Resources

Optimising Nutrition Management of Hardwood Plantations for Sustainable Productivity and Profitability

Project number: PNC478-1819

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Forest & Wood Products Australia

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Prepared for

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EXECUTIVE SUMMARY

Background

Field research during recent decades and literature reviews have provided insights into nutrition dynamics and other factors that affect the productivity of forest plantations. Key issues for nutrient management are harvest residues, fertilisers and weeds. Managers generally use adequate levels of weed control in plantations, which has a strong evidence-base in research. However, there remains a lack of reliable predictors for responsiveness to harvest residue retention or nutrient application across a variety of multi-rotation hardwood sites.

Process-based modelling can help in understanding these issues, but onerous input requirements and a lack of validation of these models in real-world situations, have meant that there is low industry confidence in using them to drive fertilizer use decisions. More recently, the development of ProFert, an empirically-based decision-making tool in the softwood industry, has led to its use by several companies, but it has not been calibrated for hardwoods or residue management.

Harwood plantation managers are seeking:

- Clearly articulated operational level fertiliser guidelines on the timing and application of nutrients to maximize growth and clarity on the best approach in different situations.
- Site indicators predicting potential growth responses to nutrient or harvest residue management.
- Access to growth and economic modelling tools such as Profert.
- An understanding of the economics of harvest residue retention on different sites and the potential of fertiliser applied at establishment to ameliorate the effects of harvest residue removal on soil nutrients and site productivity across different sites.

The current project proposed to:

- Establish a nutrition trial network designed to address the gaps in nutrition response knowledge consisting of:
    - fertiliser rate experiments and larger scale with and without fertiliser responsiveness trials in mid-rotation stands (2-6 years)
    - harvest residue retention compared to removal experiments, both with and without fertiliser, at sites harvested prior to replanting
- Use results from the proposed nutrition trial network combined with data from past experiments to develop tools that allow hardwood plantation managers to better target their fertilizer management on a site-specific basis, as follows:
    - Develop a site screening tool to assist managers in identifying sites that are likely to be responsive to nutrient management.
    - Adapt the ProFert tool for use in hardwood plantations to help optimise multi-rotation nutrient management based on site diagnostics and the economics of fertiliser application.

The trials were established in 2019. This report summarises three years of data, of an expected ten-year rotation targeting pulpwood production. The research continues for another three years as Project VNC590 2223 '*Enhancing the knowledge base for hardwood plantation management* '.

Responses to fertiliser applied between 2-5 years of age

The overall productivity of hardwood plantations and the responses to nitrogen appeared to be influenced by temperature and water availability. When nutrient supply was eliminated as a constraint on growth by providing adequate supplies of Nitrogen (N), Phosphorus (P) and Potassium (K), and water supply was high, the potential productivity of plantations more than doubled from 20 to 45 m^3/ha/y as temperature increased from 14^0C to 22^0C across sites. When water supply was limited by rainfall and evaporation, productivity was lower than the potential productivity determined by temperature alone.

There were no significant responses to phosphorus or potassium applications across these trials.

There were significant responses to N. Across the Rates trials, these ranged up to ~55%. In the Response trials, a similar range of response was found except for two trials at Scott River (WA) where responses of 93% and 130% were recorded. There was a progressive increase in response up to 200 kg N/ha (equivalent to 435 kg/ha of urea). Based on the trial data, applying 200 kg N/ha will result in an average increase in production of 20% during the first two years following fertiliser application, however this declined to 16% by year three. Importantly, the annual responses to lower rates of N (50 and 100 kg N/ha) were lower and the responses declined more quickly than when higher applications were used. The operational rate applications (~50 kg N/ha) used by the industry partners did not enhance growth significantly. On infertile (low nitrogen) sites with favourable climatic conditions (higher temperature and greater climate wetness index), the response to N tended to be higher than the average response.

Soil N concentration (total N) may provide an indication of the upper limit of the response to applied N under favourable temperature and water availability. Conversely, on sites where growth was limited by either low temperature or water supply, the responses to N were generally lower. On these temperature or water limited sites, limiting soil N concentrations were lower. For example, the upper limit to N response was approximately 0.6% N on warm well-watered sites while responses ceased at 0.4% N on slower growing, cold or dry sites.

Based on growth responses during the first three years post-fertiliser application, we provide the following recommendations:

1. Phosphorus and K applications appear unnecessary on ex-agricultural sites. However, it is likely that the supply of P from prior agricultural fertiliser application will decline over time and so requires monitoring.
2. Applying 200 kg N/ha (equivalent to ~435 kg/ha urea or 952 kg SOA) is expected to increase plantation productivity on many sites. Higher rates did not uniformly or consistently further increase the productivity of the plantations.
3. The strongest responses to nitrogen application were observed on relatively warm wet sites. Thus, responses to N application will be strongest on wetter sites in southern WA.
4. Conversely, the colder Tasmanian sites, which generally had higher soil N concentrations, demonstrated more limited responses to applied N. Thus, the lower responses on those sites may have been due to the higher N supply on those sites and/or the restricted growth observed at lower temperatures.

Predicting responses to N fertilisation and incorporation of results into Profert

For the rates and response trials, we examined the available climatic, soil and foliar measures as predictors of growth responses to N fertiliser. Relationships with the capacity to provide useful predictions of potential responsiveness of sites to fertiliser were identified, which provided the option of using two alternative combinations of input variables:

% N Response = f(foliar N, NDVI, CWI and Tmax)[1] $r^2 = 0.43$, Adj $r^2 = 0.35$, SE = 22.7

% N Response = f(soil N, soil C, CWI, and Tmax)[1] $r^2 = 0.30$, Adj $r^2 = 0.21$, SE = 25.1

The above relationships have been incorporated into ProFert to provide estimates of the likely profitability of applying fertilisers to these types of stands. In ProFert, underlying growth curves for stands (assumed to represent the growth of the unfertilised stand) are provided by the user or can be derived from the estimated MAIs using a generic eucalypt growth model.

Relationships developed from the current study enable ProFert to predict responses to N fertiliser in *E. globulus* plantations across southern Australia. While there are a considerable number of uncertainties and assumptions in these relationships, the resultant model is expected to provide a useful tool for growers. ProFert represents a major improvement on current methods for identifying potentially responsive young stands to fertiliser and the ability to determine the optimum rate of fertiliser to apply. The updated version of ProFert has been provided to growers for testing and is expected to be refined and improved based on their feedback and the incorporation of results from the continuing project.

Fertiliser and residue management effects at establishment

1. There was a clear and substantial positive effect of fertiliser on individual tree growth at all sites, averaging ~10% increase for height and diameter (DBHOB) for the maximum rate of fertiliser applied (~32g N, 18gP and 25gK per tree). There was no indication of a plateauing of response for the highest rate indicating that the response was not maximised. Tree survival was negatively affected by fertiliser, decreasing, on average, from 89% without fertiliser to 81% with the highest rate. Hence, although individual trees greatly needed fertiliser, in some cases it increased mortality. We suspect that fertiliser in these cases was not appropriately applied, i.e. too much might have been placed too close to seedlings in the wrong form at the wrong time. Overall, poor tree survival associated with fertiliser, and at some sites, harvest residue retention, moderated or negated the positive effects of these treatments on growth. Despite this, the highest rates of fertiliser boosted stand volume by an average of 17% on the slash removed treatment and by 30% on the slash retained treatment. The effects of fertiliser did not depend on the type of residue management.
2. A range of harvest residue management methods were used across the sites. No significant effects were detected when grouped into similar methods, because (a) of the variability that remained within the groups, and (b) harvest residue management was not replicated within sites.
3. Insect browsing at one site was probably the cause of substantial mortality, reduced tree growth rates, and a consequent low volume per ha. Hence, it can be crucial to control insect browsing.
4. The current advice is that (a) harvest residue should be retained as a precautionary measure where practical, and (b) fertilizer should be applied to newly planted seedlings at the operational rate.

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[1] NDVI: Normalised difference vegetation index, CWI: Climate wetness index (ratio of Rain/Evaporation), Tmax: Annual mean monthly maximum temperature.

BACKGROUND

Improving nutrition management is recognised as one of the main opportunities for boosting growth and improving the long-term sustainability of wood production from plantations. In the parallel hardwood Yield Gap project (*Optimising productivity of hardwood plantations* VNC516 1920) nutrient status and low nitrogen supply was identified as the major contributor to suboptimal plantation productivity (McGrath et al. 2022/in review). Plantation nutrition can be managed through various combinations of, appropriate management of harvest residues (litter, foliage, wood and bark components of residual stems, branches and roots) and weeds, additional fertilizer inputs at establishment, and/or further fertilizer inputs through the rotation.

There has been a lack of consensus amongst hardwood plantation growers as to what constitutes a 'best practice' plantation residue and fertiliser management regime. Research during the past two decades, including a number of reviews, has provided key insights into nutrition dynamics and factors affecting productivity, including the retention of harvest residue. However, there remains a lack of reliable predictors for responsiveness to harvest residue retention or nutrient applications across multi-rotation sites. Further research into weed control as part of nutritional management was not considered a priority, as managers were generally satisfied with the current level of weed control used. Instead, the plantation industry requires guidance on operational considerations of:

- when to apply fertilizer,
- what rates of fertilizer to apply,
- what sites require fertilizer inputs, and
- whether to retain or remove harvest residue.

As with harvest residue management, there is a lack of empirical evidence to support nutrition management decisions across multi-rotation hardwood sites. To circumvent the lack of fertiliser and harvest residue evidence, researchers have used process-based modelling approaches. However, onerous input requirements to run these models and a lack of validation of them in real-world situations have meant that there is low industry confidence in using the models to drive fertilizer use decisions. More recently, the development of ProFert[2], an empirically-based decision-making tool in the softwood industry, has led to good industry take-up, but it has not yet been calibrated for hardwoods.

There is a need to obtain nutrient response data from multi-rotation hardwood sites to inform nutrient management decisions across the current plantation estate. Tools that predict nutrient responses across a range of sites would assist plantation managers with fertilizer application decision-making. Key knowledge and capability gaps to be addressed to improve nutrition management across sites are:

- Benefits of harvest residue retention across a broad range of sites,
- Timing and rates of major nutrient inputs,
- Site indicators for predicting potential growth responses to nutrient or harvest residue management and
- Effective nutrient management decision-making tools for plantation managers.

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[2] *PNC 342-1415 (2017) - Profert - a fertiliser tool for softwood plantations in southern Australia*

LITERATURE REVIEW

Australia's total commercial plantation area was 1.78 M hectares in 2019–20, as reported by plantation growers and managers; with hardwood plantations comprising 0.72 M hectares or 41% of the total area (ABARES 2021). The national hardwood plantation estate is dominated by Tasmanian blue gum (52.7%) and shining gum (25.2%), both of which are managed primarily for pulpwood production. The bulk of forest plantations are in the southern regions of Australia covering a wide range of soil types and climatic conditions. In a variety of contexts, both softwood and hardwood plantation productivities are known to decline over successive rotations if productivity drivers are not adequately managed.

The key drivers of productivity in plantations are water availability (e.g. White et al. 2009, White et al 2014), temperature (e.g. Ryan 2010, Way and Oren 2010) nutrition and pest and disease. These are often related, as low water availability can reduce potential growth responses to nutrition and water stress can predispose trees to pest and disease attack. The influence of temperature on eucalypt plantation productivity has not previously been examined on such a wide scale in Australia. The most suitable temperature for eucalypts in Australia varied with species and provenance (Booth and Prior 1991). Northern provenances of *E. camaldulensis* had an optimum annual air temperature in the range 18- 28^{o}C compared with southern provenances where the range was 10 -22^{0}C. The optimal annual air temperature for the more southerly species *E. nitens* and *E. globulus* ranges from 9-18^{0}C (Booth and Prior 1991). Recent assessments of temperature thresholds for eucalypt species and hybrids indicated that the optimum temperature varied between 15 and 27^{0}C (Queiroz et al. 2020, Watts et al. 2014)

Plantation nutrition research spans almost the entire period of plantation establishment in Australia. Numerous studies have reviewed fertiliser use in softwood and hardwood plantations (Birk 1994; Smethurst et al. 2004; Turner et al. 2001, May 2009a; McGrath and Mendham 2022). Others have quantified growth and other responses to fertiliser and evaluated the economics of fertiliser usage (Knott et al. 1996; Smethurst et al. 2001; Snowdon and Waring 1990). Several studies have attempted to explain the soil and plant processes involved in fertiliser response and the effects on nutrients in soil or water (Fife and Nambiar 1999; Forsyth et al. 2006; Snowdon 1995). Much of this work has focussed on fertiliser usage in softwood plantations although a significant number of studies have investigated nutrient management across hardwood plantations (Adams et al. 2003, Battaglia et al. 2015; Cromer et al. 2002, Mendham et al. 2002, Mendham et al. 2013, 2014; Moroni et al. 2002, Moroni and Smethurst 2003, Smethurst 2000, Smethurst et al. 2001, Smethurst et al. 2003, White et al. 2009, 2010, 2014, Wang et al. 1996; 1998).

Early plantation nutrition research in softwoods resulted from observations in the 1960's that productivity of radiata pine plantations in the Green Triangle (SE SA and SW Victoria) tended to decline between first and second rotations (Keeves 1966). This discovery led to years of intensive research into the causality of the decline and development of strategies to boost productivity of subsequent rotations. Key factors identified included:

- Windrowing and burning of harvest residues resulted in reductions in soil organic matter and loss of key nutrients due to volatilisation (C and N loss through burning), increased leaching (cations and P) and physical removal.
- Increased seed load of introduced pasture and weed species combined with poor weed control resulting partly from the elevation of available nutrients mineralised through burning of harvest residue and lack of measures to remove weeds.

- Inappropriate fertiliser use with no fertiliser applied on some sites or the incorrect types, rates and timing of fertiliser on other sites.

Productivity declines over successive rotations were also observed in hardwood plantations in WA and the factors involved broadly mirrored those outlined above along with the additional factor of declining water availability (Mendham et al., 2011; Turner et al. 2001, Turner and Lambert 2014; White et al. 2009, 2010, 2014). Unlike softwood plantations, which were mostly established on ex-native forest land, the hardwood plantations established across Australia in the 1990's and 2000's were mostly located on ex-pasture sites that had received regular fertiliser and that had accumulated substantial stores of soil water. As a result, during their first rotation, these plantations were able to effectively use relatively large amounts of water and nutrients that have not been replaced in successive rotations. Further, up until recently, common harvest residue management practices such as burning were likely to exacerbate the problem through the removal of nutrients in the short term and potential reductions in organic matter over the longer term.

Mendham et al. (2014) demonstrated that harvest residue removal reduced productivity of one of the two plantations studied in the second rotation and that of both plantations in the third rotation. Furthermore, when the amount of retained harvest residue was doubled, there was no apparent reduction in productivity at either site over the two rotations indicating that, at least over this time frame, this treatment effectively maintained site productivity. Addition of fertiliser together with harvest residue retention at the lower productivity site substantially increased productivity compared with harvest residue alone indicating that, even with harvest residue retained, tree growth was limited by low nutrient availability. However, the experimental design did not include a harvest residue removal plus fertiliser treatment, so it is not possible to say whether fertiliser alone could ameliorate the reduction in growth associated with harvest residue removal. In addition to reducing nutrient loss, harvest residue retention has the potential to improve the conditions for seedling establishment by reducing evaporation losses, increasing soil moisture content, and reducing the temperature of the surface soil. It also acts as a barrier against weed competition, although it can also harbour damaging insect populations. Furthermore, burning of harvest residue can create a variety of social and environmental problems including smoke and increased leaching of nutrients and increased runoff containing particulates and nutrients into waterways.

However, harvest residue retention poses a variety of operational and environmental problems, as already recognised during the early phase of large-scale hardwood plantation establishment in 1990's (Smethurst 1998). These include a potential increase in fire risk, difficulties in preparing sites for planting and problems for access and safety of tree planting crews. Furthermore, the different methods currently used to harvest plantations, i.e. cut to length (CTL) versus whole tree removal to roadside for in-field chipping (IFC), and to establish the next crop (seedling verses coppice), combined with the lack of knowledge of the effects of site productivity, soil type and rainfall on responses to harvest residue retention and fertiliser application make it difficult for forest managers to select where and how to retain harvest residue on different sites. Hardwood residues are also difficult to handle mechanically and more so than softwood residues. As a result, until recently, most hardwood growers still removed harvest residue mechanically and/or burnt it prior to planting.

Plantation nutrition research in Australia has led to notable improvements to nutrition management practices including: the phasing out of harvest residue-burning and the adoption of harvest residue retention; improved weed control at establishment; and the application of macro and micro-nutrients to rectify known deficiencies. Despite these achievements, the lack of ongoing R&D extension activities has meant that the knowledge gained from nutrition R&D within some growing regions or plantation types (e.g. softwoods) has not been broadly implemented across other regions or contexts. There is an industry perception that much of the research undertaken may only be applicable to particular regions, species, rotation, or site situations. This perception has been further exacerbated by the loss of knowledge and experience within forestry organisations through retirements or industry restructuring.

Plantation managers have recognised the importance of ongoing research and refinement of nutrition management practices and are seeking:

- Clearly articulated, operational level fertiliser guidelines on the timing and application of nutrients to maximize growth and clarity on the best approach in different situations.
- Access to growth and economic modelling tools such as FPOS (Mendham et al. 2013) and Profert (May et al. 2009a), which were not deemed to be operationally useful or were not adapted to use in hardwood plantations.
- An understanding of the economics of harvest residue retention on different sites and the potential of fertiliser applied at establishment to ameliorate the effects of harvest residue removal on soil nutrients and site productivity across different sites.

Building on the review of hardwood nutrition issues (FWPA VNC422-1617, McGrath and Mendham 2022) the project proposed to:

- Establish a nutrition trial network designed to address the gaps in nutrition response knowledge consisting of:
    - **fertiliser rate experiments and with/without fertiliser response trials** in mid-rotation stands (2-6 years)
    - **harvest residue retention/removal with or without fertiliser** in harvested stands prior to planting
- Use results from the proposed nutrition trial network, combined with data from past experiments to develop tools that allow hardwood plantation managers to determine fertiliser applications on a site-specific basis, to deliver:
    - Improved understanding of the effects of nutrient management on the growth of multi-rotation hardwood plantations across a range of site types,
    - Identification of key diagnostic factors and guidelines to identify nutrient responsive sites,
    - Adaptation of the ProFert nutrition response tool to provide improved growth response prediction tools for hardwood plantations,
    - Guidelines on suitable nutrition rates to apply across a range of hardwood site types, and
    - Improved understanding of the effects of slash management on the growth of multi-rotation hardwood plantations across a range of site types.

