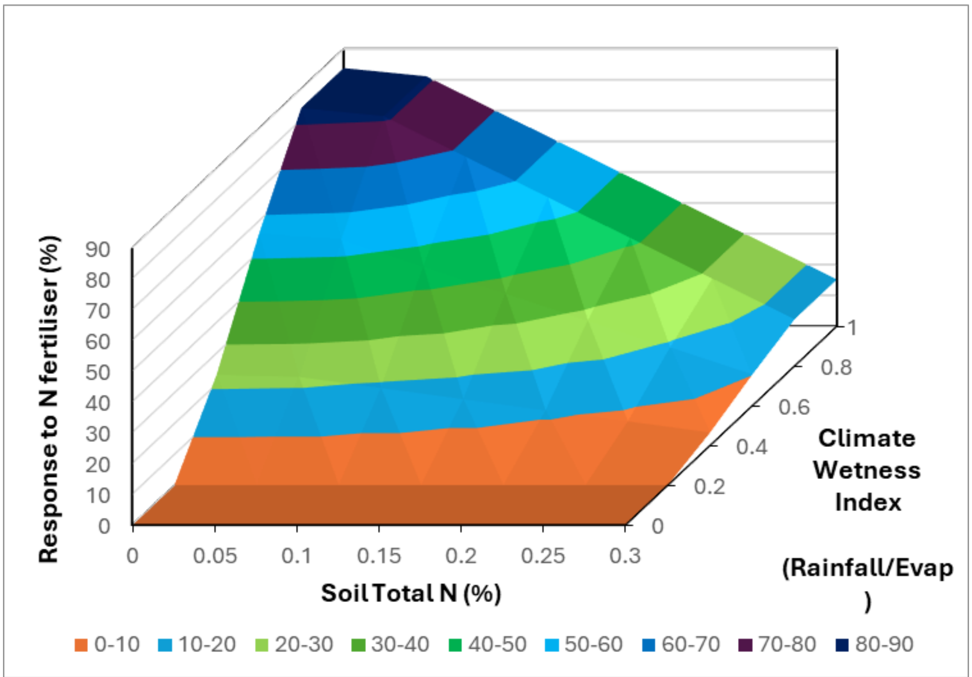


Figure 55. Integrated response to water availability (CWI) and soil nitrogen status (measured as total soil N).

Modelling the time course of responses.

In order to estimate responses to fertiliser over different time periods, ProFert converts expected cumulative four-year responses to annual responses for periods of up to 20 years. For WA, the raw data for these annual responses is based on results from the Tallanalla experiment, where responses to single application of N, P and N+P fertiliser were measured for 10 years (Figure 19, 26a 26b).
A variety of different treatments with different rates of N, P or both were applied at Tallanalla. These consisted of five rates of N (0, 67.5, 130, 270 and 540 kg N/ha) and 5 rates

of P (0, 45, 90, 180, 360 kg P ha) either alone or together. Significant responses were recorded most rates of P with applied either alone or together with N as well as significant NxP interactions for the higher rates of N. However, there was no significant response to N alone. To determine the change in response to N or P time, the average annual % responses to these treatments with significant responses were calculated as follows:

- Response to N: Average response to N across treatments at least 135 kg N/ha was applied together with P (90 kg P/ha or greater)
- Response to P: Average response to P across all N treatments (0, 67, 135, 270 and 540 kg N/ha) and P treatments

The average annual responses to N and P treatments are shown in Figure 56. Trendlines based on cubic relationships were fitted to each set of data points. The data and trendlines indicate that the response to N appears to decrease more quickly than that to P. Furthermore, the response to N peaked in the first two years post-application, while that to P appeared to peak 4-5 years after application. Importantly, the response to P and N+P fertiliser appears to continue well beyond the final measurement, 10 years after application, while the response to N appears to drop off quickly after two years, decreasing to zero 5-year post-application and possibly even becoming negative until around 10 years post-application.

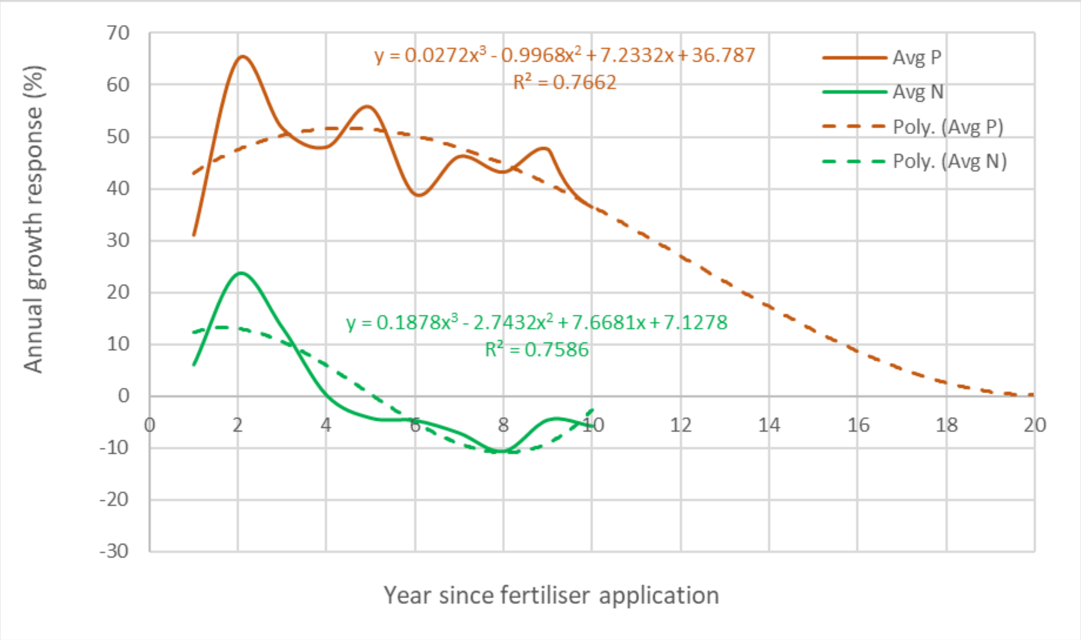


Figure 56: Average annual growth responses for N and P fertiliser relative to the control at Tallanalla site over 10 years and extrapolated to 20 years.

These results are consistent with those from other studies which have demonstrated that responses to N fertiliser tend to be relatively short lived – typically persisting for up to 4-6 years, while those to P fertiliser can persist for 20 years or more (May *et al.* 2009). Annual responses to N fertiliser in the Green Triangle fell to zero after 6 years, with responses to N alone becoming significantly negative for a number of years after that before stabilizing at zero 10 years post-application.

Because the responses to P clearly continue beyond the period for the available data, for the purpose of fitting the polynomial curve to the data, it was assumed that the response to P continued up to 20 years post-application.

For use by ProFert the annual growth responses were standardized by expressing them relative to the 4-year cumulative response (the response period used for developing the predictive relationships based on soil N and P and CWI). This allows ProFert to calculate the relative annual response to fertiliser by multiplying the predicted 4 years cumulative response by the standardized annual response each year after fertiliser application. The resultant standardized data and polynomial relationships are shown in Figure 57.

The coefficients and standard errors for the relationships for N and P are shown in Table 10. The general form of the relationships is:

$$y = ax^3 + bx^2 + cx + d$$

where:

y is the standardized annual response,
x is the time (in years) post fertiliser application and
a, b, c and d are the coefficients for the relationship.

Table 10: Parameters, SE and R2 values for the fitted equations used to determine the variation in annual response over time since application.

Nutrient	Parameter				SE	R^2
	a	b	c	d		
N	0.0168	-0.2453	0.6857	0.637	0.575	0.759
P	0.0005	-0.0201	0.1461	0.743	0.196	0.766

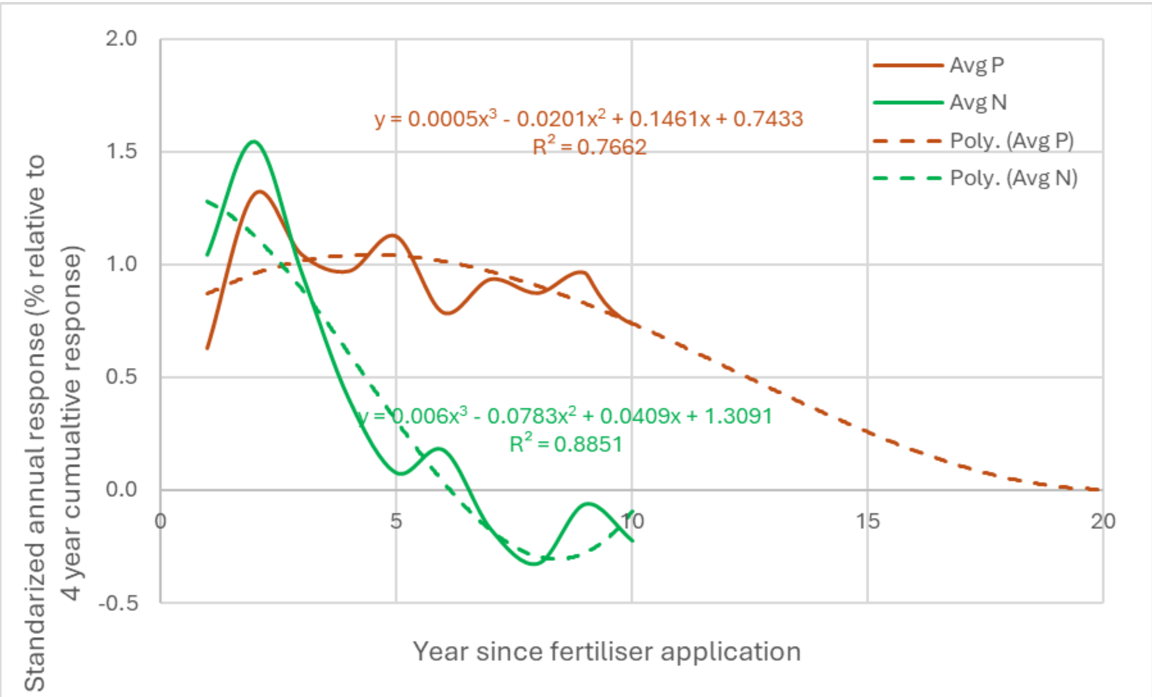


Figure 57: Annual responses at four years to N, P and N+P fertiser expressed relative to the cumulative response to each treatment at 4 years at Tallanalla.

Example of the final predictions for annual growth responses as calculated by ProFert.

Effect of water availability and nutrition.

An example of the predicted response from ProFert for two sites based on the new calibrations for WA for CWI, soil total N and soil bicarbonate P and given growth rates and rates of N and P fertiliser applications are shown in Figures 59-61. The underlying data for each of the examples is shown in the table below (Table 11).

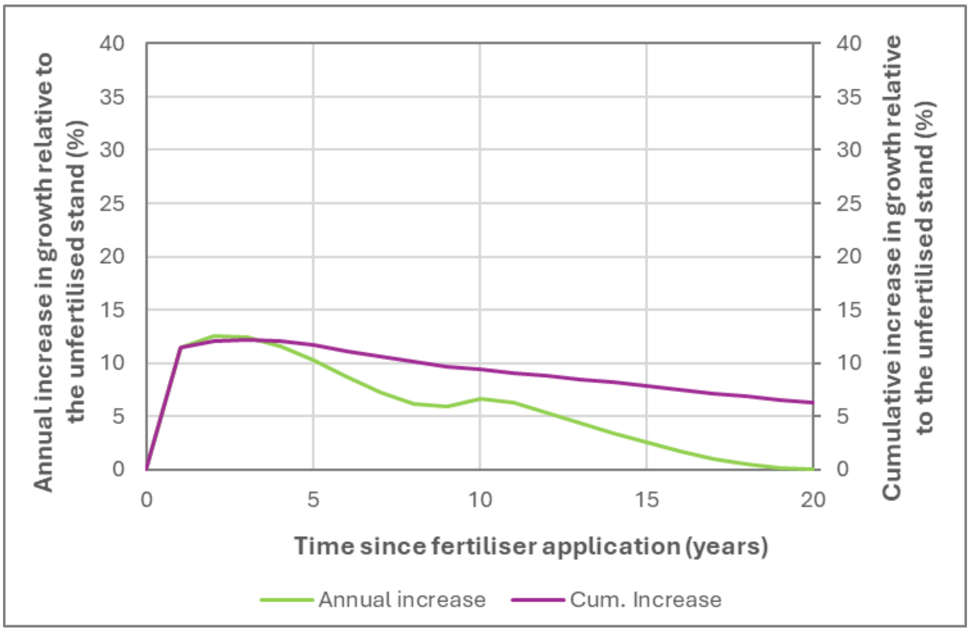
Table 11: Underlying data for predicted response curves.

Site	MAI	CWI	Soil N (%)	HCO_3 P (ppm)	P rate (kg P/ha)	N rate (kg N/ha)
A	18	0.4	0.05	10	100	150
B	25	0.8	0.10	15	100	150

Both stands are assumed to be fertilised once with a combination of urea and DAP at age 15 years (one year after first thinning), thinned again at age 21 and 28 years and clearfelled at age 35 years.

The predicted four-year relative responses to N+P fertiliser (applied at a rate of 100 kg N + 100 kg P per hectare) are 12% for site A and 32% for site B (Figure 58). This translates into a total increase in volume harvested over the rotation of 18 m^3/ha for site A and 59 m^3/ha for site B (Figure 59). These results indicate that even though site A is less fertile (as indicated by lower soil N and P) and has a slower growth rate, site B is likely to be more profitable to fertilise. This is because the response to fertiliser at site A is limited by low water availability. Note that these simulations use relatively low rates of fertiliser and hence the responses are relatively modest.

Site A



Site B

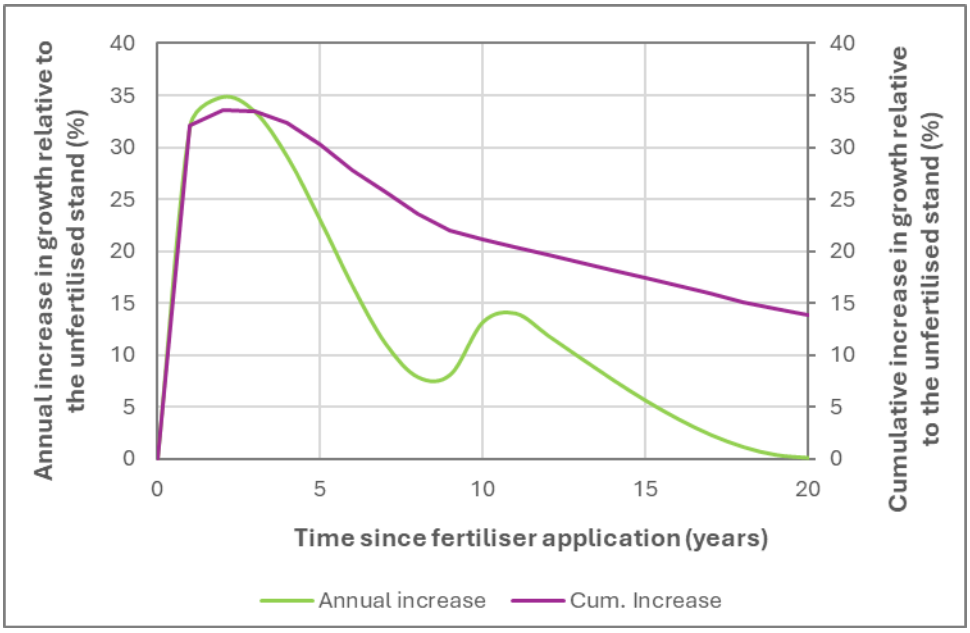
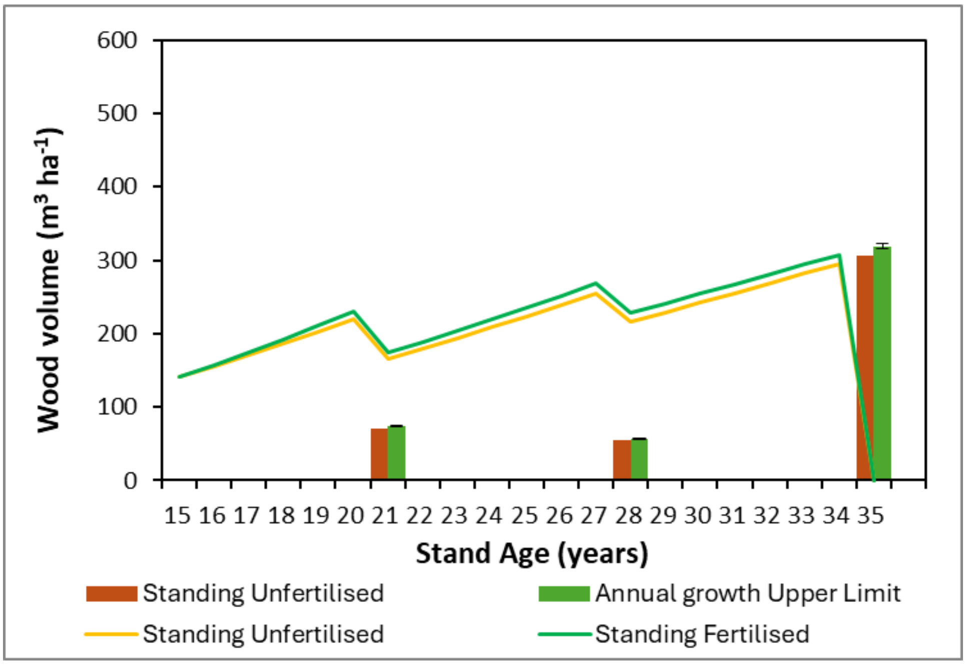


Figure 58: Predicted annual and cumulative relative responses to fertiliser at sites A and B.