These deliverables will allow individual companies to assess the economics of fertiliser management using tools such as Profert.

PROJECT OBJECTIVES AND APPROACH

The development of predictive tools to assist decision making by plantation managers utilized both existing and additional data developed in this project. A network of forty-five nutrient trials located across three states (WA, Vic, Tas) was established to generate data on when to apply fertiliser, what nutrients generate growth response on various sites, what rates of fertiliser to use, what sites will respond to nutrient inputs, and whether to retain harvest residue at establishment. The trials covered three components.

- **Component 1. Responsiveness of multi-rotation plantations to nutrient application at mid-rotation (ages 2-5) –** Twenty-three diagnostic responsiveness trials were designed to assess the relationships between nutrition diagnostic factors and tree growth response to NPK fertiliser across a regionally representative set of plantation sites. This allowed the potential calibration of nutrient responses to assessments of soil fertility and foliage nutrient concentrations. These trials also increased the available data on the interaction between nutrient supply and climate as outlined in the rates trial series.
- **Component 2. Responsiveness of multi-rotation plantations to the *rate* and *type* of nutrient input at mid-rotation (ages 2-5**). Fourteen factorial rates trials explored the tree growth response to different rates of nitrogen, phosphorus and potassium and/or combinations thereof applied across sites with a range of fertility and climate. This allowed the interaction between nutrient supply and climate as well as the response to specific nutrients to be investigated.
- **Component 3. Responsiveness of multi-rotation plantations to nutrient inputs and/or harvest residue retention at re-establishment.** Eight experiments were established and designed to quantify the main effects and interactions of harvest residue and fertiliser management during establishment of eucalypt plantations in temperate Australia. These experiments examined the diagnostic factors identifying those sites most likely to be affected by harvest residue removal and most responsive to NPK fertiliser applied at establishment across a regionally representative set of sites. Key climate, site, and soil, diagnostics were characterised.

COMPONENTS 1 AND 2: RESPONSE AND RATE FERTILIZER TRIALS

Materials and methods

Responsiveness trials

Trial design

The response of tree growth to uniform rates of nitrogen, phosphorus and potassium that were assumed to be adequate to optimise tree growth was measured at 23 sites across southern Australia. There were 9 trials in WA, 10 in Victoria and 4 in Tasmania (Table 1, Figure2). The trials were operational in scale (strips of 8-10 rows wide and 400-500 m long ≈ 2ha) and the common treatments included: (1) nil fertiliser, (2) adequate/luxury rates of N, P and K fertiliser (i.e. N400/P100/K100, Table 2). Plot sizes varied to provide 30 measurement trees/plot with at least 2 row buffers around the measured internal plot. In PFO's trials, an additional treatment, equivalent to the standard operational rate used in WA and the GT, was applied. Tree species, climate and soil characteristics for each site are shown in Table 1.

Site details

Table 1. **Location and site description of the responsiveness trials (Component 1)**

State	Site name	Treatment date	Age	Coordinates		Species	Soil type	Mean rainfall	#CWI (R/E)
				Lat.	Long.				
TAS	Erriba	1/10/19	2	41.45	146.12	N	Loamy over clay	1472	1.82
TAS	Preston	2/10/19	2	41.29	148.04	N	Loamy over clay	1472	1.39
TAS	Railton 1	15/11/19	2	41.35	146.44	B/G	Dermosol	1058	0.88
TAS	Railton 2	15/11/19	2	41.35	146.44	B/G	Dermosol	1058	0.88
VIC	Convey	16/10/19	3	38.46	143.19	B/G	Loam over clay	1000	0.71
VIC	Meade	16/10/19	3	38.48	143.32	B/G	Sandy loam/ clay	1000	0.78
VIC	Cowland	5/09/19	1	38.06	142.11	B/G	Sandy loam	715	0.57
VIC	Smith	22/08/19	2	37.89	141.64	B/G	Sandy loam	687	0.55
VIC	Pepper	4/09/19	3	37.85	141.68	B/G	Clay Loam	680	0.55
VIC	The Springs	10/10/18	1	37.87	141.61	B/G	Sandy loam	675	0.59
Vic	Gumbough	9/10/18	1	37.45	141.56	B/G	Clay loam	666	0.54
VIC	Annadale	1/09/18	1	37.45	141.61	B/G	Clay loam	676	0.54
VIC	Lindsay	3/09/19	3	37.52	141.25	B/G	Sand	669	0.55
VIC	Danyenah	16/09/19	3	37.91	141.85	B/G	clay loam	653	0.50
WA	Lake Jasper	16/10/18	2	34.37	115.69	B/G	Deep sandy	1050	0.79
WA	Lake Jasper	19/06/19	3	34.37	115.69	B/G	Deep sandy	1050	0.79
WA	Dingup	2/10/18	2	34.27	116.26	B/G	Yellow duplex	800	0.57
WA	Dingup	17/06/19	3	34.27	116.26	B/G	gravel (Dy's)	800	0.57
WA	Triangulee	2/05/19	2	34.69	117.43	B/G	Sand	758	0.55
WA	Wisbey	30/04/19	2	34.89	117.86	B/G	Sand	757	0.54
WA	O'Callaghan	30/04/19	2	34.82	117.67	B/G	Sandy Loam	744	0.53
WA	Greville	26/09/18	2	34.11	116.31	B/G	Yellow duplex	700	0.52
WA	Greville	17/06/19	3	34.11	116.31	B/G	gravel/sand	700	0.52

* Species N = *E. nitens*, B/G = *E. globulus*, # CWI = Rainfall/Evaporation

Figure 1. **Location of responsiveness trials**

Fertiliser treatments

Table 2. **Treatments and application rates for responsiveness trials**

Treatment	Elemental nutrients (kg/ha)		
	N	P	K
1	0	0	0
2	400	100	100
Operational	41-71	15-24	15

Note: Full details of the treatments are provided in Appendix 1. The operational rates varied depending on the company and the location. All Operational Rates were low relative to the experimental treatments.

Establishment dates

Six trials were established in spring 2018 and the remaining 17 trials were established in 2019 (Table 3). At three WA sites (Lake Jasper, Dingup and Greville) paired trials were established which were fertilised in 2018 (aged 2 years) and 2019 (aged 3 years). Full details of establishment/coppicing, soil, foliar sampling and measurement dates are provided in Appendix 1.

Rates trials

Trial design

Fourteen trials were established across southern Australia to evaluate responses to different rates of N and P fertiliser. There were 6 trials in WA, 6 in Victoria and 2 in Tasmania (Table 3, Figure 2). Each experiment comprised 30 plots, consisting of 3 replicates x 4 N rates (0, 100, 200, 400 kg N/ha) x 2 P rates (0,100 kg P/ha) + 2 K rates (0,100 kg K/ha) which were applied to the control and the highest N and P applications (Table 4a). Additional treatments were installed at ten sites by the industry participants to address questions related to their specific situations (Table 4b). The additional treatments were used to enhance the range of treatments and to compare standard operational rates with other treatments.

Site details

***Table 3*. Location and site description of the rates trials (Component 2).**

State	Site name	Treatment date	Age	Coordinates		Species	Soil type	Mean rainfall	CWI (R/E)#
				Lat.	Long.				
TAS	Hays	1/10/19	2	-41.41	146.15	N	Loamy/clay	1472	1.40
TAS	Myrtle Bank	7/06/19	2	-41.29	147.35	N	Dermosol	1292	1.43
VIC	Karlinski	16/10/19	3	-38.55	143.16	B/G	Clay loam/clay	1000	0.76
VIC	Andrew	21/08/19	1	-37.90	141.10	B/G	Sand	741	0.60
VIC	Henke	5/09/18	1	-37.98	141.19	B/G	Sandy Loam	740	0.63
VIC	Moorabinda	19/08/19	1	-37.44	141.68	B/G	Brown clay loam	658	0.53
Vic	Danyenah	16/09/19	3	37.91	141.85	B/G	clay loam	653	0.50
VIC	Wallabadah	5/09/18	3	-37.41	141.60	B/G	Clay Loam	652	0.52
WA	Lake Jasper	5/10/18	2	-34.37	115.68	B/G	Deep sand	1050	0.79
WA	Fagan	17/04/19	2	-34.91	117.13	B/G	Sandy Loam	989	0.73
WA	Jones	24/06/19	2	-34.70	117.33	B/G	Sandy Loam	787	0.57
WA	Parola	20/06/19	2	-34.80	117.96	B/G	Sandy Loam	773	0.53
WA	Lyon	12/05/19	2	-34.83	118.07	B/G	Sandy Loam	699	0.50
WA	Burrell	11/04/19	3	-34.71	118.31	B/G	Sandy Loam	614	0.43

* Species N = *E. nitens*, B/G = *E. globulus*, # CWI = climate wetness index (Rainfall/Evaporation)

***Figure 2.* Location of factorial rates trials**

Fertiliser treatments

Table 4(a). **Treatments and application rates for NxPxK rates interaction trials**

Treatment	Elemental nutrients (kg/ha)		
	N	P	K
1	0	0	0
2	0	0	100
3	0	100	100
4	100	0	100
5	100	100	100
6	200	0	100
7	200	100	100
8	400	0	100
9	400	100	100
10	400	100	0

Table 4(b). **Additional treatments installed by industry partners**

Treatment	Company	Elemental nutrients (kg/ha)				Sites
		N	P	K	Trace	
11	PFO	0	50	100	nil	All PFO sites
12	PFO	50	0	100	nil	All PFO sites
13	PFO	50	25	15	nil	All PFO sites
14	PFO	50	100	100	nil	All PFO sites
15	PFO	100	50	100	nil	All PFO sites except Moorabinda
16	PFO	200	50	100	nil	All PFO sites except Moorabinda
17	Forico	100	0	0	nil	Myrtlebank
18	Forico	0	100	0	nil	Myrtle Bank
19	ABP	133	23	0	nil	Jones, Parola
20	ABP	133	23	0	trace	Jones, Parola
21	ABP	133	46	0	nil	Jones

Note: Full details of the treatments applied are provided in Appendix 1

Establishment dates

Three trials (Henke, Wallabadah and Lake Jasper) were established in September 2018 and the remaining 11

trials were established in 2019, Table 3). Full details of the trial establishment and maintenance procedures including details of the fertilizers applied and application techniques are provided in Appendix 1.

Initial site conditions and nutrient status

Soil and plant samples were collected prior to the application of fertilizer treatments to enable initial site fertility to be estimated. Foliar nutrients were measured by collecting fully expanded, healthy leaves from the upper third of at least 5 trees per plot (with at least 4 plots per site) in May-October, storing them in coolers in labelled zip-lock bags (one bulked sample per plot) and sending them for analysis as soon as practicable. Soil samples from the top 10 cm of soil using a soil sampling device with 5 samples per plot and at least 4 plots per site in May-July. Samples from each plot were bulked, well mixed, and a subsample removed and placed in a labelled zip-lock bag for analysis.

Climate data was accessed from the SILO website: https://www.longpaddock.qld.gov.au/silo/point-data/ which provides Australian climate data from 1889 to yesterday. Temperature, annual average rainfall (R) and evaporation (E) data were accessed for the 10-year period prior to fertiliser application and the 3 years period following fertiliser application, and climate wetness index (CWI = R/E) was calculated. Climate data for the periods during which growth was monitored (i.e. the three years following fertiliser application) were used to define the relationships between climate and growth.

Details of the soil and plant analysis methods are provided in Appendix 1

Pre-treatment soil nitrogen concentrations varied from 0.15 - 0.8% for the Response trials (Table 5) while, for the Rates Trials, soil nitrogen varied from 0.17% to 0.58% (Table 6). HCO_3 extractable P (Colwell P) varied from 5 - 105 mg/g (Response trials, Table 5) and from < 8.0 mg/g to > 50 mg/g (Rates trials, Table 5). Extractable potassium varied from 45- 318 mg/g (Response trials, Table 5) and 32 to 380 mg/g (Rates trials, Table 6). Soil pH was mildly acid at all sites (Tables 5 and 6).

Table 5. **Initial average soil nutrient concentrations for individual sites in the responsiveness trials**

Site		Date sampled	Col P mg/kg	Col K mg/kg	Sulfur mg/kg	Org. C %	Elec. Con. dS/m	pH$_{(CaCl_2)}$	pH $_{(H_2O)}$	PBI	Total N %
Erriba	Tas	29/07/19	21.9	318.5		5.7	0.1	4.3			0.80
Preston	Tas	29/07/19	108.6	258.0		5.0	0.1	4.5			0.51
Railton 1	Tas	14/08/19	12.0	47.5	3.8	2.6	0.0	4.0	5.0		0.17
Railton 2	Tas	14/08/19	42.9	134.5	8.0	3.5	0.1	4.5	5.3		0.32
Convey	Vic	15/05/19	54.8	91.5		4.3	0.1	4.7	5.5		0.32
Meade	Vic	15/05/19	33.1	157.5		3.8	0.1	4.7	5.6		0.27
Cowland	Vic	22/05/19	40.3	70.0	11.5	2.6	0.1	4.5	5.2	61.0	0.20
Smith	Vic	16/05/19	26.6	83.5	5.2	3.6	0.1	4.1	5.0	160.9	0.27
Pepper	Vic	11/06/19	19.8	66.6	4.6	3.7	0.0	4.1	5.1	167.3	0.33
The Springs	Vic		25.13	126.75	5.81	3.44	0.22	6.23	6.85	175.00	0.26
Gumbough	Vic		14.58	155.25	6.46	4.51	0.11	5.38	6.13	237.50	0.34
Annadale	Vic		20.63	90.75	5.20	4.04	0.05	4.56	5.61	127.50	0.30
Lindsay	Vic	11/06/19	5.4	64.6	3.4	2.0	0.0	4.7	5.8	2.0	0.15
Danyenah	Vic	16/09/19	18.0	113.1	3.9	2.8	0.0	4.6	5.7	83.1	0.20
Lk Jasper 18	WA	7/09/18	14.8	43.8	10.2	4.6	0.0	4.4	5.5	630.2	0.25
Lk Jasper 19	WA	7/09/18	8.2	45.7	8.1	5.0	0.1	3.9	5.1	573.3	0.34
Dingup 18	WA	7/09/18	30.9	55.6	7.3	4.4	0.1	5.5	6.3	259.4	0.45
Dingup 19	WA	28/03/19	32.0	75.3	10.1	4.7	0.0	5.2	6.0	281.9	0.40
Triangulee	WA	29/04/19	20.6	37.8	5.2	3.8	0.1	4.1	5.2	97.4	0.36
Wisbey	WA	30/04/19	17.1	45.9	3.6	2.8	0.1	3.9	5.2	29.7	0.27
O'Callaghan	WA	02/05/19	13.1	81.3	5.4	3.1	0.0	5.3	6.1	98.7	0.23
Greville 18	WA	7/09/18	33.3	84.9	9.0	4.4	0.0	4.8	5.8	1078.5	0.36
Greville 19	WA	28/03/19	40.8	93.5	9.5	5.0	0.0	4.4	5.5	1459.6	0.45
Mean			**29.7**	**98.5**	**6.8**	**3.9**	**0.1**	**4.5**	**5.5**	**355.9**	**0.33**

***Table 6.* Initial average soil nutrient concentrations for individual sites in the rates trials**

Trial		Date sampled	Col P mg/kg	Col K mg/kg	Sulfur mg/kg	OC %	Elec. Con. dS/m	pH $_{(CaCl_2)}$	pH $_{(H_2O)}$	PBI	Total N %
Hays	Tas	16/09/19	43.7	381.6	4.5	5.0	0.0	4.8	5.8	897.7	0.58
Myrtle Bank	Tas	16/08/19	20.4	222.5	9.1	4.7	0.1	4.2	4.9		0.49
Karlinski	Vic	15/05/19	52.5	293.0		6.6	0.1	5.0	5.8		0.44
Andrew	Vic	8/06/19	14.8	58.5	8.5	3.1	0.1	3.9	5.1	10.2	0.22
Henke	Vic	13/09/18	10.6	42.8	2.9	4.0	0.0	4.4	5.5	10.7	0.25
Moorabinda	Vic	1/08/19	51.3	153.5	12.2	2.7	0.1	5.0	5.7	120.3	0.23
Danyenah	Vic	16/09/19	19.2	113.0	4.8	2.2	0.1	5.8	6.5	83.4	0.17
Wallabadah	Vic	13/09/18	11.6	122.6	4.1	3.5	0.0	4.4	5.4	127.4	0.29
Lake Jasper	WA	27/09/18	8.2	31.6	5.6	4.6	0.0	4.3	5.4	134.5	0.32
PFO Fagan	WA	23/04/19	7.7	59.6	9.2	4.1	0.1	3.4	4.5	6.5	0.27
ABP Jones	WA	8/08/19	23.0	83.6	9.2	4.3	0.1	4.8	5.6	1810.3	0.28
ABP Parola	WA	20/06/19	26.7	94.2	6.0	2.6	0.0	5.4	6.3	61.4	0.18
PFO Lyon	WA	14/05/19	12.0	64.4	3.8	4.0	0.0	3.6	5.0	31.7	0.29
PFO Burrell	WA	18/06/19	16.5	64.2	5.7	2.8	0.0	4.4	5.6	31.0	0.27
Mean			**22.7**	**127.5**	**6.6**	**3.9**	**0.1**	**4.5**	**5.5**	**277.1**	**0.31**

The approximately three-fold variation in foliar N was similar to that for soil with values ranging from 0.88% (Response trials, Table 7a) to 2.48% (Rates trials, Table 7b). For juvenile E. globulus, foliar N concentrations less than 1.0% are considered deficient while those greater than 2.0% are adequate and 1.7% to 2% are considered marginal (Reuter and Robinson, 1997). Based on these values, only one site would have been considered nitrogen deficient (Table 7a), 23 sites would have had marginal N status (Tables 7a and b) and eight sites had adequate N status. The variation in foliar phosphorus concentrations was lower than for soil, varying from 0.09- 0.25%. Foliar P concentrations less than 0.1% are considered deficient while those greater than 0.14% are adequate and 0.12% to 0.14% are considered marginal (Reuter and Robinson 1997). Foliar potassium varied from 0.44% to 1.43% (Table 7a) which was significantly lower than for the variation in soil K concentrations. Foliar K concentrations less than 0.4% are considered deficient while those greater than 0.8% are adequate (Reuter and Robinson 1997).

The nutrients that have previously been demonstrated to affect the performance of blue gums on ex-farmland are N and, to a lesser extent, P. A site level analysis revealed no relationship between soil N and foliar N (Figure 3) and, similarly for P, there was no relationship between soil P and foliar P (Figure 4). This aligns with previous reviews of blue gum nutrition where foliar nutrient concentrations were not related to growth (Szota et al. 2014, McGrath and Mendham 2022). In contrast, growth responses have been related to soil N concentrations (McGrath and Mendham, 2018; Smethurst et al. 2004; White et al. 2009). Consistent with numerous studies, there was a significant relationship between soil carbon and soil nitrogen (Figure 5). However, C/N ratios ranged from 7.6 to 19.3 (average 13).

***Table 7.* Initial site mean foliar nutrient concentrations in a) the responsiveness trials and b) the rates trials**

a)

Site	Date	% N	% P	% K	mg/kg Cu	mg/kg Zn	mg/kg Mn	mg/kg B	% Ca	mg/kg Fe	% Mg	% Na	% S
RMS Erriba	29/07/2019	1.73	0.10	0.78	7.41	17.65	1163.11	23.83	0.62	53.61	0.13	0.03	0.13
RMS Preston	29/07/2019	2.24	0.15	0.85	7.75	17.42	581.03	36.22	0.71	51.00	0.12	0.03	0.15
Forico Railton 1	14/08/2019	1.73	0.09	0.45	3.82	13.88	595.45	29.96	0.66	55.85	0.10	0.03	0.11
Forico Railton 2	14/08/2019	1.78	0.10	0.49	3.14	13.02	475.25	24.44	0.59	58.86	0.10	0.02	0.12
Midway Convey	30/09/2019	1.18	0.09	0.44	3.44	10.47	295.42	16.89	0.93	50.33	0.17	0.22	0.09
Midway Meade	30/09/2019	1.70	0.14	0.65	8.18	12.75	403.75	21.16	0.75	52.58	0.19	0.22	0.12
PFO Cowland	24/10/2019	1.38	0.14	0.58	4.73	13.75	555.83	27.33	1.30	155.33	0.26	0.20	0.12
PFO Smith	22/08/2019	1.71	0.12	0.56	5.85	11.67	632.50	21.83	0.97	56.42	0.23	0.21	0.13
PFO Pepper	5/09/2019	1.24	0.09	0.44	3.72	9.13	373.33	20.83	0.75	47.33	0.15	0.18	0.09
PFO Lindsay	3/09/2019	0.88	0.09	0.54	4.71	8.99	176.67	32.58	1.58	46.33	0.15	0.20	0.08
SFM Danyenah	18/09/2019	1.38	0.10	0.60	4.16	8.99	413.75	24.13	11.40	61.00	0.19	0.24	0.10
Wapres Lake Jasper 18	17/10/2018	2.20	0.25	1.43	9.14	18.60	51.42	16.21	0.46	39.00	0.19	0.26	0.16
Wapres Lake Jasper 19	22/05/2019	1.16	0.10	0.79	5.39	12.21	35.08	14.27	0.64	33.61	0.21	0.22	0.09
Wapres Dingup 18	7/09/2018	1.92	0.19	0.91	7.60	19.37	268.92	21.00	0.66	43.42	0.19	0.22	0.17
Wapres Dingup 19	23/05/2019	1.32	0.11	0.78	6.71	10.96	131.42	18.13	0.61	36.92	0.23	0.17	0.11
PFO Triangulee	26/08/2019	1.95	0.17	0.76	8.66	15.59	191.73	16.22	0.65	32.75	0.19	0.15	0.13
PFO Wisbey	26/08/2019	2.31	0.20	0.95	10.69	21.11	91.06	23.19	0.55	43.72	0.16	0.18	0.18
PFO O'Callaghan	26/08/2019	2.27	0.21	1.02	9.88	17.71	111.37	23.18	0.53	37.88	0.19	0.18	0.17
Wapres Greville 18	6/09/2018	1.64	0.14	0.72	5.09	13.16	334.54	21.32	0.83	32.34	0.20	0.20	0.14
Wapres Greville 19	24/05/2019	1.37	0.12	0.81	5.56	11.48	219.83	21.57	0.57	42.17	0.21	0.22	0.11
Overall mean		**1.65**	**0.13**	**0.73**	**6.28**	**13.89**	**355.07**	**22.71**	**1.29**	**51.52**	**0.18**	**0.17**	**0.13**

b)

Site	Date	% N	% P	% K	mg/kg Cu	mg/kg Zn	mg/kg Mn	mg/kg B	% Ca	mg/kg Fe	% Mg	% Na	% S
RMS Hays (Wilmott)	16/09/2019	2.07	0.13	0.68	6.26	15.90	931.69	25.50	0.43	33.85	0.10	0.01	0.14
Forico Myrtle Bank	25/10/2019	1.78	0.11	0.54	6.50	16.35	2157.70	25.30	0.58	53.15	0.12	0.03	0.13
Midway Karlinski	30/09/2019	1.58	0.10	0.48	4.31	9.18	166.74	12.98	0.73	50.11	0.17	0.23	0.11
PFO Andrew	19/08/2019	2.39	0.16	0.70	3.85	13.80	345.33	27.23	0.86	48.77	0.18	0.23	0.14
PFO Henke	13/09/2019	1.62	0.13	0.81	4.44	13.07	148.67	31.03	1.24	56.60	0.24	0.27	0.13
PFO Moorabinda	19/08/2019	2.43	0.14	0.67	4.68	14.47	456.00	17.30	0.75	52.07	0.20	0.18	0.14
SFM Danyenah	18/09/2019	1.48	0.11	0.62	4.75	8.01	794.33	27.73	1.02	59.33	0.17	0.22	0.11
PFO Wallabadah	13/09/2018	1.11	0.09	0.49	2.90	8.53	677.67	22.87	1.47	46.63	0.15	0.21	0.09
Wapres Lake Jasper	27/09/2018	1.56	0.11	0.60	6.85	11.50	67.28	23.60	0.99	31.43	0.15	0.20	0.12
PFO Fagan	3/09/2019	1.88	0.18	0.89	9.75	16.98	207.82	21.92	0.75	37.90	0.18	0.19	0.14
ABP Jones	27/08/2019	2.29	0.20	0.84	9.56	19.93	151.34	21.09	0.52	49.69	0.19	0.16	0.16
ABP Parola	22/08/2019	2.48	0.25	1.13	9.84	23.44	125.03	27.28	0.58	49.95	0.22	0.19	0.20
PFO Lyon	16/08/2019	1.98	0.16	0.80	8.91	14.64	96.30	24.10	0.79	43.70	0.19	0.21	0.15
PFO Burrell	20/08/2019	1.38	0.11	0.72	5.88	9.54	190.54	22.50	0.90	38.91	0.19	0.21	0.10
Overall mean		**1.86**	**0.14**	**0.71**	**6.32**	**13.95**	**465.46**	**23.60**	**0.83**	**46.58**	**0.18**	**0.18**	**0.13**

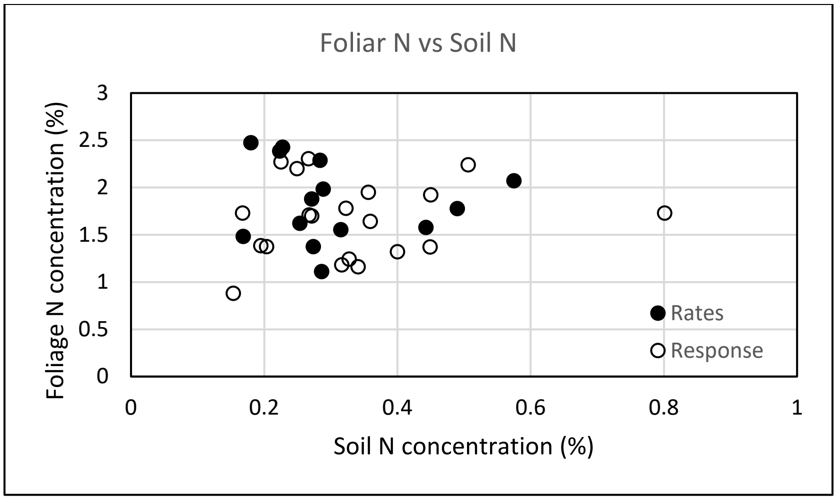


Figure 3. **Relationship between soil N and foliage N for rates and responsiveness trials**

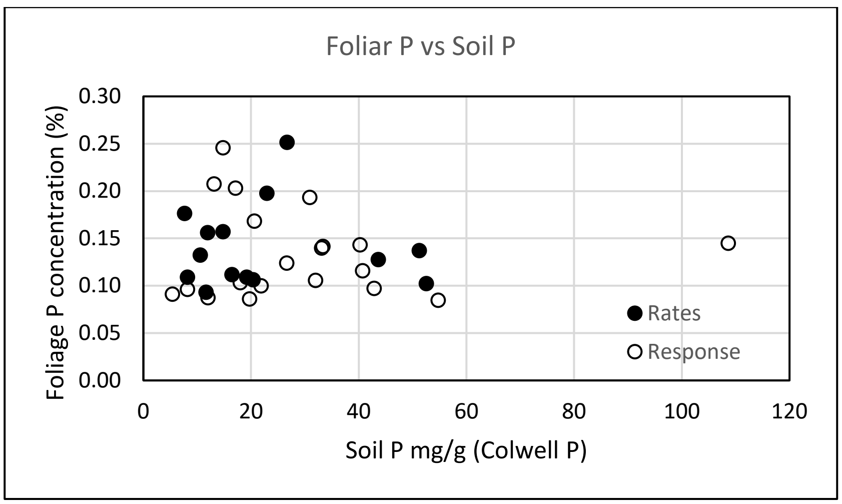


Figure 4. **Relationship between soil P and foliage P for rates and responsiveness trials**

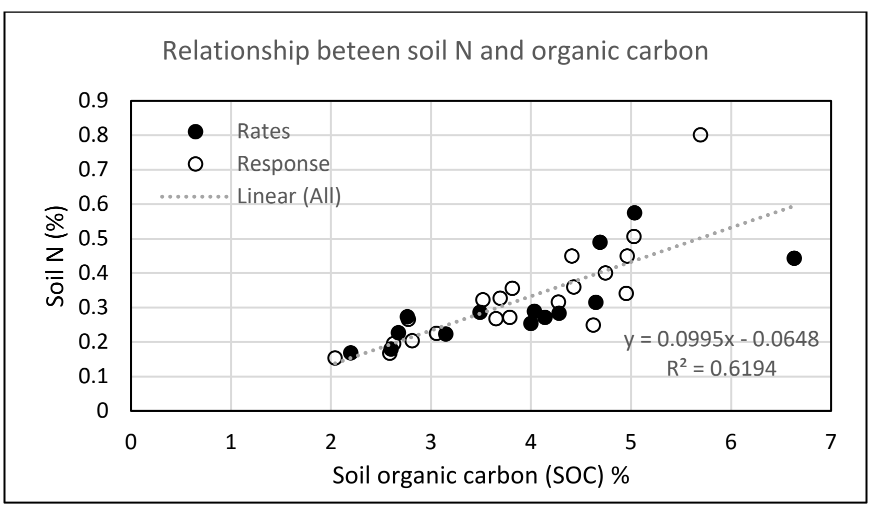


Figure 5. **Relationship between soil N and soil organic carbon for rates and response trials**

NDVI estimates for response and rate trials

NDVI (normalised difference vegetation index) was calculated for fertilised and unfertilised plots using imagery collected by the Copernicus Sentinel-2 (S2) satellites. The wavelengths most sensitive to vegetation greenness include the Red and Near Infra-Red (NIR) bands. For the S2 satellites, these wavelengths are covered by Bands 4, 5, 6, 7, 8 and 8A which have a spatial resolution of 10-20 m (i.e. producing imagery with pixels with areas of 100–400 m^2).

NDVI was calculated from the Red and Near Infrared bands (bands 4 and 8 for Sentinel data) and averaged for the year prior to fertiliser application:

$$NDVI = \frac{(\text{Band } 8 - \text{Band } 4)}{(\text{Band } 8 + \text{Band } 4)}$$

Healthy (i.e. green) vegetation tends to reflect less light in the red band (Band 4) and more light in the NIR band (Band 8) and so has an NDVI close to 1, while less healthy vegetation tends to be less green and has an NDVI closer to 0 (See Appendix 2, Figure 1). So, for vegetation, NDVI generally ranges from 0 to 1.

A more extensive description of the NDVI technique is provided in Appendix 2.

Statistical analysis of data

Results from the rates and responsiveness trials were analysed to determine whether there were significant differences between treatments, and whether there were significant relationships between tree growth or response to fertiliser (dependent variables) and pre-treatment soil and foliar nutrient concentrations, climate or NDVI (independent variables).

Analyses of growth data

To determine whether there were significant differences in tree growth for the various treatments Analysis of covariance (ANCOVA) was used. Initial stand volume and basal area were tested as covariates to help account for underlying within-site variation in growth. Initial measurements were found to be correlated with growth at most of the sites, which indicated that the results could have been misleading without the removal of the effect of this covariate. For example, at the Erriba site, an analysis of variance with no covariate indicated that there was a 4.7 m^3/ha increase in growth in response to fertiliser over the three years which was equivalent to a 14% response (Figure 6a). However, after accounting for the differences in growth due to the variation in initial volume in an ANCOVA, the absolute response decreased to 0.4 m^3/ha (equivalent to a 1.4% response).

Volume and Basal area growth over the 3 years were analysed using ANCOVAs for each site individually using Treatment and Rep (Block) as class variables and initial basal area or growth.

a) b)

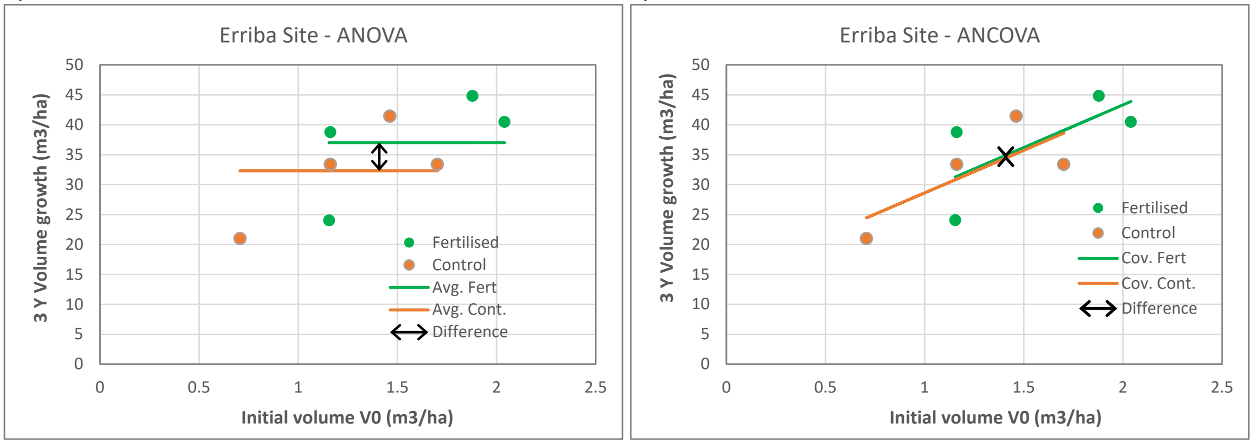


Figure 6. **Example of the effect of including initial volume as a covariate in determining the response to fertiliser at the Erriba site showing a) the estimated means for the fertilised and control treatments if the effect of initial volume is ignored and b) the fitted relationship and difference between the treatments (which was negligible) if initial volume is included.**

Statistical design for responsiveness trials

For responsiveness trials, just one statistical design was used within each site:

Vol Gth = aV0 + bT + cB + e or

BA Gth = aBA0 + bT + cB + e

where:

- Vol Gth is volume growth over the three years,
- T is treatment (control, fertilised and standard) with the fertilised treatments receiving 400 kg N/ha, 100 kg P/ha and 100 kg K/ha and the standard treatments[3] (where included) receiving the standard operational rate of fertiliser applied for the company and region,
- B is the block or replicate
- a, b, c are the parameters for each effect, and
- e is the amount of unexplained variation remaining after the analysis.

There were 4 replicates per treatment, which provided 8-12 plots for the analyses with 3-6 degrees of freedom.

Statistical design for rates trials

The rates trials had 10 core treatments and up to 6 additional treatments selected by individual companies. This created a more complex series of statistical designs that could be used to examine the effects of different rates of N and P fertiliser as well as interactions between N, P and K on growth. The designs tested included (note only the designs including volume growth are shown):

1) Effect of treatment:

   Vol Gth = aV0 + bT + cB + e

   including all treatments

[3] Note, for the operational treatment, the two rates of fertiliser (Table 2) were grouped as one treatment.

2) Effect of N rate +/-P:

   Vol Gth = aV0 + bN + cP + dNxP + fB + e

   Including treatments 2-9 with 4 rates of N (0, 100, 200, 400 kg N/ha) and 2 rates of P (0, 100 kg P/ha) with K applied at a rate of 100 kg K/ha to all plots.

   This design allowed the effect of different rates of N with or without P and any NxP interaction to be determined.

3) Effect of K +/- N+P

   Vol Gth = aV0 + bK + cN+P + dKx(N+P) + fB + e

   Including treatments 1-2 and 9-10 with 2 rates K (0 and 100 kg K/ha) and 2 rates of N+P (N0P0 and N400P100).

   This design allowed the effect of K with or without N and P fertiliser to be determined. No significant response to K or any Kx(N+P) interaction was evident at any of the sites. So, the means for the treatments with and without K were used to calculate the absolute and relative response to N+P fertiliser at each of the sites. These means were used in subsequent regression analyses to determine the effect of different site and stand factors on growth and response.

In addition, two other analytic designs were used for PFO's rates trials in which lower rates of N and P were applied. These treatments included 50 kg N/ha with and without 100 kg P/ha and 50 kg P/ha with N applied at rates of 0, 100 and 200 kg N/ha. All additional treatments also included 100 kg K/ha. The designs for these analyses were:

4) Effect of N rate +/- P

   Vol Gth = aV0 + bN + cP + dNxP + fB + e

   Including treatments 2-9, 11 and 12-15 with 5 rates of N (0, 50, 100, 200, 400 kg N/ha) and 2 rates of P (0, 100 kg P/ha) with K applied at a rate of 100 kg K/ha to all plots.

5) Effect of N rate x P rate

   Vol Gth = aV0 + bN + cP + dNxP + fB + e

   Including treatments 2-7, 11 and 15-16 with 3 rates of N (0, 100, 200 kg N/ha) and 3 rates of P (0, 50, 100 kg P/ha) with K applied at a rate of 100 kg K/ha to all plots.