Site A



Site B

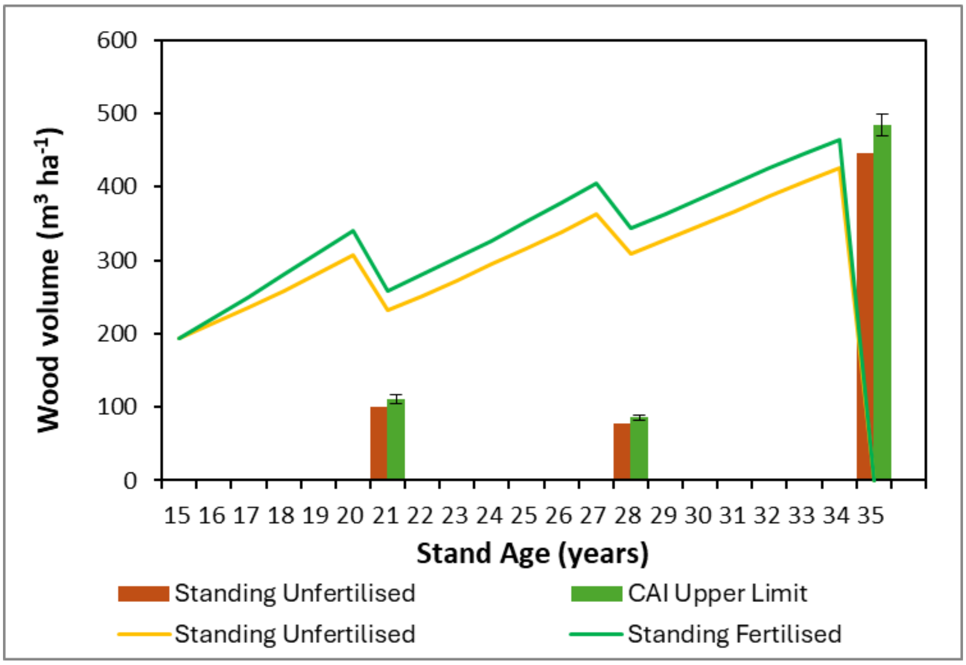
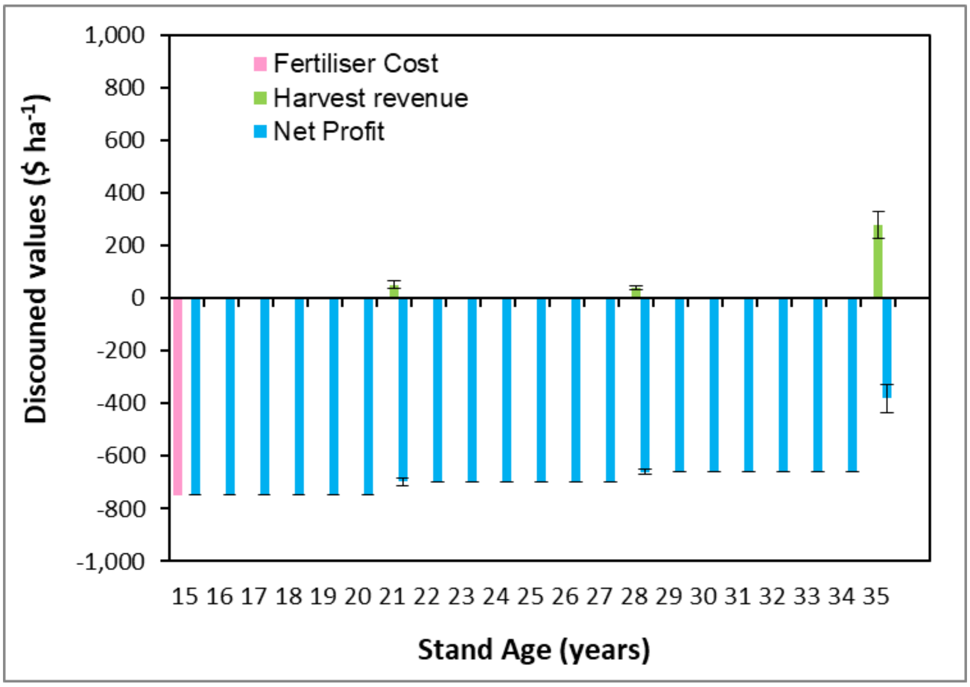


Figure 59: Predicted annual and cumulative absolute responses to fertiliser at sites A and B.

In terms of the profitability of fertiliser use, the cost of the fertiliser (based on 2022 values) is estimated to be $750/ha including a $100/ha application cost. The nominal total increase in stand value at clearfell age (including the value of thinnings removed) is estimated to be $$880 for stand A and $3,310 for stand B (Figure 60). However, the increase in value in today's terms is equivalent to $290/ha for stand A and $1,080/ha for stand B (using a discount rate of 6.5%, Figure 60). As a result, the NPV of fertilising the stands is $-380/ha for stand A and $700/ha for stand B. Hence, this analysis indicates that only stand B would be profitable to fertilise.

Site A



Site B

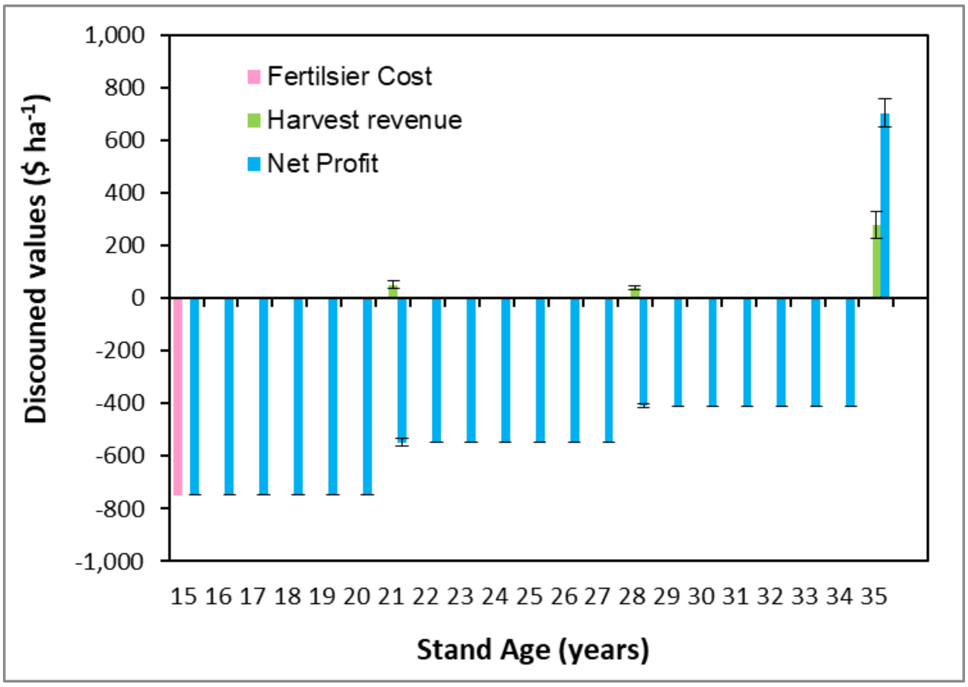


Figure 60: Fertiliser costs, predicted increase due to fertiliser in the value in wood harvested (expressed in today's terms assuming a discount rate of 6.5%) and net discounted profit of fertilising sites A and B.

This analysis using ProFert demonstrated the importance of factoring in the limitation due to water availability when trying to predict a stands potential response to fertiliser. Previous versions of ProFert lacked this component because of the limited range in rainfall in the available datasets. The dataset from WA has therefore added substantial value by allowing the effect of rainfall and evaporation to be considered.

These updated relationships are now being tested against the original and new datasets from Victoria, SA, Tasmania and NSW to see if the effects of CWI on response observed in WA are consistent with the measured responses across other experiments.

Effect of multiple fertiliser applications.

As well as modelling the effect of a single applications of fertiliser, ProFert has been designed to allow multiple fertiliser applications (up to 10 over a single rotation) to be tested. To demonstrate this capability and investigate the benefit of multiple verses single fertiliser applications, the scenario used for site B above was used, but with fertiliser applied one year after both T2 (i.e. at age 25 years) and T3 (at age 29 years) as well as one year after T1 (i.e. at age 15 years).

The results for this scenario are shown together with those for the original (singe fertiliser application) scenario in Figures 61, 62, 63. After a single application of fertiliser, the annual response decreased rapidly from 35% in the 2nd year after application to around 10% for years 7-13 before gradually decreasing to 0% by the time of clearfelling (Figure 61). In contrast, multiple applications resulted in the response increasing again to 38%, 3 years after T2 and to 26%, 3 years after T3. This increased the average response from the time of the first application to the time of clearfelling from 14% for the single application to 24% for the multiple applications (Figure 61).

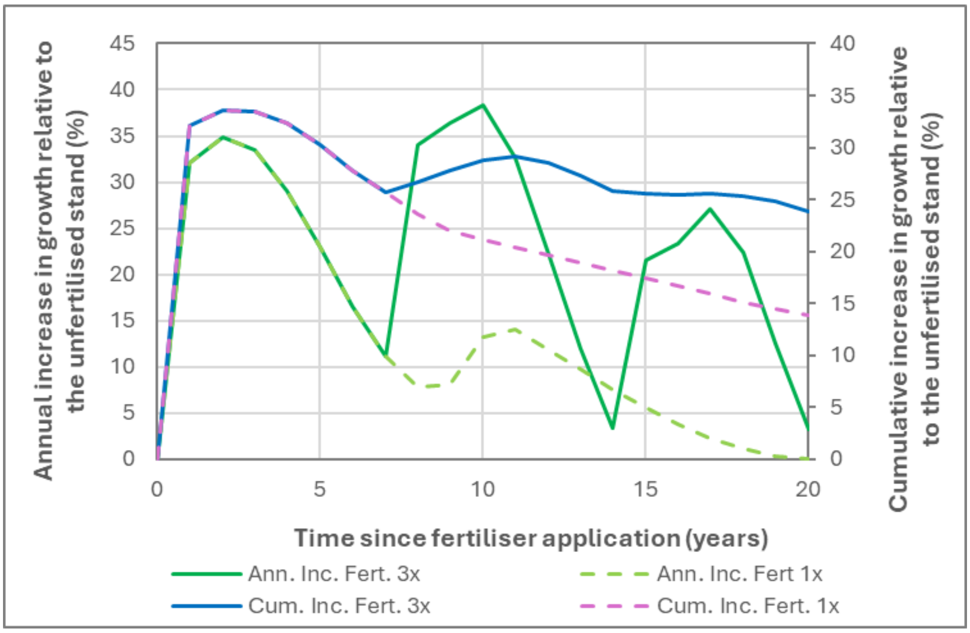


Figure 61: Predicted annual and cumulative relative responses to fertiliser at site B after a single application (1x) and multiple applications (3x) of N and P.