These latter two designs allowed the effect of lower rates of N on growth and any relationship between P rate and response to be determined.

Relating growth data to site and stand factors

Relationships between site and stand factors and underlying growth of the unfertilized and fertilised treatments as well as the absolute (m^3/ha) and relative (%) differences between the N400P100 treatment and control were analysed using simple and multiple regressions. Data from all sites was pooled for this analysis using the control (N0P0K0) and luxury fertiliser treatments (N400P100K100) from the response trials, and the means of the N0P0 (treatments 1 and 2) and N400P100 (treatments 9 and 10) treatments with and without K fertiliser from the rates trials.

Stand and site variables tested for these analyses included:

- Soil variables: total N, organic C, Colwell P, Colwell K, pH($CaCl_2$) and EC
- Foliar nutrients: N, P, K, Ca, S, Mg, Fe, Cu, Zn, Mn, B
- Satellite data: NDVI
- Climate data: Avg. annual rainfall, evaporation and avg. monthly max and min temperatures, solar radiation and VP deficit.
- Other factors: age of fertiliser application, initial volume or basal area.

Soil and foliar nutrient data were collected prior to fertiliser application, NDVI data were compiled for the period Dec 2018 (the earliest period available for Sentinel 2 data) to Dec 2022 and climate data were compiled for the 3-year period from the time of fertiliser application (July 2018 – June 2021 or July 2019 – June 2022 depending on the year of application) as well as for the 10-year period from 2008-18.

Simple linear regressions were used to test whether relationships existed between underlying growth (of both controls and fertilised treatments) as well as responses to fertilizer and the various site and stand variables. Multiple regression analysis was then used to determine whether including multiple factors in the relationships significantly improved the relationships.

The maximum number of variables selected for any relationship was kept at four to avoid overfitting the data against the responses across the 37 sites. As a general rule, a maximum of 10 observations are required for every independent variable included in a multiple regression (Max and Lynn 2004), although it has been argued that this may be too conservative and 5-9 observations per predictive variable may be adequate (Vittinghoff and McCulloch 2007). The one in ten rule implies that a maximum of 3-4 predictive variables can be used to explain variation in the current dataset with some degree of confidence. In general, only variables that were significant (i.e. with P values < 0.05) were included.

A stepwise approach was used to determine the best mix of variables that explained stand growth or response to fertiliser. Two general sets of data were tested for each regression:

- One based on foliar data and NDVI together with climatic variables,
- Another based on soil data plus climatic variables with and without NDVI.

This approach assumed that potential users may want to use either soil sampling or foliar analysis (but not both), although there were no improvements in the relationships when we tested combinations of soil and foliar variables. Since climate and NDVI data is freely available it was assumed that users could include these variables with minimal additional cost.

Climate data for the 3 years post fertiliser application was used in the relationships, as this was considered to provide the best indication of actual conditions experienced by the trees. In addition, climate data for the 10 years prior to fertiliser application (2008-18) was also tested, as this represents data that would actually be used to predict response prior to fertilising a site, in order to determine if this could be expected to reduce the strength of the relationships.

All relationships and outputs were calculated using the Microsoft Excel Linest function. These provided the following outputs for each regression:

- r^2, and df of the regression,
- Means of parameter coefficients and intercept, and
- Standard errors for the regression and parameter coefficients.

In addition, the probabilities of all coefficients were calculated together with the adjusted r^2 value, fitted values and residuals for the relationships. Fitted (i.e. predicted) values were plotted against actual values for volume growth of the controls and fertilised treatments as well as the % and absolute responses to fertiliser.

The best relationships for explaining observed growth and responses to fertiliser were selected on the following basis:

- Using only variables known to potentially influence growth or response to fertiliser across the sites,
- Sensible coefficients for explanatory variables (e.g. we would expect growth and response to fertiliser to increase with higher water availability, higher temperatures and higher solar radiation),
- 4 or fewer explanatory variables included,
- Highest adj. r^2 values and lowest standard errors;
- All explanatory variables significant or marginally significant; and
- Residuals normally distributed.

Results and Discussion

Fertilizer responses

Responsiveness trials growth responses

Significant volume responses to adequate fertilizer application (N400 P100 K100) were recorded at 9 of the 23 sites (Figures 7, 8). Of those sites with significant responses, volume increases ranged from 18 - 130% with a mean response of 46% (Figure 7). Five sites had responses between 18 and 50% and 4 sites had responses >50% with the two sites at Lake Jasper recording 91% and 130% increases (Figure 7).

Applying lower rates of N, P, K, as used with typical operational applications by a number of companies, provided no statistically significant responses relative to the unfertilized control growth over the first 3 years after application (Figure 7, Figure 8, Figure 9). Where the low-rate application was used, the response was generally much lower than the high-rate application. The exception to this was the Triangulee site where the responses to the two treatments were similar. However, the treatment strips at this site were in different compartments making the comparisons difficult. This site will likely not be carried forward into the second phase of the trials due to this design issue.

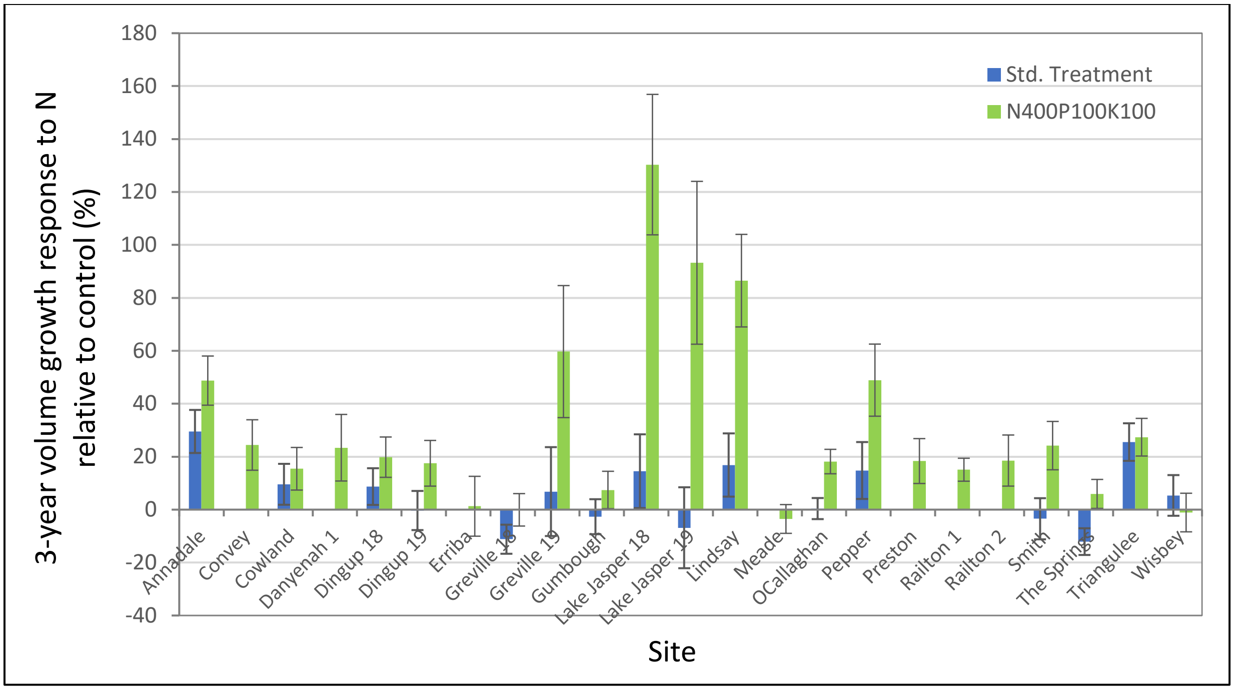


Figure 7. **Percentage volume responses to operational (standard) and high applications of NPK fertilizers. Error bars indicate standard errors of means.**

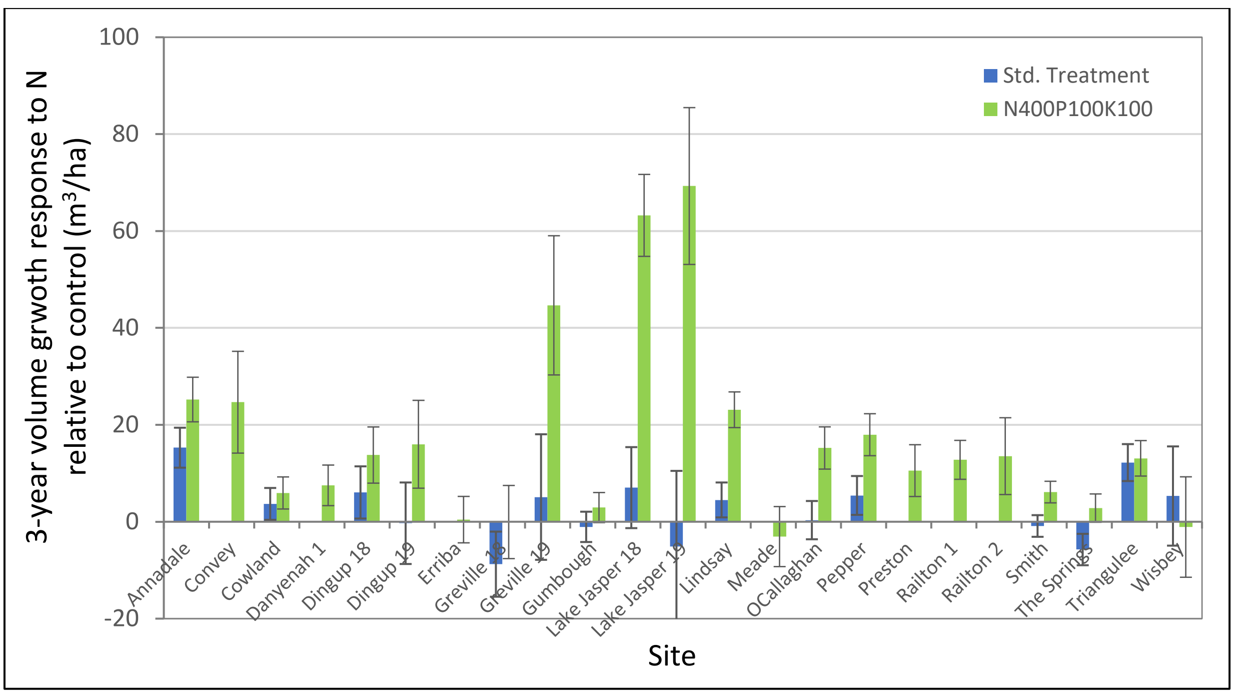


***Figure 8*. Absolute (m^3/ha) volume responses to operational (standard) and high applications of NPK fertilizers relative to control. Error bars indicate standard errors of means.**

Note: The error bars on Figures 7 and 8 are standard errors of means (s.e.) and 2 x s.e. approximates the 95% confidence interval of the mean, so where the bars don't overlap the differences are significant. The non-randomised arrangement of the treatments means that the comparisons within each site are not strictly statistically valid.

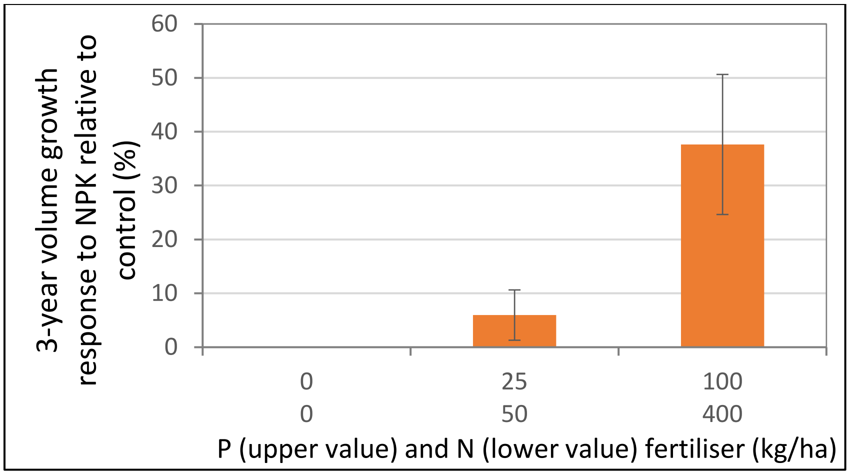


***Figure 9*. Average volume response to different rates of combined NPK fertilizer three years after application across all 23 responsiveness sites. Error bars indicate standard errors of means.**[4]

Rates trials growth responses

Phosphorus responses

Three years after fertilisation, there was no significant response (P < 0.05) to phosphorus although the response was marginally significant at two sites (Hays P = 0.088) and Burrell (P = 0.073) . Ten of the 14 sites had a response of 5% or less relative to the control (Figure 10). The remaining four sites had responses between 5 and 8%. The average volume response across all sites was 2.0%.

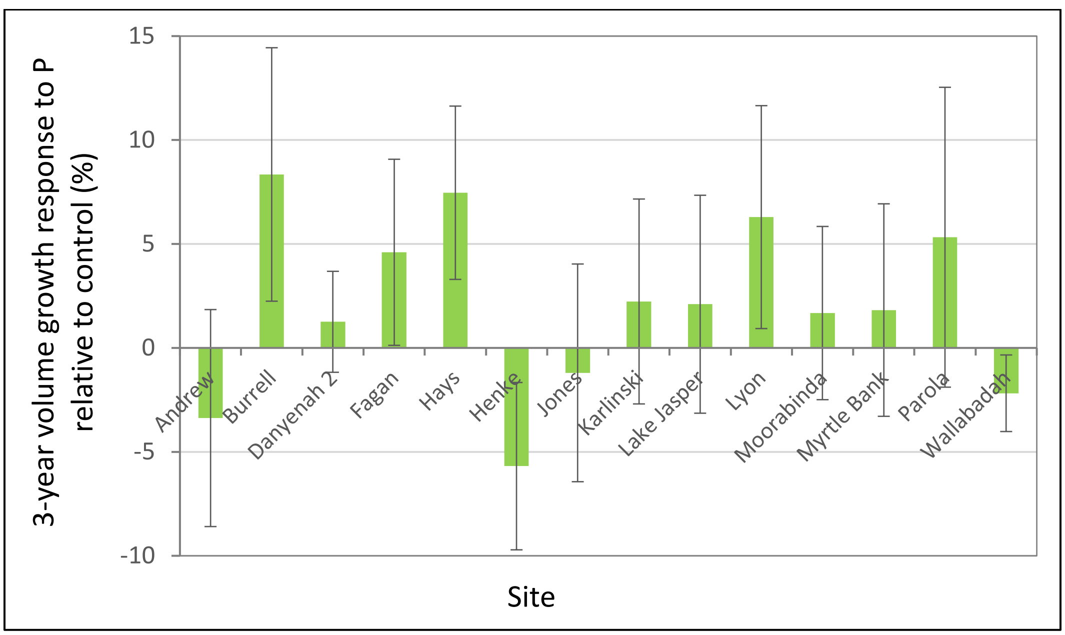


***Figure 10*. Percentage volume response to 100 kg P 3 years post application. Error bars indicate standard errors of means. Note, none of the responses to P were statistically significant at P < 0.05.**

[4] Note, for the analysis, the standard operational treatments applied to PFOs sites were assumed to be the same. However, 50 kg N/ha + 25 kg P/ha was applied to GT sites and 71 kg N/ha + 15 kg P/ha to WA sites.

Six of the PFO Rates trials had an additional treatment of 50 kg P/ha applied while all other trials had only 0 and 100 kg/ha P treatments. The small non-significant responses observed across individual sites and lack of a significant response to P when averaged across all sites, mean that it is not possible to define a rate response curve for phosphorus from these trials. Similar to the overall series of trials, the response to applied P was small at the PFO sites with 3 sites (Andrew, Wallabadah and Henke) showing small negative responses, and (Fagan, Lyon and Burrell) with small positive responses of between 4 and 8% at 100 kg P/ha (Figure 11, Table 8). As the average response was 3.0% (compared with 1.7% across all 14 sites) and was not significantly greater than zero (Figures 10, 11). The cumulative P response at the Burrell site, which was statistically significant two years after fertilization, declined to 8% by the third year and by which time it was not statistically significant .

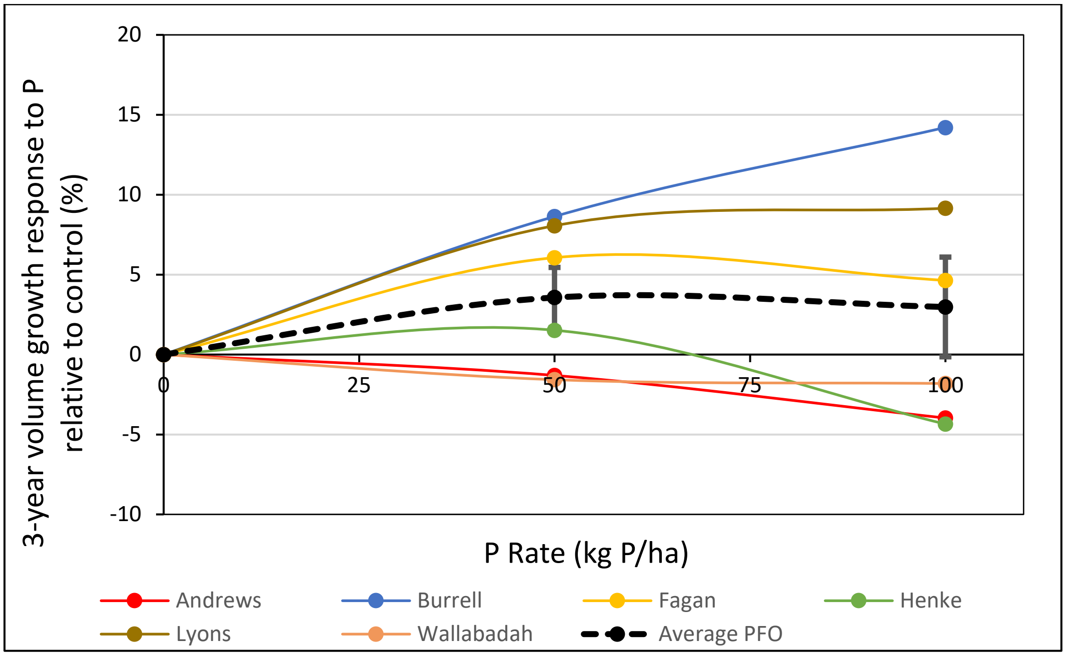


Figure 11. **Response to increasing P application at the six PFO trials with increasing rates of P. Error bars indicate standard errors of the values for the averages across all sites.**

The general lack of any significant responses to applied P at any site indicates that phosphorus was not limiting at ages 1-5 years across this suite of trials. This is likely a result of previous agricultural and plantation applications of phosphorus fertiliser and indicates that these past applications may continue to support tree growth over at least two rotations. It is also likely that operational fertiliser applications at establishment helped mitigate any potential P deficiencies in the young plantations. This is consistent with the extended responses to phosphorus observed in softwood plantations (McGrath, et al 2003, Turner 1982, Turner et al. 2002) The small responses detected at some sites suggest that responses to P could emerge as the availability of P declines over time. These small responses to P make it difficult to define useful critical levels of soil P or foliar P or to develop categories of P availability.

While the HCO_3 P (Colwell P) concentrations appear relatively low, with a range from 8-17 for the sites with response curves (Table 8) the absence of a response to phosphorus at these low levels of available P is likely due to the low phosphate buffering index (PBI) at these sites along with efficient P uptake mechanisms of eucalypts. Colwell P is a useful measure of the quantity of P available in the soil and can be used to calibrate growth responses after the P buffering capacity (PBI) of the soil is taken into consideration, or soils with similar P buffering are grouped together. For example, Colwell P greater than 10 ppm in light textured soils (sands – low PBI) is adequate for tree growth in *P. radiata,* whereas in heavier textured soils (loams/clays – high PBI) it increases to 15 ppm to compensate for the higher buffering capacity. Mendham et al. (2002) found that critical Colwell P concentrations were poorly defined in the range 21-71 ppm, and it was speculated that this range was elevated due to the inclusion of a high proportion of soils with a high P buffering capacity. Similarly, with pasture species, higher HCO_3 P concentrations were required to achieve yield targets as PBI values increased (Summers and Weaver 2011, Rogers et al. 2021).

Table 8. **Response to Phosphorus at 6 PFO trial sites**

Site	% Response at P50	% Response at P100	Foliar P	Soil HCO_3 P	PBI (Phosphate buffering Index)
			(%)	(mg/kg)	
Andrew	-1	-3	0.16	15	10
Wallabadah	-2	-2	0.09	12	127
Henke	2	-6	0.13	11	11
Fagan	6	4	0.18	8	7
Lyon	6	6	0.16	12	32
Moorabinda	1	3	0.16	12	32
Burrell	5	8	0.11	17	31

The absence of P responses and the understanding of P responses in other plantation species indicates that P fertilization is not required, and if it emerges as an issue can be remedied with an application at planting or early in the rotation. To pre-emptively diagnose emerging P deficiencies, additional work is required to provide a better understanding of the relationships between soil P and the responses to P fertiliser in hardwood plantations. This will require the identification of sites with deficient levels of phosphorus, which could provide significant responses to P fertiliser additions.

Nitrogen responses

The range of responses in the rates trials was smaller than for the response trials (Figure 7 vs Figure 12), because of the high responses (93 and 130%) at the two Lake Jasper response trials.

In contrast to P, for which there was no response to phosphorus application either in the presence or absence of applied nitrogen (Figure 13), the mean increase in growth to an optimum N application was 9.8 m^3/ha over three years (Figure 13). This translates to a mean 18% increase in growth over all the trials (Figure 14). There was a significant positive NxP interaction at the Danyenah site where there was evidence of a very small positive effect of P on N (the response to N+P was 12% compared with -4% for N alone). There was a significant, but again quite small, negative NxP interaction at Wallabadah where the response to N+P was 5% compared with 11% for N alone. There was no NxP interaction at the other sites which leads to the overall absence of evidence an NxP interaction in the treatment responses when averaged across all sites (Figures 13 and 14).

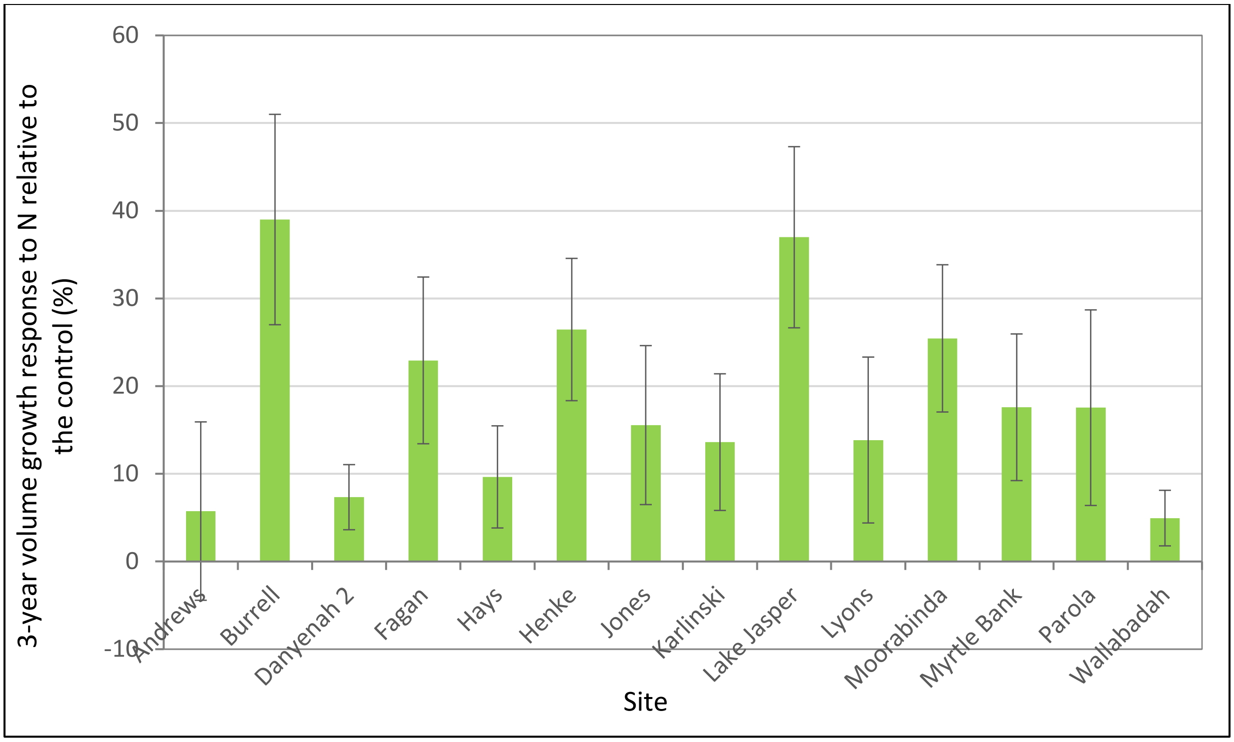


Figure 12. **Three years relative response to 400 kg N/ha for the 14 rates trials. Error bars indicate standard errors of means.**

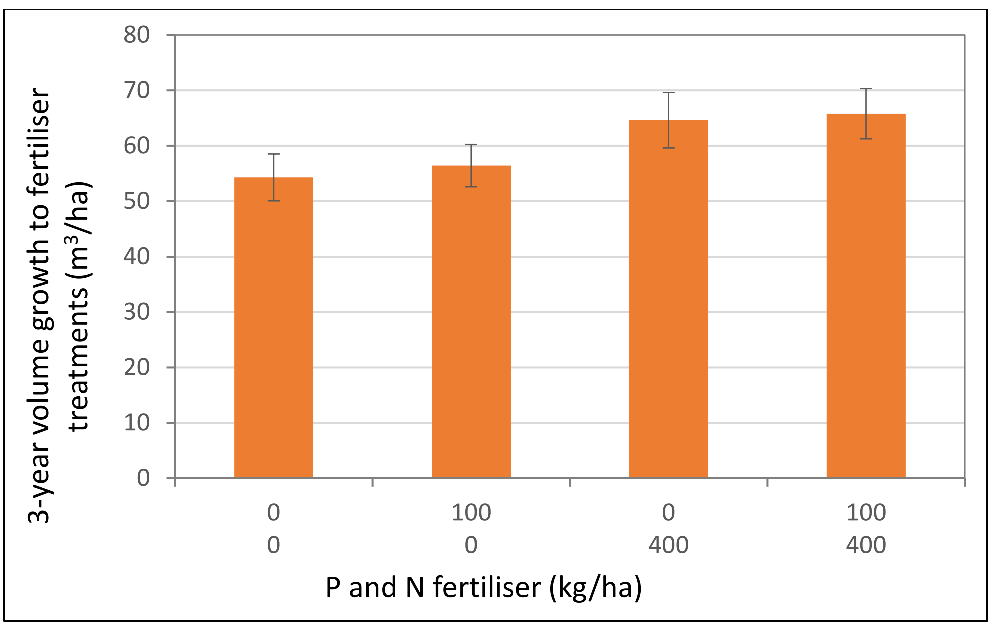


Figure 13. **Influence of P (upper value) and N (lower value) supply on overall growth. Error bars indicate standard errors of means.**

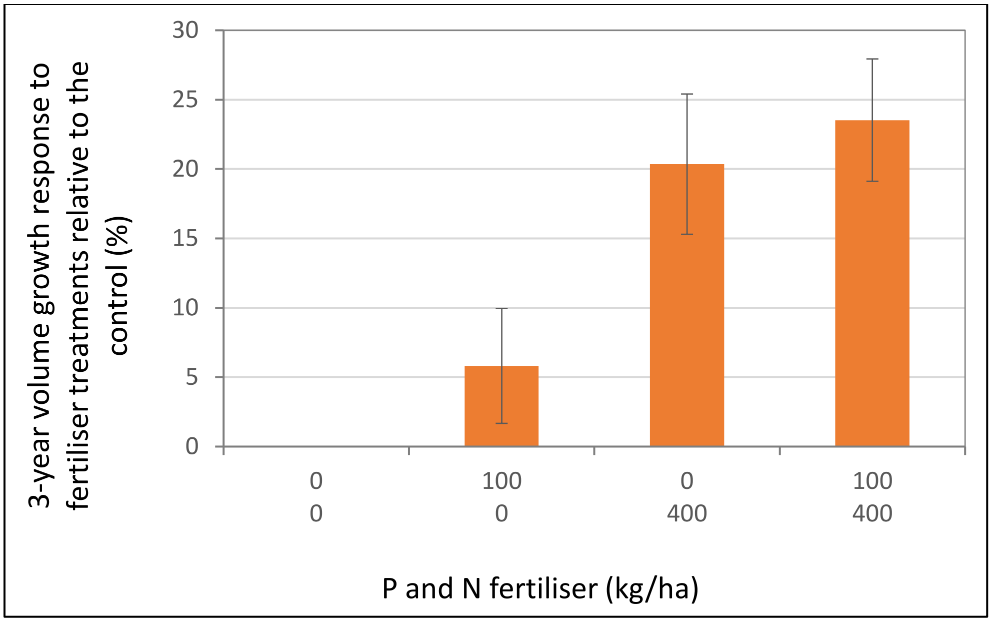


***Figure 14*. Influence of P (upper value) and N (lower value) supply on the percentage growth response to P and N application. Error bars indicate standard errors of means.**

The pattern of response with increasing nitrogen application varied between the sites (Figure 15). The response continued to increase with N rates up to 400 kg N/ha for 5 sites, at six sites there appeared to be a plateau between 50 and 100 kg N/ha and at the remaining three sites (Andrews, Fagan and Lyons) there appeared to be a decrease in response for 400 kg N/ha compared with 200 kg N/ha. The small negative response to 100 kg N/ha at Hays site is likely to be noise (error) as the overall response at this site was relatively small.

The average response to nitrogen (Figure 15, the dashed line) indicates that an overall response of 18%, was achieved with an application of 400 kg N/ha. However, the response to 200kg N/ha was not significantly lower than that to the 400 kg/N/ha application. The range in response to 400 kg N/ha was 5-40%, noting that the responses at the Lake Jasper Response trials were greater.

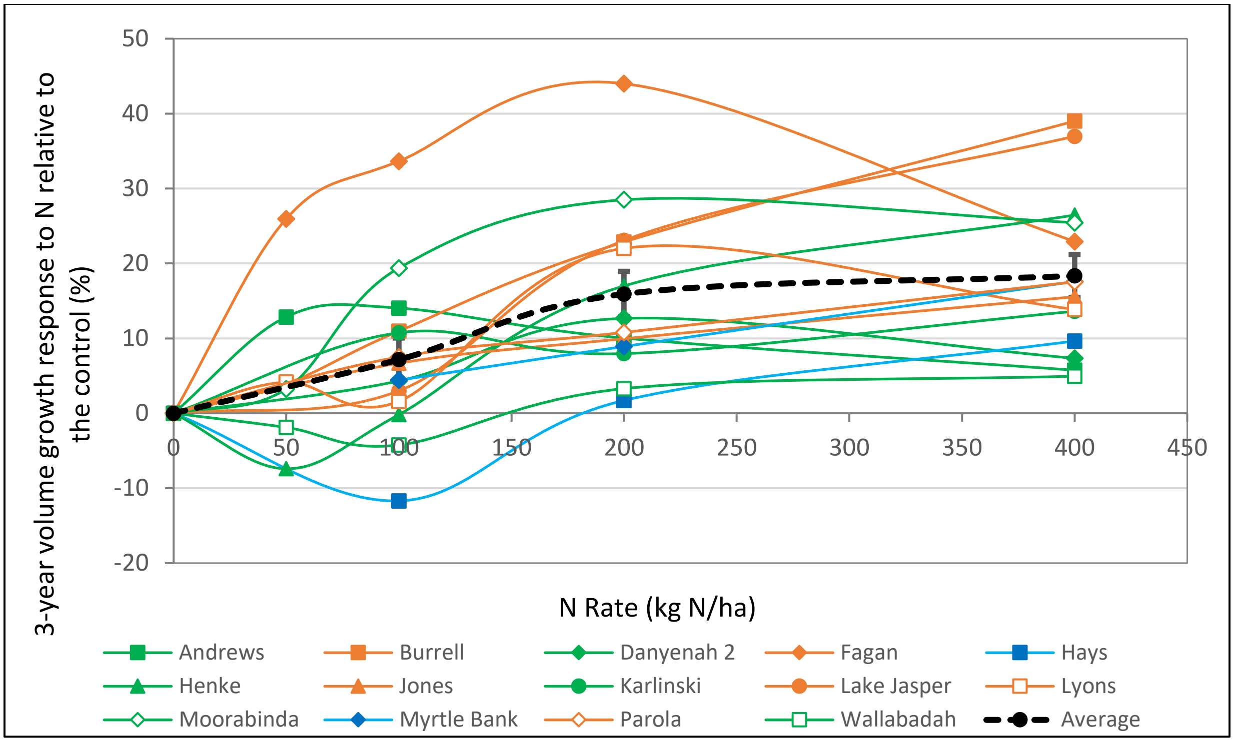


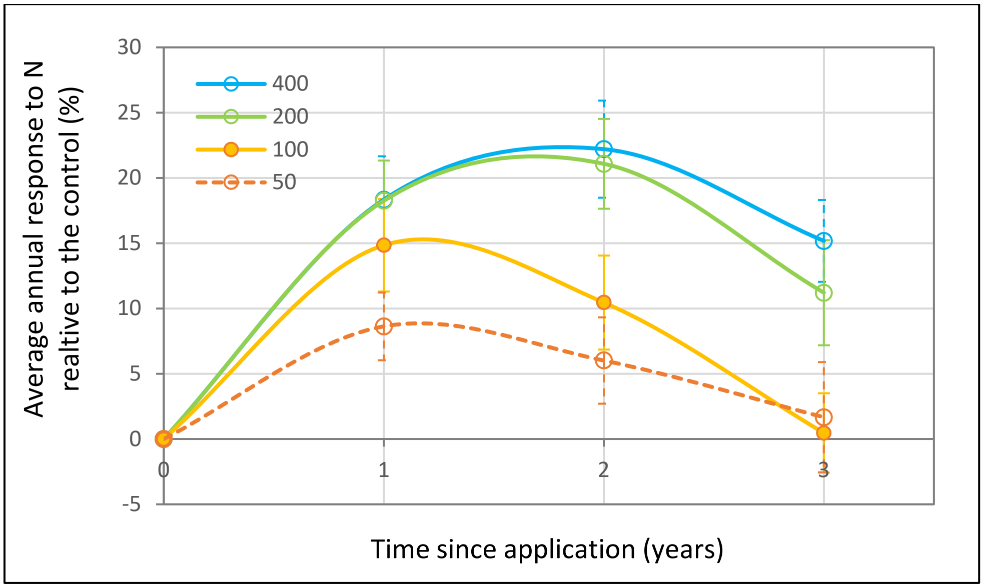
Figure 15. **Three-year volume responses to increasing nitrogen rates. Error bars indicate standard errors of values for the averages across all sites.**

Apart from influencing the overall response after 3 years, the rate of N application also appeared to influence the pattern of response over the three years since fertiliser application. The shapes of the average annual and cumulative response curves plotted against time since application varied substantially as the rate of N increased (Figure 16a and b). These relationships demonstrated that response to higher rates of N appeared to peak later and decline more slowly compared with lower rates of N (Figure 16 a and b). The peak response to the lower rates (50 and 100 kg/ha) occurred during the first year while at the higher rates (200, 400 kg/ha) the average peak response of 22% occurred during the second year (Figure 16a). By the third year after application, the annual response to the 50 and 100 kg/ha applications had disappeared, indicating that the response to lower applications only lasted two growing seasons. While the peak response to the 200 and 400 kg/ha applications was similar (~22%),the response also appeared to decline more rapidly for the lower (200 kg/ha) application (Figure 16a).

The decline in the cumulative % response after the first year for the lower rates and after the 2nd year for the higher rates (Figure 16b) was driven by the decline in the annual response to N over time. By 3 years, the cumulative response to N was 5% for 50 kg/ha compared with 18% at the highest (400 kg/ha) application. However, the time-course response charts indicate that the difference in responses between the higher and lower N rates is likely to increase over time. This means that optimising the response for N rate may require a minimum application of 200 kg N/ha.