The effect of the increase in average % response was a net increase in the volume of wood produced compared with the unfertilised stand, from a total of 59 m^3/ha for the single application to 102 m^3/ha for the three applications (Figures 62 and 63). Furthermore, even though tripling the amount of fertiliser applied increased the cost from \$750/ha to \$1,660 (in today's terms) the net profitability also increased from \$700/ha to \$960/ha (Figure 63). Thus, applying fertiliser after each thinning not only increased the amount of wood produced by over 70% but also boosted net profitability by almost 40%.

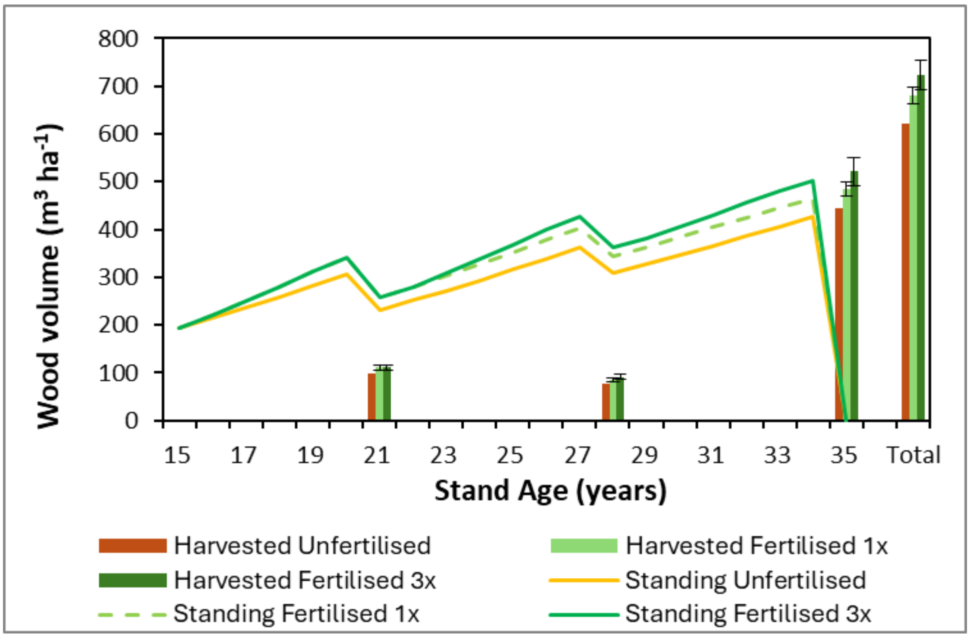


Figure 62: Predicted annual and cumulative relative responses to fertiliser at site B after a single application (1x) and multiple applications (3x) of N and P.

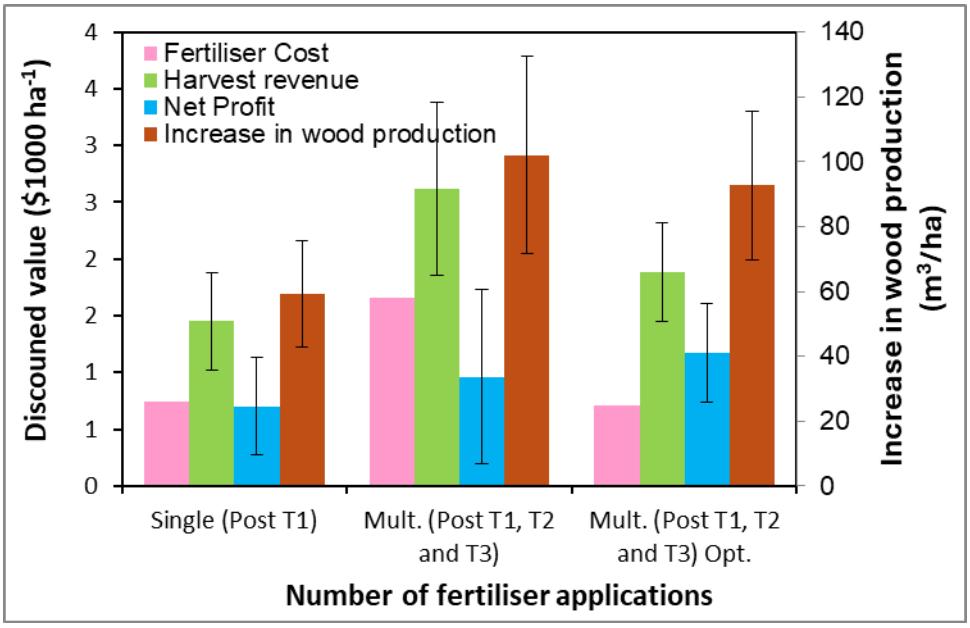


Figure 63: Predicted cumulative costs and revenue following fertiliser at site B after a single application (1x) and multiple applications (3x) of N and P with and without optimising the fertilizer application.

The economics of multiple applications verses single applications of fertiliser will vary depending on site and stand conditions as well as the cost of fertiliser, harvesting and haulage and the value and recovery rates of different products. The optimum amounts of different nutrients applied at different times during the rotation will also vary from site to site. ProFert includes an option for the user to automatically select the optimum fertilizer regime for individual sites. The results of optimizing the fertiliser regime for site B are shown in Figure 63 together with the other two scenarios tested for the site. The optimized scenario involved using lower rates of DAP (200 kg P/ha after T1 and T3 and 300 g/ha after T2 compared with 500 kg/ha after each thinning) with urea applied only after T3 and at a higher rate (300 kg/ha) than originally used (130 kg/ha). The effect of these changes was to more than halve the discounted cost of fertiliser applied over the rotation (from $1,660/ha to

\$710/ha while reducing the total amount of additional wood produced by only 9% (from 102 m^3/ha to 93 m^3/ha). Net profitability was boosted by 21% from \$960/ha to \$1,170/ha.

Recommendations

The Profert model currently builds on research in softwood plantations from eastern Australia and now includes the best information available for WA plantations including the effect of climate on fertiliser responses. It therefore should provide a useful tool to helping boost wood production across WA softwood plantations.

- Due to the demonstrated impact of climate, fertility and stand conditions on the responses to fertilizer and the large variation in these factors within the WA softwood plantations, it is recommended that plantation managers employ site-specific silviculture across their estate to optimise productivity and/or profitability.

- Based on the demonstrated role for ProFert in identifying opportunities to increase wood production and or profitability, it is recommended that plantation managers use the ProFert tool to identify the most responsive sites to fertilise and to optimize the different fertiliser scenarios that could be implemented over the course of the rotation.

- As the accuracy of ProFert's predictions depends on the quality of the data and underlying assumptions on which the relationships in the model are based it may not always be applicable to all sites and could change with advances in genetics and variations in climate, stand management and site and stand conditions. Therefore, it is important to continue to test and improve the calibrations within the model. It is recommended that the growth of fertilised stands be monitored, paired plots in fertilised and unfertilised areas be established to measure growth responses and additional fertiliser trials be installed to extend the range of sites where fertilizer responses have been measured.

References

Battaglia, M., Sands, P., White, D., Mummery, D. (2004). CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. Forest Ecology and Management **193**: 251–282.

Bolland, M, Russell, B, and Weaver, D. (2010), Phosphorus for high rainfall pastures. Department of Primary Industries and Regional Development, Western Australia, Perth. Bulletin 4808

Bubb, K. (2008). Review of phosphorus fertilising program in second rotation exotic pine. Internal report from the Plantation Development Unit of Forestry Plantations Queensland.

Butcher, T.B. (1977). Impact of moisture relationships on the management of *Pinus pinaster* Ait. plantations in Western Australia. *Forest Ecology and Management* **1,** 97-107.

Butcher, T.B. and Havel, J.J. (1976). Influence of moisture relationships on thinning practice. N. Z. J. For. Sci. **6**, 158–170.

Fife, D.N. and Nambiar, E.K.S. (1999). Response to phosphorus application of second rotation radiata pine on podsolised sands from planting to first thinning: implications for management. Australian Forestry **62**, 109-119.

Gentle, S.W., Humphreys, F.R., Lambert, M.J., (1986). Continuing response of *Pinus radiata* to phosphatic fertilisers over two rotations. Forest Science **32**, 822-829.

Hopmans, P., Collett, N.C., Smith, I.W., Elms, S.R., (2008). Growth and nutrition of *Pinus radiata* in response to fertiliser applied after thinning and interaction with defoliation associated with *Essigella californica*. Forest Ecology and Management **255**, 2118-2128.