The response to 400 kg N/ha was sustained over the 3-year period (16a). This response pattern demonstrated that the optimum application of 400 kg N/ha used in the response trials would have provided sufficient N to both maximize and sustain the response for at least 3 years.

a)



b)

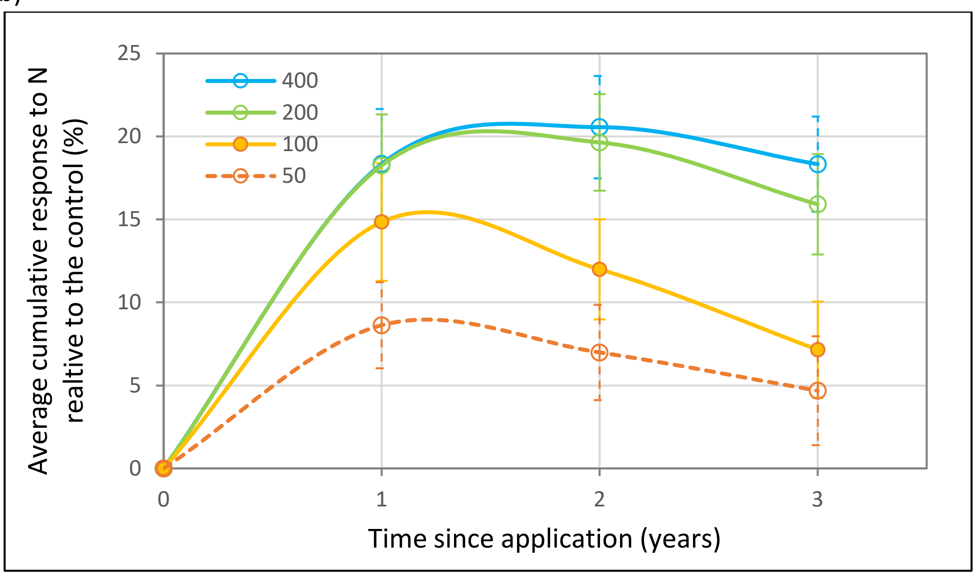


Figure 16. **(a) Annual percentage responses to increasing rates of nitrogen application in the three years after application and (b) Cumulative percentage responses to increasing rates of nitrogen in the three years after application. Error bars indicate standard errors of the means.**

Potassium responses

There were no significant responses to potassium at any of the 14 rates trial (Figure 17). This occurred whether adequate N and P were applied or when the supply of N and P was limited (data not shown).

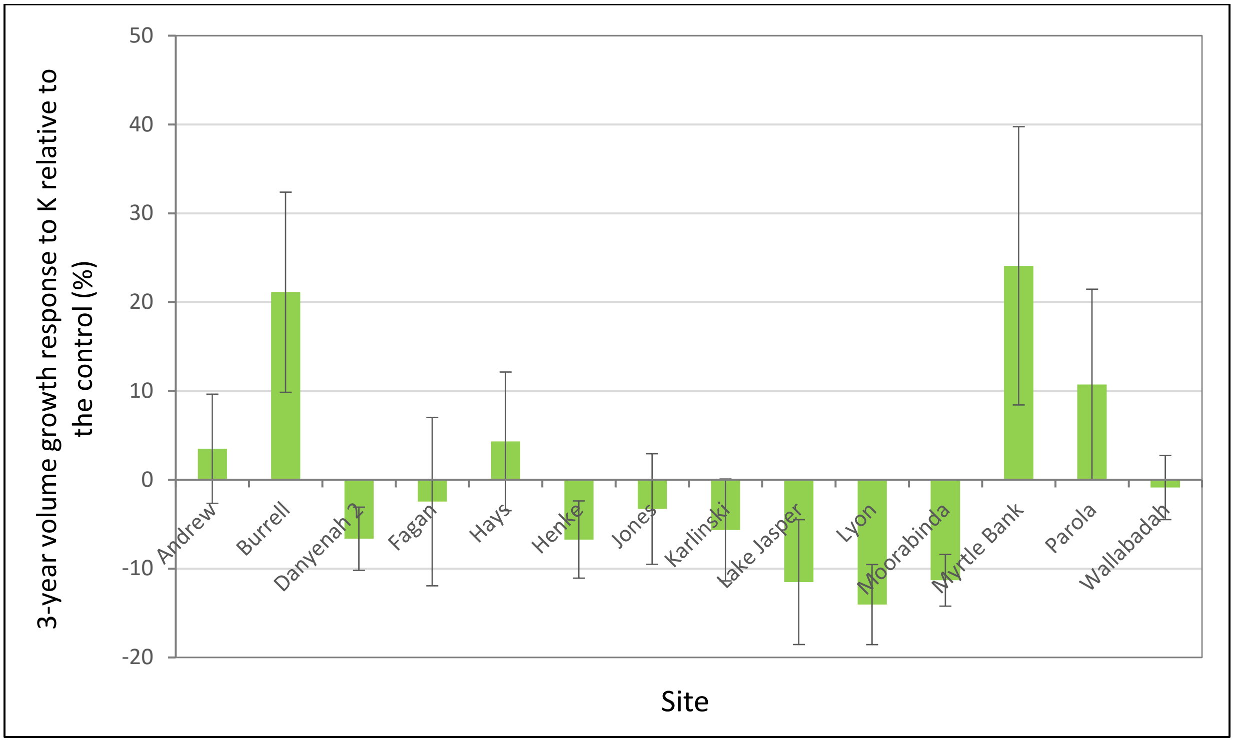


***Figure 17.* Response to the application of 100 kg/ha potassium. Error bars indicate standard errors of the means.**

Timing of fertilizer application

To assess whether single fertilizer applications at age 2 years (2018) or age 3 years (2019) influenced the response, paired trials were established at three locations in WA (Greville, Dingup, Lake Jasper). Due to logistic constraints, the fertilizers were applied on different dates in 2018 and 2019. Fertilizer was applied on 26/09/2018 at Greville, 13/09/2018 at Dingup and 05/11/2018 at Lake Jasper (Table 3). For 2019, all sites were fertilized in June, between 17/06/2019 and 24/06/2019 (Table 3). In addition to the variation in timing of fertilizer application, the weather conditions also varied with both 2018 and 2019 being drier at Greville and Dingup than 2020 and 2021 (Table 9). The rainfall at Lake Jasper was similar across all 4 growing seasons (rainfall varied from 996 – 1066 mm), though the CWI at Lake Jasper varied due to variations in the potential evaporation over the four years (Table 9).

The responses observed over three years post fertilization at Dingup (14 vs 16 m^3/ha) and Lake Jasper (63 vs 69 m^3/ha) were similar for the two years (Figure 8). This result contrasted with the Greville site where there was no response to the age 2 (2018) application compared with an increase of 45 m^3/ha with the age 3 (2019) application (Figure 8).

Table 9. **Monthly rain (mm) and evaporation (mm) for paired 2018 and 2019 response trials at Greville (a), Dingup (b), Lake Jasper (c). Highlights show the 3 months post application in 2018 and 2019**

(a)	2018/19		2019/20		2020/21		2021/22	
Month	**Rain**	**Evap**	**Rain**	**Evap**	**Rain**	**Evap**	**Rain**	**Evap**
June	83.7	35.9	130.5	53.2	130.6	45.5	105.9	39.1
July	130.5	56.8	78.4	36.7	113.6	45.1	174.3	51.1
Aug	159.2	49.9	101.4	63.1	77.4	56.1	105.7	56.5
Sept	35.9	70.2	35.9	80.5	108.1	78.8	89.9	79.2
Oct	43.6	100.8	28.5	125.3	31.1	139.1	90.3	91.8
Nov	11.1	117.8	23.3	172.3	77.9	129.9	11.1	147.9
Dec	20.2	193.9	3.6	249.2	8	200.1	6.9	231.2
Jan	5.9	202.3	10.9	218.6	2.1	256.7	0	247.9
Feb	0	175.3	13.1	185.2	84	159.2	4.3	210.1
Mar	34.6	135.3	31.9	147.5	22.6	133.8	20.6	162.5
Apr	38.8	89.1	38.8	86.8	91.7	94.3	32.8	91.9
May	23.2	50.9	123.8	59.1	111.5	53	100.1	64.2
Total	**586.7**	**1278.2**	**620.1**	**1477.5**	**858.6**	**1391.6**	**741.9**	**1473.4**
CWI		**0.46**		**0.42**		**0.62**		**0.50**

(b)	2018/19		2019/20		2020/21		2021/22	
Month	**Rain**	**Evap**	**Rain**	**Evap**	**Rain**	**Evap**	**Rain**	**Evap**
June	86.1	36.1	142	55.2	129.7	47.4	101.5	41.2
July	159.9	58.3	96.8	37.6	124.2	46	217.5	53.1
Aug	173.6	51.3	111.5	64.9	92.5	59	121.8	58.3
Sept	40.3	72	47.9	79.6	132.7	81.7	92.7	80.9
Oct	53.2	100.2	35.8	125.4	35.8	138.7	95.2	92.9
Nov	16.5	118.1	31.1	168.5	76.6	130.1	16.5	149.2
Dec	31.5	193.1	5.5	247.7	18.6	201	9.6	232.1
Jan	11.6	199.2	18.5	215.7	5.6	256.3	0.6	249.5
Feb	0.2	173.7	22.5	185.2	83.4	159.6	8.4	211.6
Mar	32.7	134.9	40.8	147.2	19.6	133.2	25.6	163.2
Apr	43.7	90.4	50.7	88.3	89.4	95.4	50.7	94.1
May	28.2	52.1	126.2	61.5	109.8	53.9	94.8	65.6
Total	**677.5**	**1279.4**	**729.3**	**1476.8**	**917.9**	**1402.3**	**834.9**	**1491.7**
CWI		**0.53**		**0.49**		**0.65**		**0.56**

(c)	2018/19		2019/20		2020/21		2021/22	
Month	**Rain**	**Evap**	**Rain**	**Evap**	**Rain**	**Evap**	**Rain**	**Evap**
June	183.8	35	228.2	59	116.6	51.4	183.9	45.5
July	270.6	62.4	126.6	41.5	162.1	49.3	225.6	57
Aug	211.8	54.6	135.9	67.2	105.2	63.8	144.3	60.7
Sept	54	74.8	73	76.5	128.9	86.3	95.5	84.4
Oct	57.8	102.2	66.6	126.3	35.7	143.2	121.6	96.5
Nov	26.1	118.9	28.3	167.4	83.3	130.9	18	155.2
Dec	27.5	191.1	11.6	244.9	8.1	206.8	9.4	233.2
Jan	20.7	195.1	32.1	214.5	8.3	258.4	1.5	253.6
Feb	2.4	172.4	36.1	186.7	83.8	163.9	24.4	216.2
Mar	26.8	133.6	65.6	150.8	20.6	131.5	39.4	166.7
Apr	63	90.9	47.5	91.5	91	98.3	85.9	99.2
May	51.2	57	155	67.6	162	56.7	116.8	69
Total	**995.7**	**1288**	**1006.5**	**1493.9**	**1005.6**	**1440.5**	**1066.3**	**1537.2**
CWI		**0.77**		**0.67**		**0.70**		**0.69**

It is difficult to make firm conclusions as to why the Greville site did not respond to the age 2 application. However, the age 2 (2018) application at this site on 26/09/2018 occurred after a relatively dry September and in an overall dry year (587 mm rain and CWI 0.46) (Table 9). The age 3 application also occurred in a dry year (620 mm rain, CWI 0.42). The difference was that the fertilizer at age three was applied in early winter and consequently had more opportunity to move into the soil profile and for the trees to absorb the applied nutrients. At the Lake Jasper site, the similar strong response to applications in both years suggests that, on this wetter site, the applied nutrients were accessible whether applied in winter or late spring. The similar modest responses in both years at Dingup suggested that the slightly earlier application at Dingup relative to Greville (~2 weeks) and the slightly wetter conditions at Dingup meant that the applied nutrients were accessible at Dingup.

Differences in rainfall over the three weeks prior to or after the application of fertilizer in 2018 did not appear related to the absence of a response at Greville in this year. At Greville, 18 mm fell prior to fertilization, and 38 mm fell in the 3 weeks after the application, totalling 56 mm. In comparison, at Dingup, 55mm fell prior to and 23 mm after fertilization (total 78 mm) and at Lake Jasper 28 mm fell prior and 24 mm after fertilization (total 52 mm). However, without being definitive it appears that applying nitrogen in spring under dry conditions may reduce the effectiveness of fertilizer, which would be expected also from a mechanistic viewpoint.

Relationships between stand growth and climate and soil and foliar parameters

Relationships between growth of fertilised stands and climate

To isolate the impact of temperature and water from variations in fertility, the productivity of the adequate/luxury fertilized treatments was used as the measurement of performance in relation to climate variables. There were strong variations in productivity across the 45 trial sites, which appeared to be related to temperature with increasing productivity associated with warmer conditions. (Figure 18).

The availability of water as measured by CWI has a strong influence on productivity with lower productivity generally associated with drier conditions. To illustrate the effects of CWI on growth and the interaction between CWI and temperature, the 37 sites were divided into two groups: CWI < 0.65 and CWI > 0.65. Within each of the CWI groups, temperature explained between 43% and 49% of the variation in growth of the fertilised treatments (Figure 18). Excluding two low performing sites (blue symbols) from the high-water availability cohort (CWI > 0.65) increased the proportion of variation explained to 72% (Figure 18 – grey line).

Of the two sites that were excluded, the Fagan site (WA) was waterlogged with significant understory competition and some tree mortality. Similarly, the rates trial at Lake Jasper grew more slowly than the nearby response trials and suffered some tree mortality, indicating that the site experienced water stress. The productivity of this site is similar to the productivity measured in the earlier nearby Drought Risk project site where there was considerable summer water stress and some tree mortality which was attributed to variable soil depth (White et al. 2009). This situation appears to likely be the case at the Lake Jasper rates trial. Based on the relationship where water is less limiting (CWI > 0.65), the three-year increment increased from 60 to 110 m^3/ha (or 60 to 130 m^3/ha with the water stressed sites excluded) over the temperature range from 14 to 22^o C (i.e. MAI from 20 to 37 m^3/ha/yr, or from 20 to 45 m^3/ha/yr). Therefore, the exclusion of these sites appears justified on the basis of soil factors which resulted in poorer than expected growth.

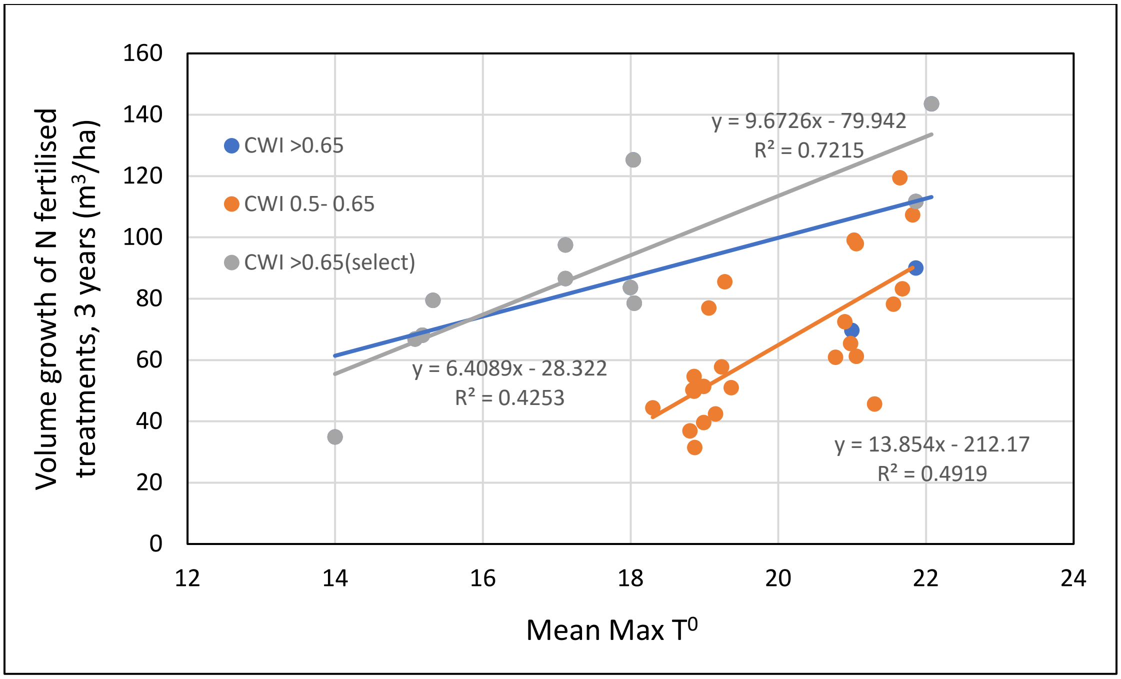


Figure 18. **Influence of temperature and CWI on the 3-year volume increment of adequately fertilized hardwood (includes data from both the rates and response trials).**

Relationships between response to N and soil and foliar N and climate

A key objective for the project is to identify diagnostic criteria for the observed nutrient responses. At this stage of the project only nitrogen fertiliser has provided statistically significant growth responses. Soil and foliage N concentrations were assessed together with climatic factors to determine if they provide useful indicators of the response to N. Data from the rates and response trial components of the current project and data available from previous fertilizer (historic, H) trials in WA have been used to assess the value of these indicators. Only soil N data was available from the historic trials.

There was a significant relationship between the response to N fertiliser and temperature with mean maximum monthly temperature over the 3 years post application explaining 13% of variation in % response (Figure 19). However, this relationship may have been influenced by the fact that there was a clear separation between the temperature regimes of the three regions in the study. Sites in Tasmania sites all had mean maximum temperatures < 18^{0}C, the Western Victoria/Green triangle sites had temperatures of 18 - 19^{0}C while the WA sites were all > 20^{0}C (Figure 19). Similarly, the Tasmanian sites tended to have the smallest responses to fertiliser (0-29%), while the WA sites tended to have the largest responses (0-130%).

There was no overall significant relationship between response to N fertiliser and soil N across the sites (r^2 of 0.02 with a P value of 0.4). However, there appeared to be a strong upper boundary to the relationship (Figure 20). However, while this boundary provides an understanding of the potential response it does not provide an understanding of the actual response for the majority of the trial sites, and hence it does not provide a useful indication of response to fertilizer. Based on the upper boundary approach, there would be no response when soil N was > 0.6%. The response increased linearly to ~170% as soil N decreased to 0.1% (Figure 20).