Hopmans, P., Flinn, D.W., Geary, P.W., Tomkins, I.B., (1993). Sustained growth response of *Pinus radiata* on podzolised sands to site management practices. Australian Forestry **56**, 27-33.

Knott, J.H., Turner, J., Lambert, M.J., (1996). Fertilisation of *Pinus radiata* plantations after thinning. II. Investment potential. Australian Forestry **59**, 22-31.

Lewis, N. B., Keeves, A., and Leech, J. W., (1976). Yield regulation in South Australian *Pinus radiata* plantations. Woods and Forests Dep., SA, Bulletin, No. **23**, 174 pp.

May, B., Carlyle, C., Lowther, R., Keeley P., Bernie, C., and Michael, M. (2009a). A decision support system for maximising profit from nutrient management of mid-rotation radiata pine. FWPA Project PNO: 03.3907, 109 pages.

May, B., Smethurst, P., Mendham, D., Bruce, J., Baillie, C. (2009b). Review of fertiliser use in Australian Forestry. Forest and Wood Products Australia Project Report No. PRC072-0708. http://www.fwpa.com.au/Review-of-fertiliser-use-in-Australian-forestry.

May, B.M. and Carlyle, C.J. (2005). Nitrogen volatilisation from urea fertiliser in mid-rotation *Pinus radiata* plantations in south-eastern Australia. Australian Forestry **68**, 20-26.

May, B.M., Elms, S., Hopmans, P., McKay, L., Hetherington, S., Bruce, J., Edwards, K., Hanssen, R. (2017). ProFert a tool for optimizing fertiliser use in softwood plantations. Forest and Wood Products Australia Project Report No. PRC072-0708. http://www.fwpa.com.au/Review-of-fertiliser-use-in-Australian-forestry.

McGrath, J.F., Copeland, B., Dumbrell, I.C. (2003a). Magnitude and duration of growth and wood quality responses to phosphorus and nitrogen in thinned *Pinus radiata* in southern Western Australia. Australian Forestry **66**, 223-230.

McGrath, J.F., Dumbrell, I.C., Hingston, R.A., Copeland, B. (2003b). Nitrogen and phosphorus increase growth of thinned late-rotation *Pinus radiata* on coastal sands in Western Australia. Australian Forestry **66**, 217-222.

McGrath, J.F. and Robson, A.D. (1984). The distribution of zinc and the diagnosis of zinc deficiency in seedlings of *Pinus radiata*, D.Don. *Australian Forest Research* **14**, 175-186.

Mendham D.S., White D.A., Battaglia M., McGrath J.F., Short T.M., Ogden G.N., Kinal J. (2011). Soil water depletion and replenishment during first- and early second-rotation

Eucalyptus globulus plantations with deep soil profiles. Agricultural and Forest Meteorology **151,** 1568– 1579.
Mendham, D., Bruce, J., Opie, K., Ogden, G. (2013). The Forest Productivity Optimisation System – A decision support tool for enhancing the management of planted forests in southern Australia under changing climate. FWPA Project No: PNC168-0910.
Neilsen, W.A., Pataczek, W., Lynch, T., Pyrke, R. (1992). Growth response of *Pinus radiata* to multiple applications of nitrogen fertiliser and evaluation of the quantity of added nitrogen remaining in the forest system. Plant and Soil **144**, 207-217.
Raupach, M., Boardman, R., and Clarke, A. R. P. (1969). Growth rates of *Pinus radiata* D. Don in relation to foliar levels of nitrogen and phosphorus for plantations in the south-east of South Australia. CSIRO Division of Soils, Soil Publication, 28 pp.
Simpson, J. A. and Grant, M J. (1991). Exotic pine fertiliser practice and its development in Queensland. Technical Paper No. **49**, Department of Forestry, Queensland, 17 pp.
Snowdon, P., Waring, H.D. (1990). Growth responses by *Pinus radiata* to combinations of superphosphate, urea and thinning type. Forest Ecology and Management **30**, 313-325.
Snowdon, P., Waring, H.D. (1995). Response of young densely stocked stands of *Pinus radiata* to thinning and refertilisation. New Forests **10**, 207-223.
Summit Fertilizers (accessed March 2023).
https://assets.website-files.com/5f22ca113eaaf544645b1f8c/5f4d967eda7be17b6c4339dd_PBI.pdf
Turner, J., Knott, J.H., Lambert, M. (1996). Fertilisation of *Pinus radiata* after thinning. I. Productivity gains. Australian Forestry **59**, 7-21.
Turner, J., Lambert, M.J., Hopmans, P., McGrath, J. (2001). Site variation in *Pinus radiata* plantations and implications for site specific management. New Forests **21**, 249-282.
Turner, J., Lambert, M.J., Humphreys, F.R. (2002). Continuing growth response to phosphate fertilisers by a *Pinus radiata* plantation over fifty years. Forest Science **48**, 556-568.
Turner, J. and Lambert, M. (2014). Analysis of long term productivity and productive capacity of a radiata pine plantation on infertile fine textured soils. PNC216-1011, Forest Wood Products Australia, Melbourne, Australia. pp. 35.
Wells, J.M. and Cohen, S. (1996). Canopy structure measurement by gap fraction analysis using commercial instrumentation. Journal of Experimental Botany **47**, 1335-1342.
White, D.A., Crombie, D.S., Kinal, J., Battaglia, M., McGrath, J.F., Mendham, D.S., Walker, S.N. (2009). Managing productivity and drought risk in *Eucalyptus globulus* plantations in south-western Australia. Forest Ecology and Management **259**: 33–44.

Acknowledgements

Funding and in-kind contributions were provided by Forests and Wood Products Australia (FWPA), the Forest Products Commission (FPC) and Wespine for the project VNC476-1819 'A tool to predict fertiliser response and profitability in softwood plantations across Australia. Component 1: South West WA**'.** Access to published and unpublished data from FPC was critical to the project and we thank Gavin Butcher, Anjanette Chandler and Jon Brand for supporting the project and providing access to the data. Anjanette Chandler tested ProFert and provided feedback on its use. The data used in this project were collected over nearly 3 decades and without the efforts in establishing and maintaining the trials and collecting and managing the data this project would not have been possible. Many people were involved over this period and we wish to particularly acknowledge the efforts of Beth Copeland, Bob Hingston, Keith Mungham, Peter Jenkins, Jane Clayton, and Shelley McArthur, Lin Wong, Terry Reilly, Ray Fremlin.

Appendix 1 Potassium responses in young pines.

In addition to the core analyses of mid-rotation fertiliser responses in WA *Pinus radiata* plantations the early rotation responses to potassium and nitrogen in young plantations growing on farmland in the south coast region were also assessed. There were two trials that assessed the response to potassium alone and to potassium and nitrogen and potassium in combination.

Table 1: Potassium trial details.

Attribute	Dennis plantation	Thorpe plantation
Location	Denbarker 34^{0}44'21' S 117^{0}30'22' E	Napier 34^{0}44'21' S 117^{0}57 E
Soils	Leached dune deep white sands.	Leached dune deep white sands.
Rainfall (1988-2004)	727 mm.	742 mm .
Evap (1988-2004)	1455 mm.	1418 mm.
CWI (1988-2004)	0.50.	0.52 .
Planted	1988.	1988.
Trial established	1990 (2 yo).	1991 (3 yo).
Design	Seven rates of K (0,25,50,100,200,300,500 kg/ha K as muriate of potash) with a basal application of N, P and trace elements.	NxPxK factorial -/+ for each element N: 272kg/ha N = 800kg Agran (NH_4NO_3) P: 137 kg/ha P = 1500 kg Superphos K: 300,kg/ha K as muriate of potash Plus $ZnSo_4$, $CuSo_4$ (5kg) $MnSo_4$ (10kg).
Replication	Four randomised blocks	Three randomised blocks
Measurements	Height annually from age two, DBHOB annually from age four. Basal area and volume estimated from measurements. Final measurements at age 15.7 years. Basal and 30 cm diameters from inception until age 3	Height and DBHOB annually from age 3-8 years. Final measurements at age 15.7 years. Basal area and volume estimated from measurements.
Foliar analysis	Bi-monthly NPK on three ages of needles from 10/1990 - 3/94.	Limited to four samplings 10/92, 8/93,3/94, 9/94.
Soil analysis prior	P, K OC, reactive Fe, pH.	P, K OC, reactive Fe, pH.
Soil analysis during trial	Dec 1991 and July 1994: N, P, K, OC, Ph, for 0-10,10-20, 20-30, 50-60, 90-100 am depths, for K0, K200, K500.	None.

Potassium rate trial (Dennis Plantation).

Fertiliser treatments were applied in Spring 1990 at age 2.1. This followed the appearance of chlorotic foliage and an initial investigation which found low potassium concentrations in the affected foliage. Diameter (DBHOB) and height measurements and estimates of basal area and volume from age four are provided.

Observations:

- The response to K measured as basal area and volume measured at age seven years was 15 m^3/ha/yr or 35% (Figure 45 and Figure 46) and this declined to ~20% at age 15.7 (Fig 46). The actual response increased over time with an additional 40 m^3/ha/yr of produced in the high potassium application treatments by age 15.7 years.
- It appeared that at the lower applications of potassium (50 and 100 kg/ha) the higher initial diameter increments relative to the unfertilised control were not sustained as by age seven the diameter of the low rates of K was similar the control (Figure 45).