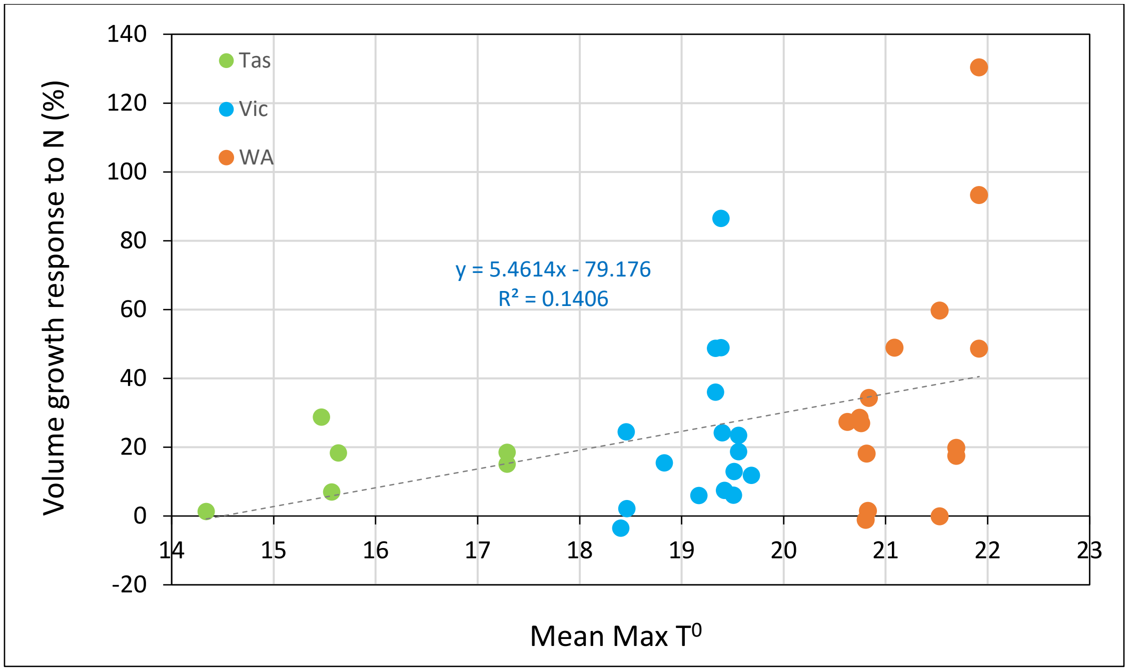


Figure 19. **Influence of temperature and CWI on the percentage volume response over 3-years post fertilization to an adequate fertilizer application (includes data from both the rates and response trials).**

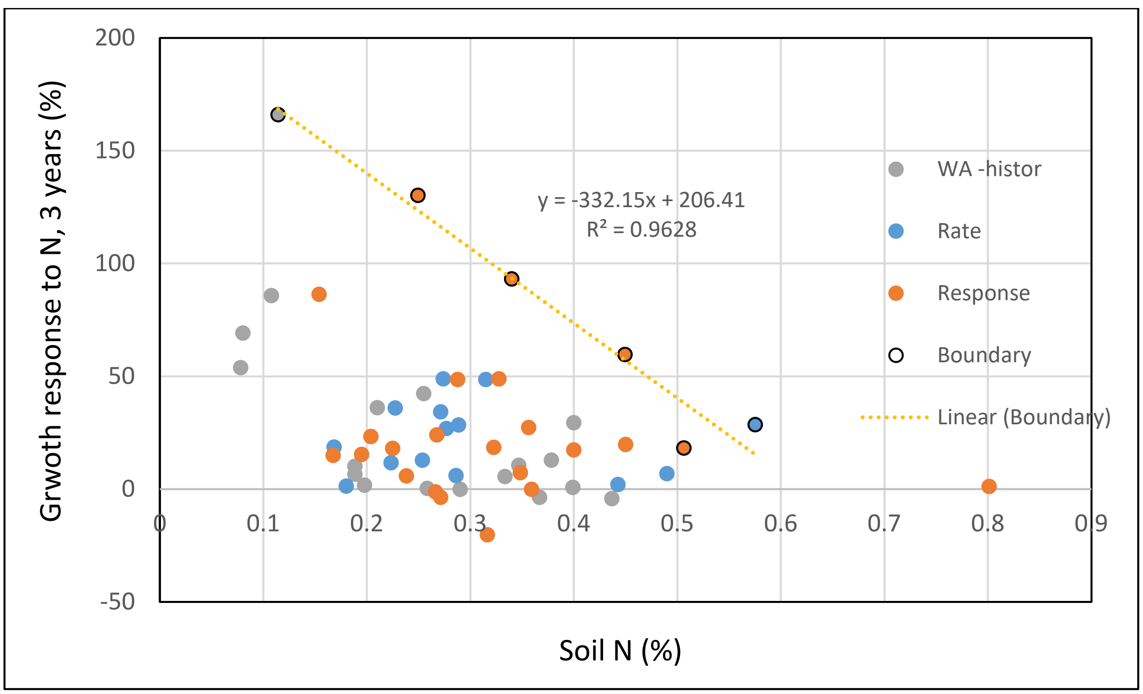


Figure 20. **Influence of soil N on the response to applied N with different data cohorts identified.**

By partitioning the response to soil N based on the temperature, the responses at low temperatures (i.e. Tasmania sites) were generally low, these sites also tended to have higher concentrations of soil N (Figure 21a). The response at the lowest soil N in the Tasmanian/low temperature cohort was ~18% relative to an observed maximum response of 95% at a similar soil N for the warmer sites (Figure 21a). Except for the high soil N data (soil N > 0.5%) the boundary to the N response is made up of data from the warmer WA sites (Figure 21a).

The relationship between response to applied N and soil C/N ratio is based on the current trials only as comprehensive soil data was absent for some of the historic trials. The relationship between soil C/N and response is the mirror image of the soil N data with larger responses at higher C/N ratios and as with the soil N response there was a strong upper limit to the response (Figure 21b). However, unlike the former, the relationship between response to fertiliser and soil C/N ratio was significant (P = 0.01) explaining 18% of variation across the sites. There was a similar separation in response between the regions as that observed for the soil N data. The Tasmanian sites demonstrated low responses, which may have been influenced by the low temperatures across these sites. The C/N ratio for the WA sites ranged from 10.3 to 19.3 and the maximum responses ranged from ~50% to 130% (Figure21b). The Victorian sites had a narrower C/N range (11.3 -13.0) and the maximum responses were similarly in a narrower band (49 to 87%, Figure 21b).

By partitioning the data based on three CWI cohorts (CWI > 0.7, 0.5- 0.7, <0.5), the impact of water availability on the response to applied N was assessed (Figure 22). None of the trials where the CWI was < 0.5 had a response near the maximum and the response for those were less than half that for the boundary relationship. While not completely clear, there was a strong tendency for trials with low CWI to have a low response to applied N relative to sites with higher water availability.

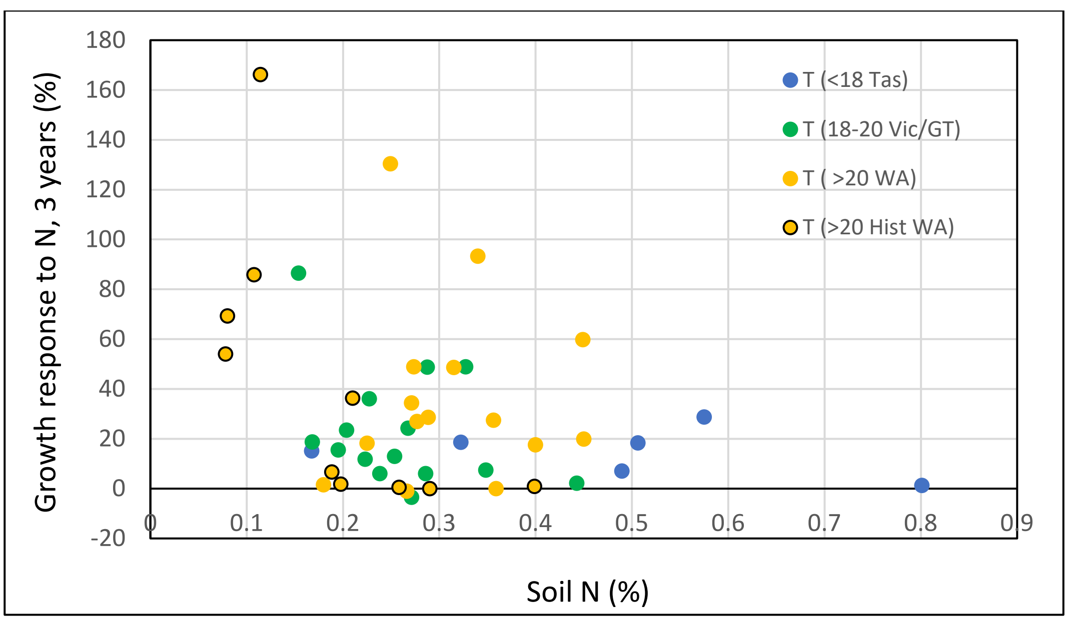


Figure 21a. **Influence of soil N and temperature on response to applied N.**

The response to applied N in relation to soil C/N ratio and water availability showed a similar trend to the responses in relation to soil N with the sites with low water availability tending to have low responses to applied N (data not shown). In contrast to the soil N data, the upper boundary contained data from across the range of water supply.

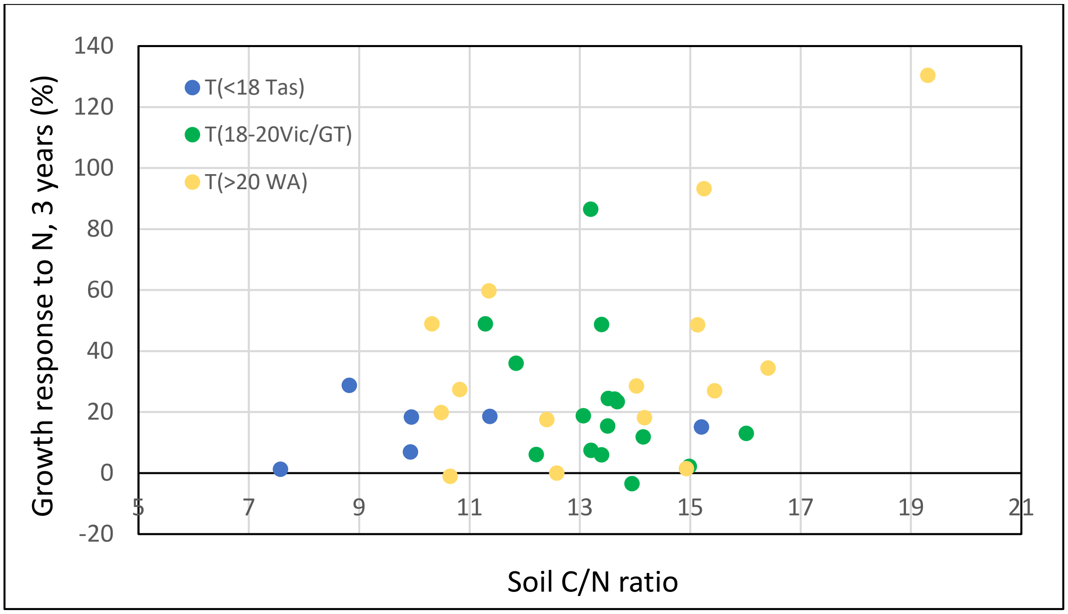


Figure 21b. **Influence of soil C/N ratio and temperature on response to applied N.**

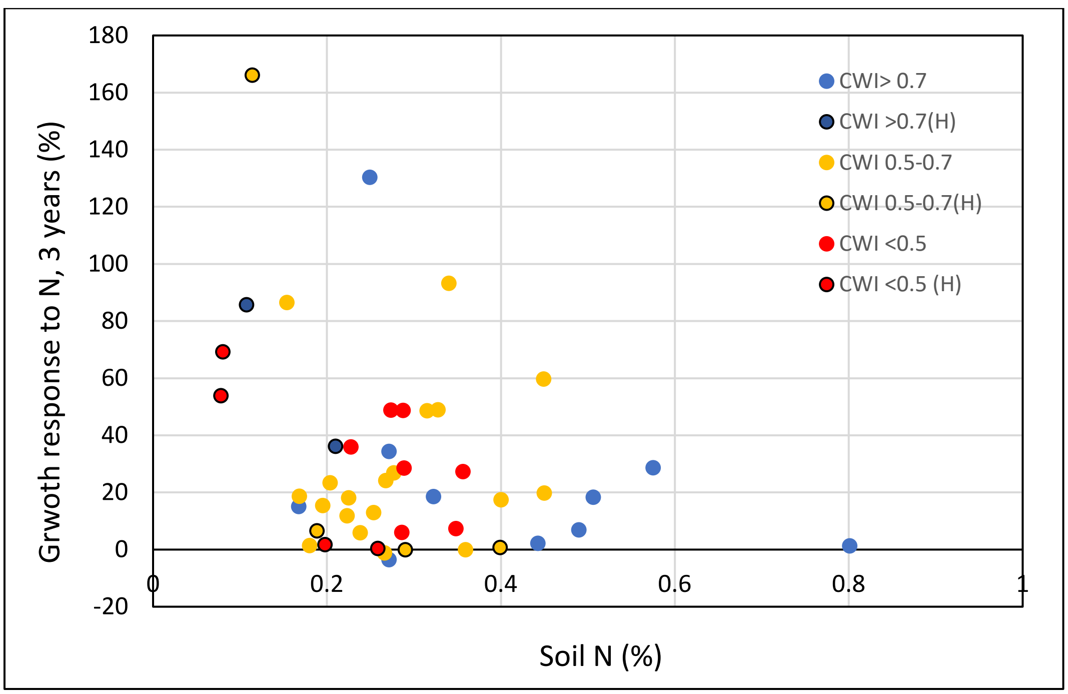


Figure 22. **Influence of CWI and soil N on response to applied N, note H = historic WA data.**

The largest percentage response in these trials occurred at a site with a medium CWI (166% response, 0.11% N Figures 21a, 22). This first rotation trial in WA was located at the foot of a long slope. It is likely that stored water from the previous agricultural land use and downslope movement of water contributed to the availability of water at this site. A paired trial upslope in the same location grew more slowly, suffered mortality in dry years and did not respond to applied fertilizer. A similar effect was observed in the *P. radiata* plantations in the steeply incised Blackwood valley region of WA where productivity was higher and the susceptibility to drought related mortality was lower in the lower slopes and valleys (water gaining positions) (McGrath et al. 1991)

While low CWI appears to contribute to the lower response, there remains considerable variation in these relationships. To isolate the influences of temperature and soil N from the influence of water availability on the response to N, data from the higher temperature WA sites (>20^{0}C) including both historic and current trials, were separated into two CWI categories and plotted against soil N (Figure 23). This categorisation demonstrated a separation between low and high-water supply and, with one exception, all the upper limits to the response were from relatively wet sites (Figure 23).

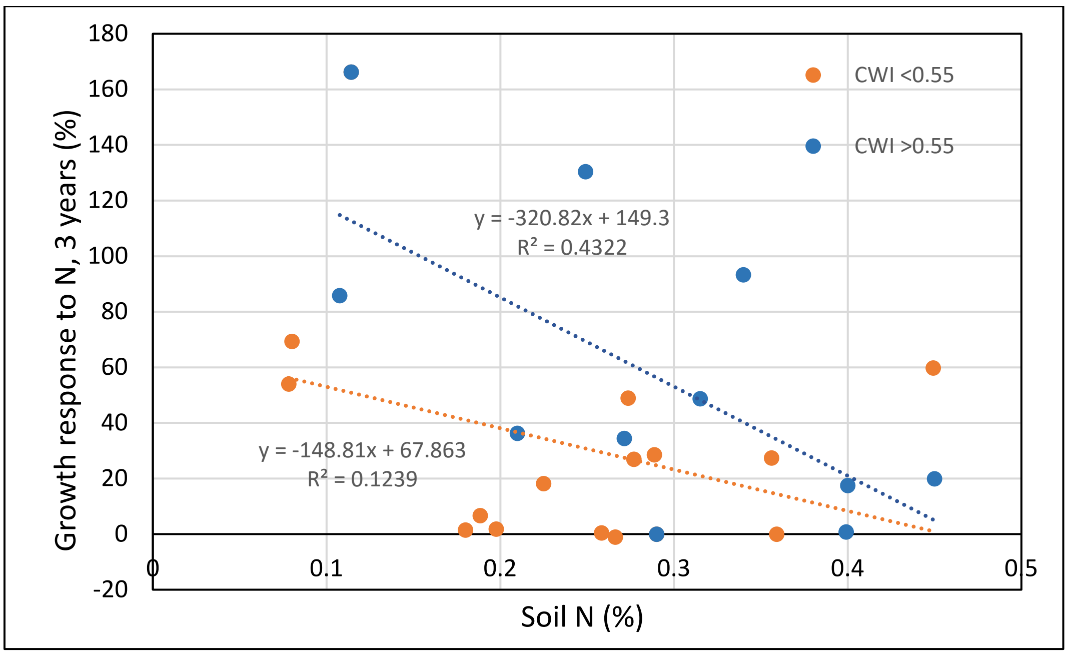


Figure 23. **Influence of CWI and soil N on the response to N, Temp >20^{0}C.**

In contrast to the large response observed at the first rotation site described above, the response at the highest rainfall trial in the Drought Risk trial series (Avery, Scott River) demonstrated an 85% response at 0.11% soil N (Figures 20 - 23). Despite the location of this trial on the Scott Coastal Plain (which has relatively high rainfall), significant summer water stress was observed in this trial due to variable and shallow soil depth (White et al. 2009), which presumably limited growth and the response to fertilizer. A similar variation in performance was observed between the three current trials located in the Scott River region (Lake Jasper trials), where the 3-year productivity of the three sites at the same location ranged from 90, 111, and 144 m^3/ha (CAI 30, 37, and 48 m^3/ha), with the lower value from the rates trial where the soil varied from sand to sand with a lateritic matrix, indicating variable soil depth. This was consistent with the variation in productivity observed at this site and dead upper canopies and some mortality observed in May 2022. These results indicate that CWI is only one of the influences on water availability with seasonal patterns of rainfall and PET, water storage capacity of the soil profile, topographic position and prior land use all potentially contributing to water availability.

It is clear that temperature and water availability influence the productivity of hardwood plantations and the response to nitrogen fertilizer (Figures 18 and 19). On warmer wetter sites in WA, soil N appeared to define an upper limit to the relative response to N fertiliser (R^2 = 0.96, Figure 20) or by a relationship between soil N and % response for the wet warm sites (R^2 = 0.43, Figure 23).

There was a statistically significant but modest relationship between foliar N concentration and the response to applied N (Figure 24). This excluded the Lake Jasper 18 site which had a far higher concentration (2.0%) than those for the adjacent plots from the same site which comprised Lake Jasper 19 (1.1%) and, when the Lake Jasper 18 site was removed, the relationship improved (r^2 increasing from 0.08 to 0.21). The trees for Lake Jasper 18 were sampled in November 2017 while those from the adjacent plots were sampled in June 2019, so it is possible that the difference may reflect seasonal variation in foliar N or that there was a problem with the earlier sampling.