- In contrast the higher rate of K appears to sustain the growth response out to 16 years (Figure 46).
- K concentrations in foliage were low in the unfertilised control and increased with increasing K application. Noting that only the 0, 50, 200 and 500 kg/ha K applications were sampled (Figures 49-52).
- A critical K concentration of ~ 0.4% in current foliage may be interpretable from this data.

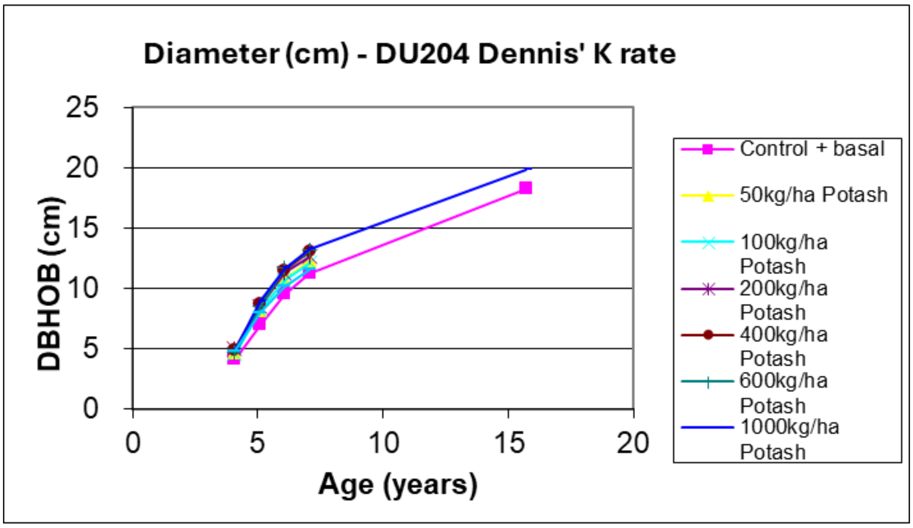


Figure 1. Influence of increasing rates of potassium fertiliser on diameter (cm) growth age 4–16 years. Dennis Plantation South Coast.

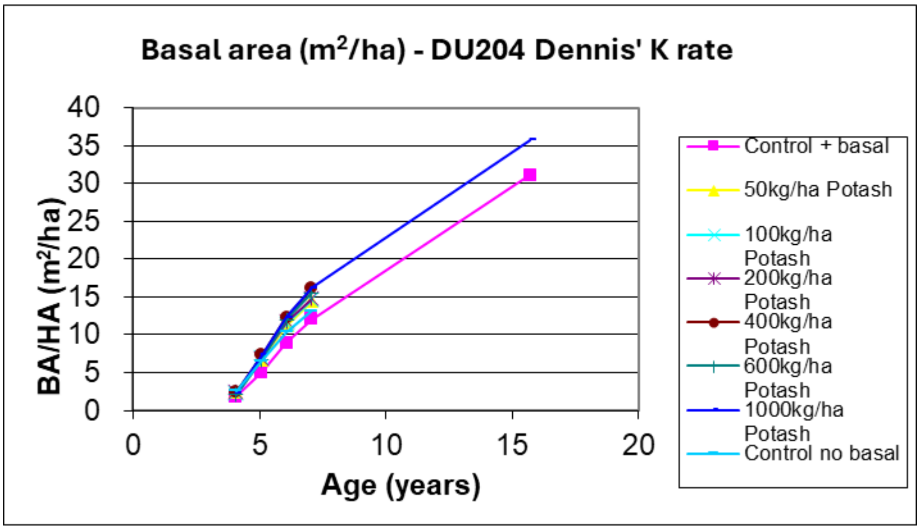


Figure 2. Influence of increasing rates of potassium fertiliser on basal area (m^2/ha) growth age 4–16 years. Dennis Plantation, South Coast.

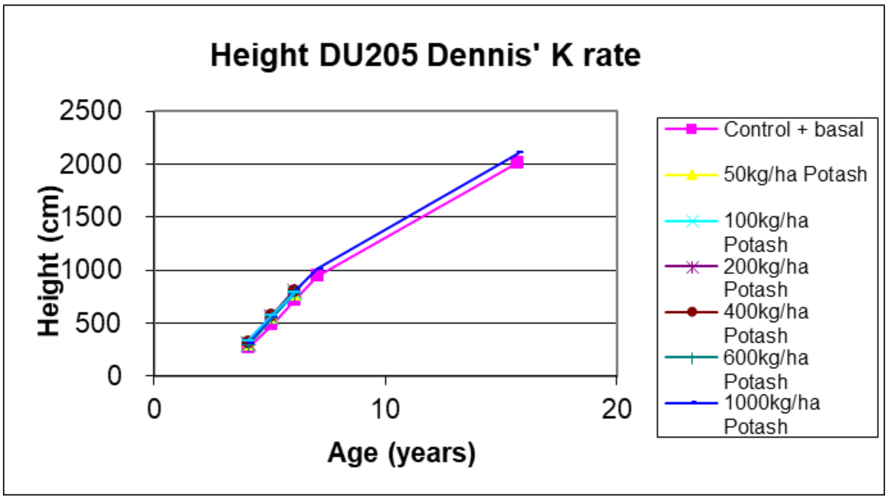


Figure 3. Influence of potassium fertiliser on height growth age 4–16 years. Dennis Plantation, South Coast.

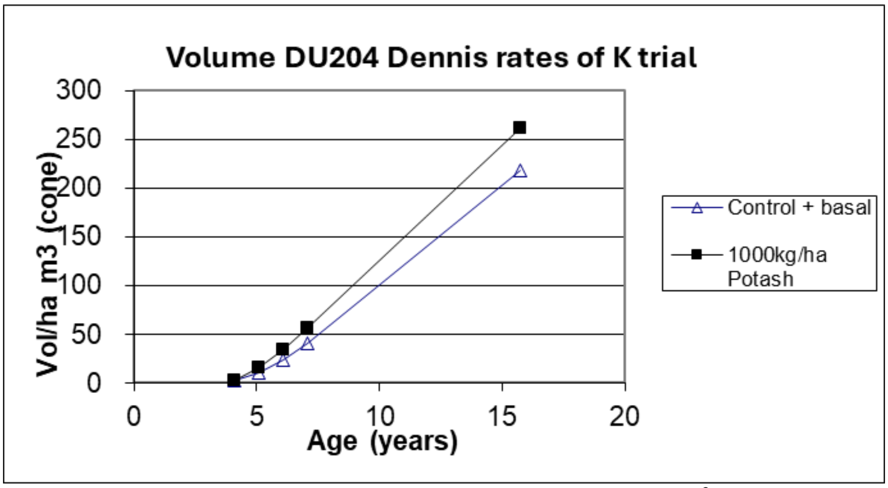


Figure 4. Influence of potassium fertiliser on volume (m^3/ha) growth age 4–16 years. Dennis Plantation. South Coast.

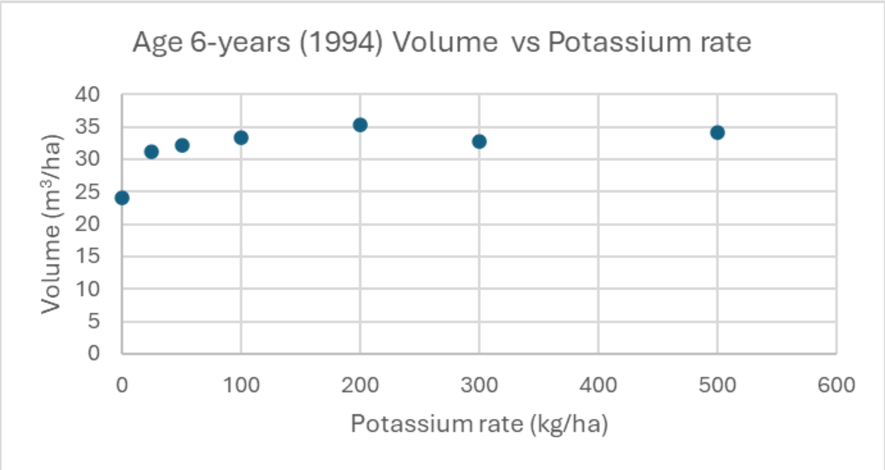


Figure 5. Relationship between potassium application (kg/ha) and volume growth at age 6-years. Dennis Plantation, South Coast.

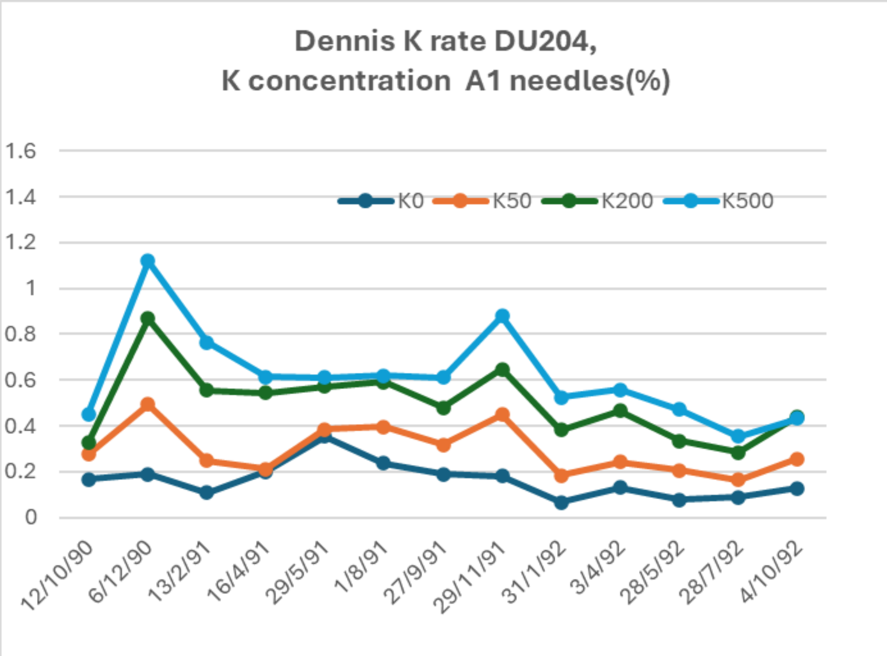


Figure 6. Influence of increasing rate of potassium on the potassium concentrations in needles aged 1 to 3 years. Sampling commenced at age 2.3 years.

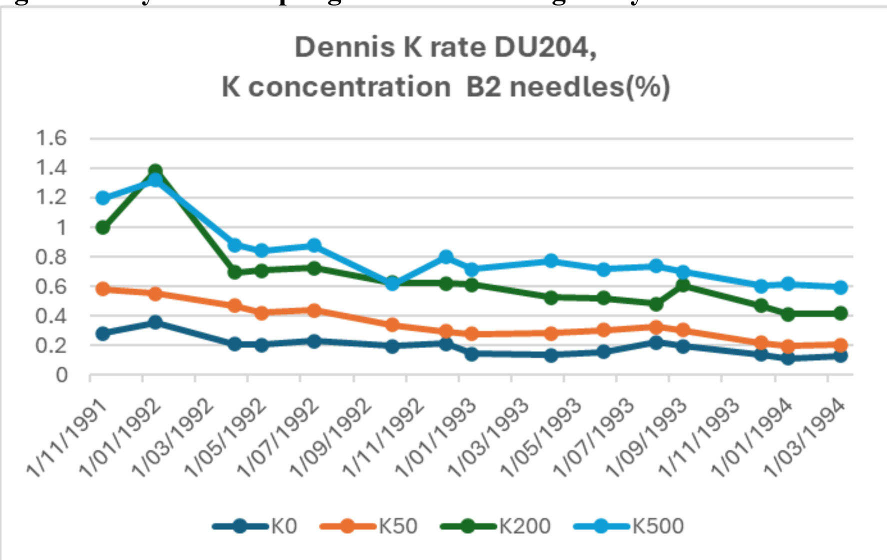


Figure 7. Influence of increasing rate of potassium on the potassium concentrations (% dry weight) in needles aged 0 to 2.5 years. Sampling commenced at age 3.3 years.

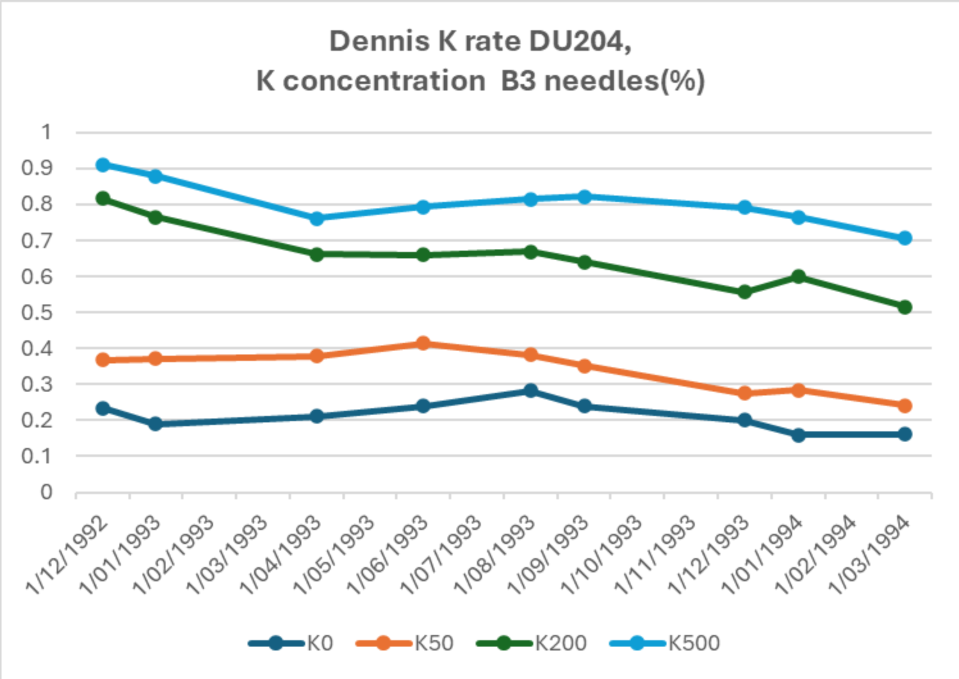


Figure 8. Influence of increasing rate of potassium on needle potassium concentrations in ages 1-3 years, sampling commenced at age 4.3 years.

Data Thorpe's N x P x K trial.

DBHOB growth for the five-year period 1991-96 (age 3-8), plus the extension to age 16 (Figure 9), Volume estimates for the same periods (Figure 10). Basal area as a total increment for the initial period (1991-96) Figure 11, and as annual increments over the five-year period (Figures 12(a) -12(e)).

Observations:

- There was no response to P (Figure 11). Figure 10 shows data with the responses to N and K only with the P treatments combined with the N and K treatments i.e. six reps.
- An initial response to N, that isn't sustained and the increments for N treatments are lower than the control treatment as time progresses (see last three increment periods Figures 12a - 12e). The initial faster growth with the N fertilization may have exacerbated other nutrient deficiencies (e.g. Cu?) which may explain the negative response to N over time.
- A response to potassium that is sustained, and the volume response gets slightly larger over time (Figure 10).
- Suggests that optimising growth on these south coast sands would require potassium, trace elements and periodic nitrogen applications.

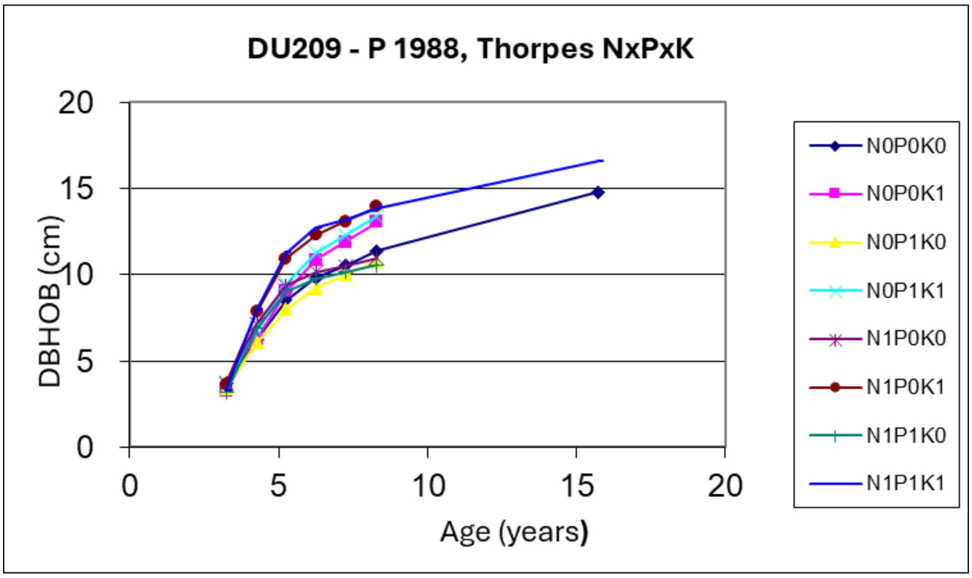


Figure 9. Diameter response to the application of N, P, K from age 3.2 years to 15.7 years.

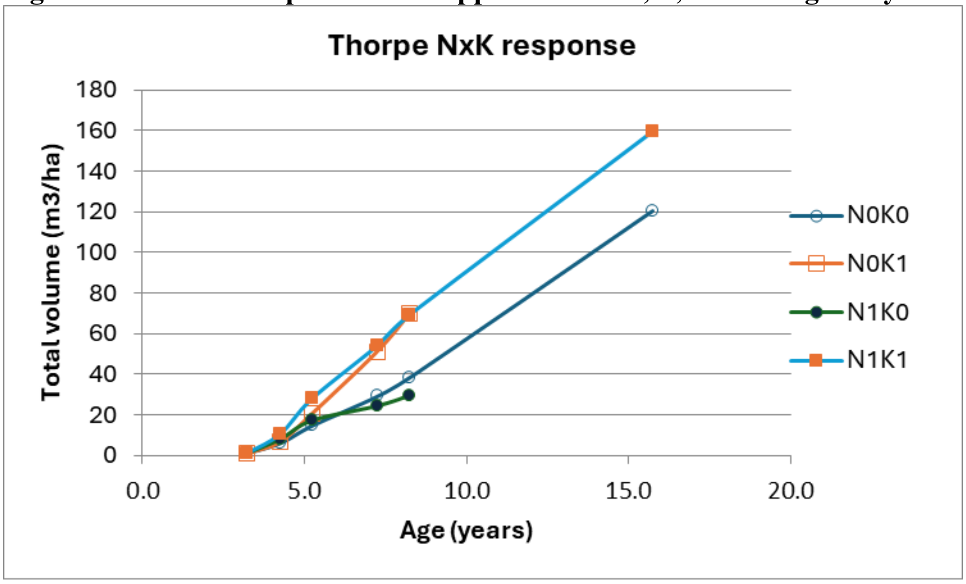


Figure 10. Volume response to the application of N and K from age 3.2 years to 15.7 years. Note in the absence of a response to P the +P treatments were combined with the N and K treatments to provide six replicates.

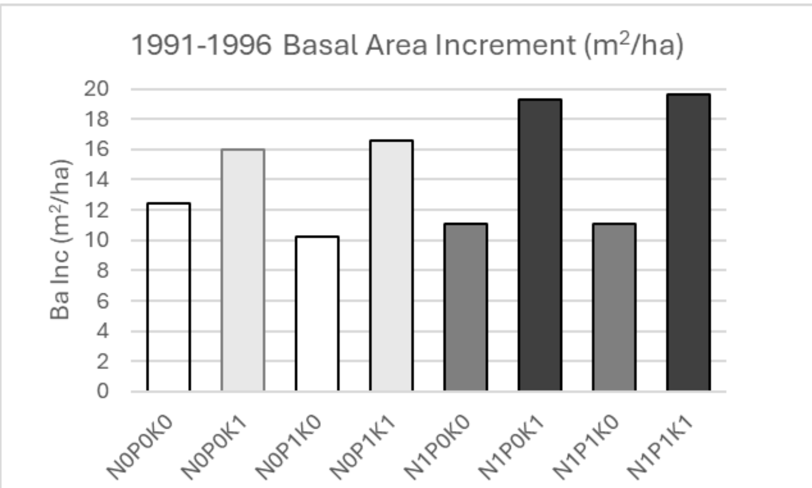


Figure 11. Influence of N, P K applications on basal area increment from age 3-8 years. Thorpe plantation South Coast WA.

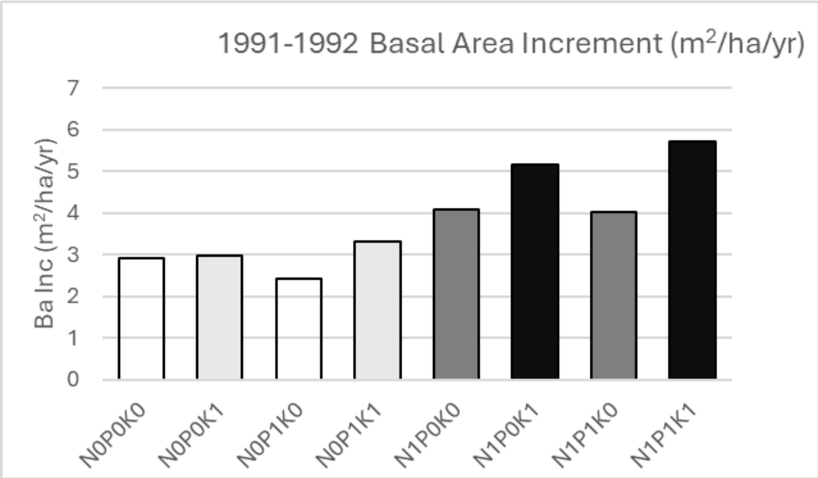


Figure 12a. Influence of N, P K applications on basal area increment from age 3 - 4 years. Thorpe plantation South Coast WA.

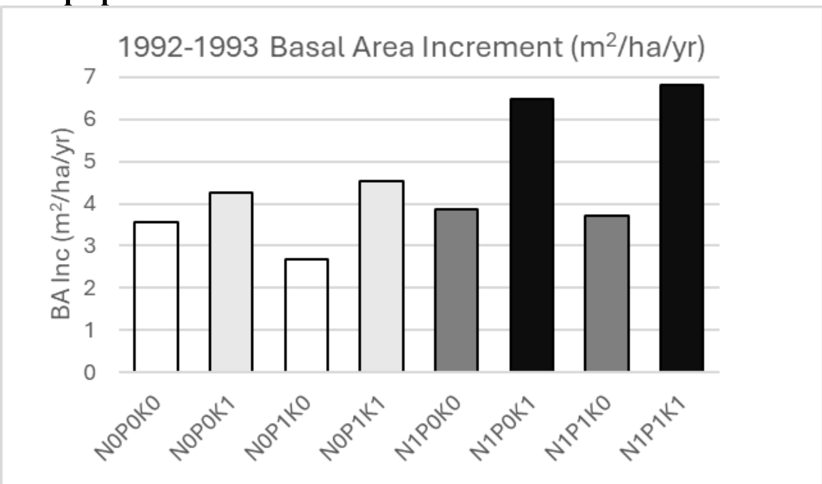


Figure 12b. Influence of N, P K applications on basal area increment from age 4 - 5 years. Thorpe plantation South Coast WA.

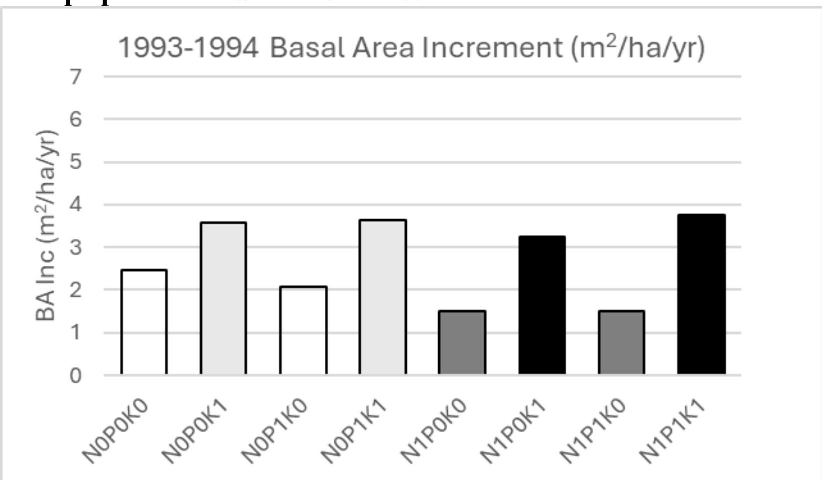


Figure 12c. Influence of N, P K applications on basal area increment from age 5 – 6 years. Thorpe plantation South Coast WA.

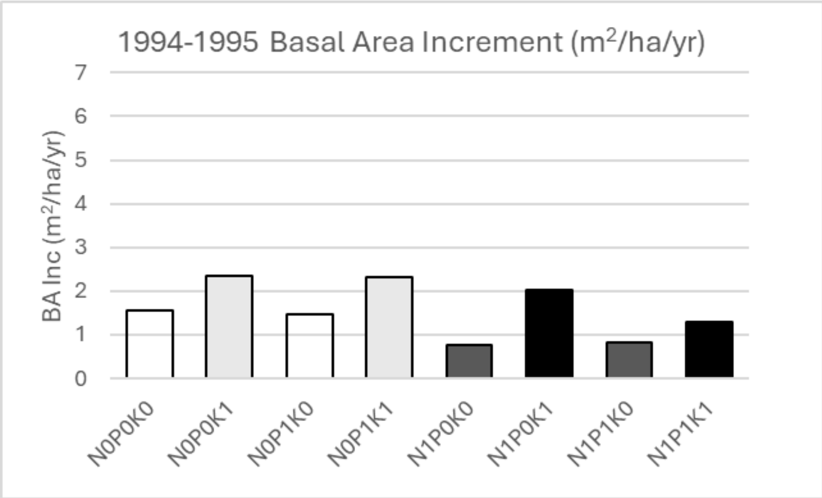


Figure 12d. Influence of N, P K applications on basal area increment from age 6 - 7 years. Thorpe plantation South Coast WA.

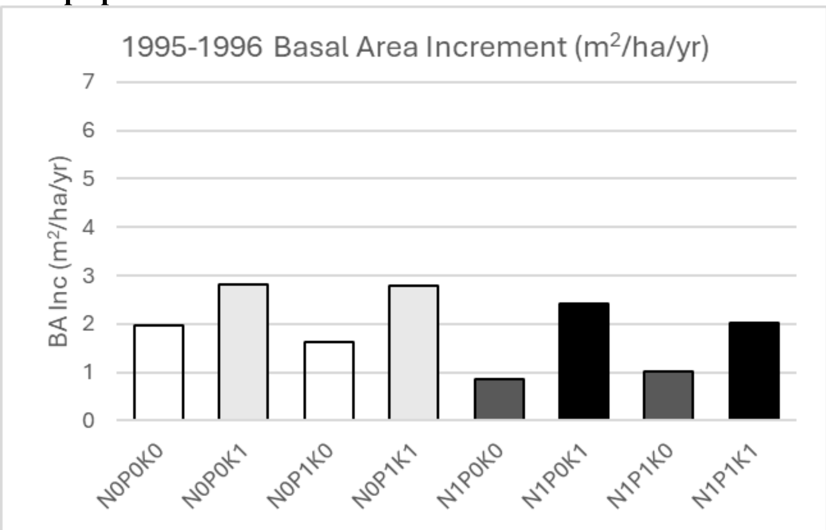


Figure 12e. Influence of N, P K applications on basal area increment from age 7 – 8 years. Thorpe plantation South Coast WA.