The relationship between response to N and foliar N was independent of any influence from CWI (Figure 24). In contrast, temperature influenced the relationship between foliar N and response (Figure 25) with the relationship for sites with mean maximum temperature >20^{0}C explaining 46% of the variation (Figure 25). The relationship for the lower temperature sites was weaker and appeared to have a lower slope (Figure 25).

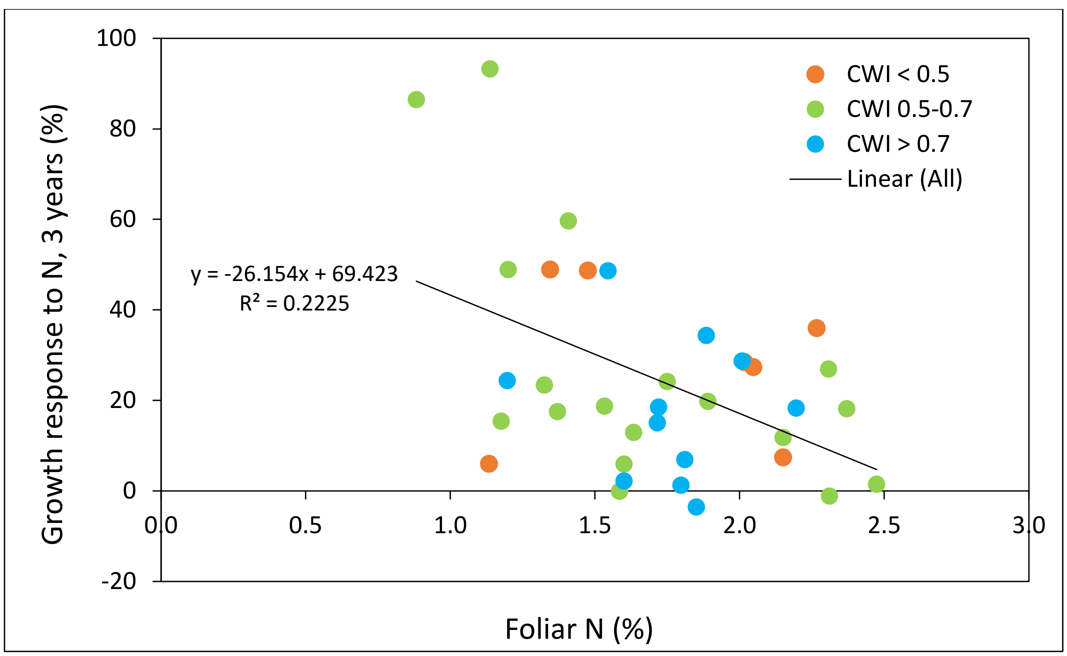


Figure 24. **Relationship between % growth response to N fertiliser and foliar N for the response and rate experiments broken down by CWI.**

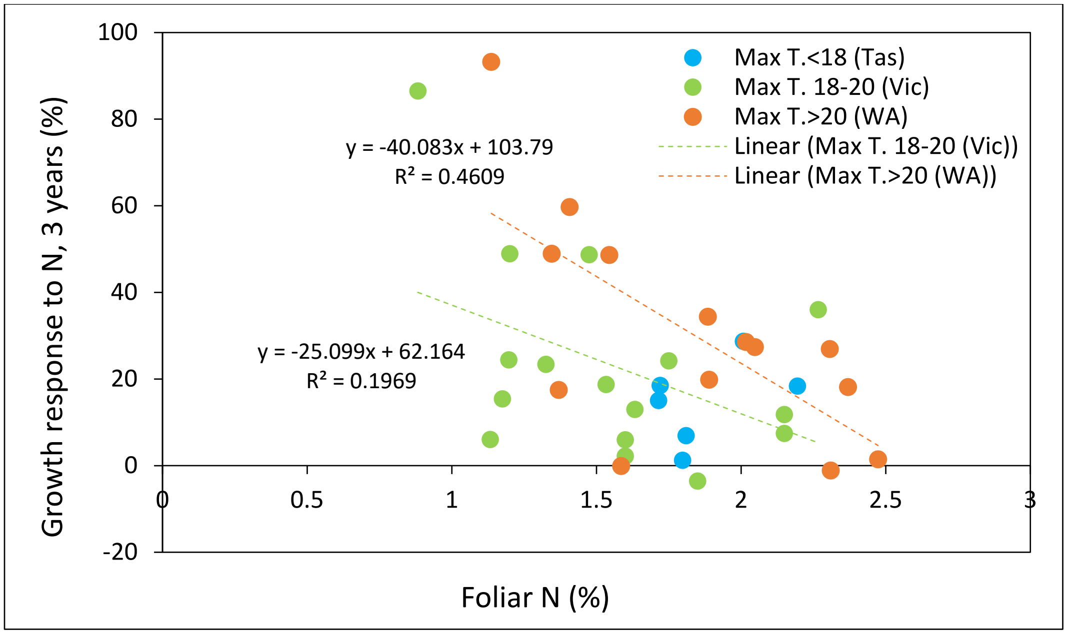


Figure 25. **Relationship between % growth response to N fertiliser and foliar N for the response and rate experiments broken down by mean monthly max. temperature.**

Soil and foliar N measure different attributes: soil N provides some measure of the capacity of the soil to supply N, while foliar N is a more direct measurement of the uptake and nutrient status of the trees and is linked to leaf area. In contrast, CWI and temperature are indicators of attributes of a site which can influence tree growth and, hence, nutrient demand. Additionally, both temperature and water availability will influence the availability of nitrogen to trees through impacts on the process of mineralisation of soil organic N into available forms. It therefore makes sense that response to fertiliser is influenced by multiple factors with soil and foliar N providing an indication of the supply of N to the stand and temperature and CWI providing an indication of the nutrient demand.

Foliar N provides an indication of the current N status of the stand and has been widely used in softwood plantations in Australia to predict potential responsiveness to N fertiliser (e.g. May 2009, 2017). Although it has been shown to be a useful predictor of growth response to N in eucalypt plantations (including *E. globulus*) overseas (Perdomo et al. 2007), this has not been shown to be the case in eucalypt plantations in Australia.

The reason for a lack of literature regarding the potential use of foliar N as a predictor of response to fertiliser in Australian *E. globulus* plantations may be due to several factors. Substantial seasonal and age-related variation in foliar nutrients in young eucalypts can make it difficult to find relationships which are stable over time or to determine the optimum time to collect foliar samples from trees (Saur et al. 2000, O'Brien et al. 2003, confidential unpublished report). Furthermore, it has been hypothesized that the rapid expansion of tree canopies in response to elevated nitrogen supply can effectively dilute foliar N concentrations making them relatively insensitive to differences in site N availability (McGrath Pers. Comm.). In the current study, the significant relationship between initial foliar N and subsequent growth response to fertiliser differs from previous findings and indicates that foliar N may in fact be a useful indicator. However, as with soil N, it needs to be considered in conjunction with other site factors including temperature, CWI as well as underlying seasonal or age-related variation foliar N.

Relationship between N availability and response to applied N.

Previous trials in WA suggested that soil nitrogen could provide a useful indicator of the response to nitrogen. The data from the current responsiveness and rates trials have been presented in a similar format (Figures 20, 21a). There appear to be modest relationships between the % response to an adequate application of N (400 kg N/ha) and both soil N (Figures 20, 21a, 21b) and foliar N concentration (Figures 24 and 25). There appears to be a strong upper boundary to the response to N with both soil N (Figure 20) and soil C/N ratio (Figure 21b, 22b). For soil nitrogen, no response occurred above ~0.6% soil N and the potential response increased as soil N decreased below this limit. Similarly, there was no response to applied N when soil the C/N ratio was less than seven with the potential response increasing as the C/N ratio increased. One significant difference is that there were more low responses in the data from the previous trials. This had previously led to the conclusion that the response to N ceased at ~0.3% N (McGrath and Mendham 2022). Based on the more recent data this limit appears to be >0.6% N.

It is important to note that, while total soil N is often related to N availability, only a small proportion of total soil N is released at any given time in a mineral form that can be readily taken up by plants (Keeney 1982). Therefore, a range of indices of N mineralization rates have been tested for measuring the capacity of soils to supply N to plants (Adams and Attiwill 1986, Carlyle et al. 1998; Moroni et al. 2004). Although, total N can be a useful indicator of N availability, the relationship can vary with previous land-use as well as soil type (Carlyle et al. 1990, Connell et al. 1995, Wang et al. 1996). Furthermore, samples collected from the surface 10 cm of soil may not reflect the total availability of N throughout the soil profile. As demonstrated in the current analysis, Soil C/N ratio can provide a more sensitive indicator of N availability than soil total N due to the closer relationship between N mineralisation rates and C/N ratios in soils (Jannsen 1996).

As outlined above, the performance of the plantations appeared to be influenced by both temperature and water supply. The volume growth of the optimum fertilizer treatment in relation to CWI (Figure 18), demonstrated that, as CWI increased in WA and Vic/GT, there was an increase in productivity. This trend was not evident in the Tasmanian data. The absence of an increase in productivity with increasing CWI in Tasmania is likely due to the higher rainfall and lower evaporation, and hence higher CWI, meaning that, at least in the early stages of the rotation, water supply did not limit productivity. In the multiple regressions, limiting the maximum CWI to 1.1 provided the best contribution from this variable to the regressions.

Normalized difference vegetation index

Normalized Difference Vegetation Index (NDVI) derived from satellite (Sentinel 2) data was tested to assess a) whether there were identifiable changes in NDVI due to fertilization and b) whether it could be used either alone or in conjunction with foliar N to predict response to fertilizer. As explained, one of the issues with using foliar N as an indicator of the N status of plantations, is the potential dilution effect associated with canopy expansion. It is possible that taking foliage mass or area into account together with foliar N concentration could provide a better predictor of potential responsiveness to N fertiliser than foliar N concentrations alone. NDVI is related to the health and cover of tree canopies and so could potentially improve the power of relationships predicting response to N.

NDVI or closely related measures derived from satellite data such as SVI (Spectral Vegetation Index) have been related to leaf area, vegetation cover and productivity across a wide range of broad leaved and needle leaved species generally (Cohrs et al. 2020; Buermann et al. 2002, Chen et al. 1996, Wang et al. 2005) and for eucalypt forests and plantations specifically (Coops et al. 1997; le Maire et al. 2012). The relationships tend to be non-linear with NDVI tending to saturate (i.e., reach a plateau) for high LAI's. However, overseas research has identified leaf area as an important factor for determining the responsiveness of *Pinus* stands to fertiliser (Albaugh 1998; Fox et al. 2007) and the use of satellite imagery for predicting both leaf area and response to fertiliser has been successfully tested in these stands (Flores et al. 2006).

No relationship between NDVI and leaf area has yet been published for *E. globulus* or *E. nitens* plantations. However, given the wide acceptance of NDVI as an indicator of leaf area in forests globally, it was considered likely that NDVI could provide a reasonable, cost-effective means of estimating leaf area and response to fertiliser in these plantations.

As explained in the methodology, there was considerable variability in the raw NDVI data. This was presumably due to clouds not being satisfactorily removed by the cloud mask layer provided by the ESA (European Space Agency) for use with the underlying reflectance data for all wavelength collected by the Sentinel 2 satellites (Coluzzi et al. 2018). Even after removal of obvious outliers, some variation remained. Because of this 'noise' combined with the large amount of data removed due to cloud effects (e.g., 30-60% of images were removed from the datasets for some sites) it was decided to only use annually averaged data.

There was a significant relationship between NDVI and underlying growth of the controls with average NDVI for 2019 explaining 32% of variation in growth over the three-year period from 2019-2022 (Figure 26). The relationship was strongest for sites in WA and Victoria (r^2 = 0.38-0.40) with no relationship for the 6 Tasmanian sites (r^2 = 0.00). This relationship is consistent with results from other studies which show that NDVI can be a useful indicator of stand productivity in eucalypt plantations overseas (Marsden et al. 2009). However, this is the first published evidence, to the authors' knowledge, that NDVI is correlated with the growth of *E. globulus* plantations in Australia.

To assess whether NDVI was sensitive to changes in stand nutrition and response to fertiliser, the relative difference between NDVI for the fertilised treatments and controls, three years after fertiliser application was plotted against the 3-year % growth response. There was a significant relationship between the % volume growth response and % NDVI response across the 37 sites (r^2 = 0.37, Figure 27). This suggests that the primary driver for the increase in growth was the increase in canopy cover and greenness of the trees and that NDVI calculated from S2 satellite imagery may be a useful measure of canopy health and response to fertiliser. The fact that NDVI appears to be a useful indicator of a primary driver of growth combined with the fact that the difference in NDVI between fertilised and unfertilised plots reflects the growth response to fertiliser suggest that it could potentially be a useful parameter in predicting response.

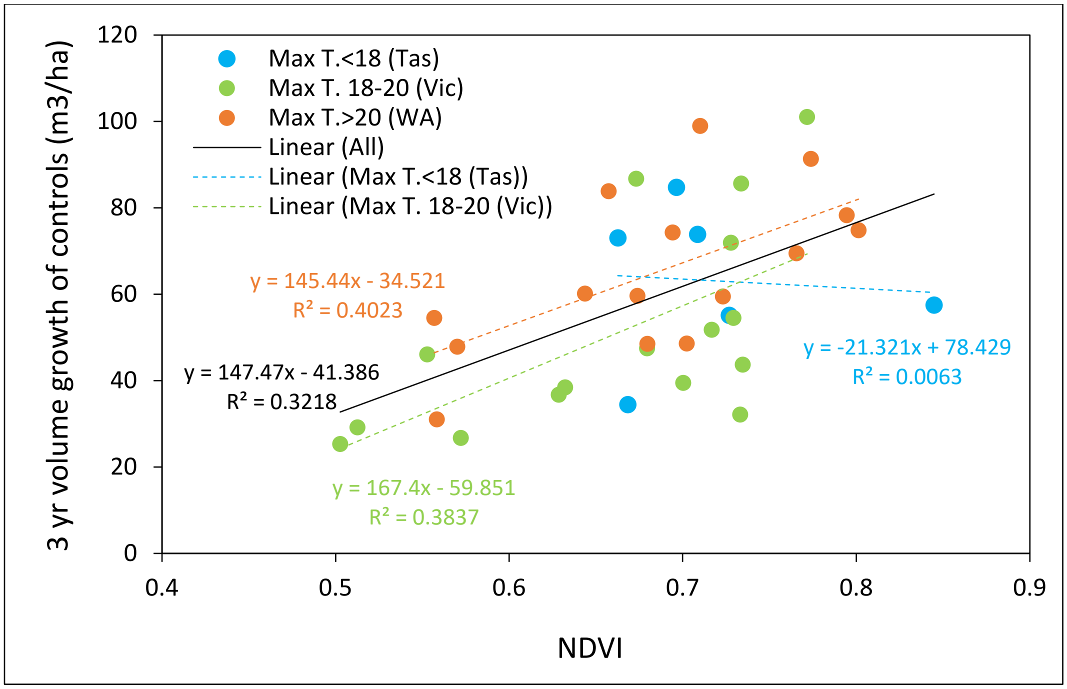


Figure 26. **Relationship between volume growth of controls for the period 2019-2022 and average NDVI for 2019 for the 37 fertiliser response and rate experiments broken down by mean monthly max. temperature.**

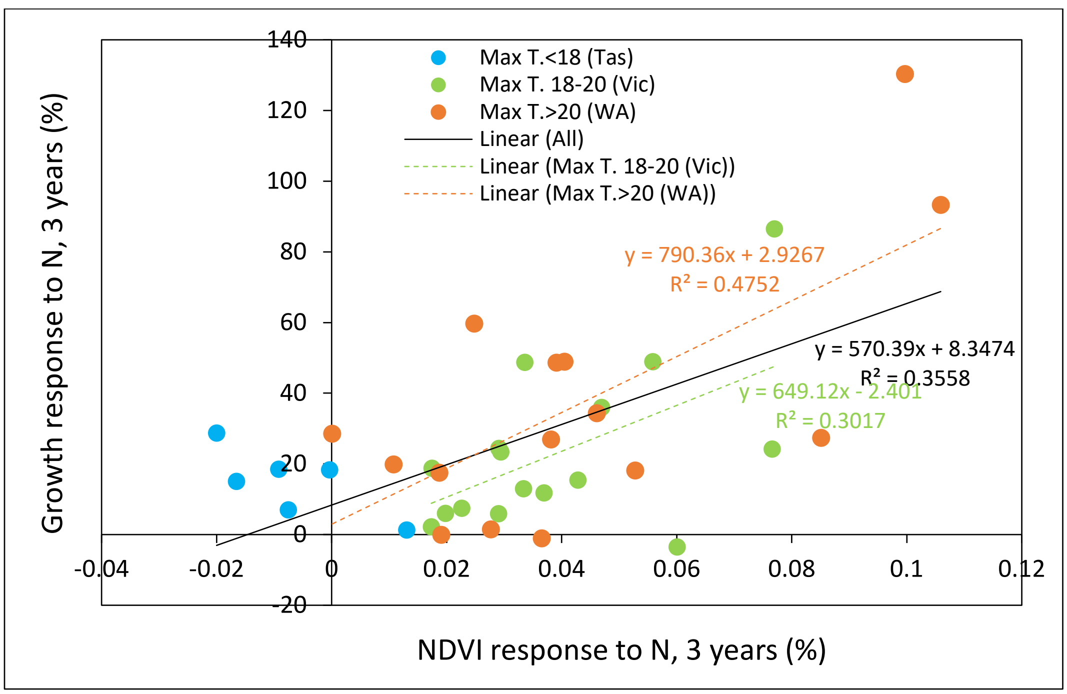


Figure 27. **Relationship between the % growth response to fertiliser and % increase in NDVI for fertilised treatments relative to controls for the first 3 years categorised by mean monthly max. temperature.**

However, NDVI alone was not significantly related to growth response to fertiliser. Average NDVI for 2019 (the earliest year that data was available) around the time of fertiliser application explained only 2% of variation in the subsequent 3 year % growth response to N fertiliser overall (Figure 28) and there was little improvement if the sites were split by maximum temperature.

In contrast, combining initial NDVI (for 2019) with initial foliar N (i.e., NDVI x foliar N concentration) to provide an indicator, termed here an 'index of canopy N content', explained 27% of variation in subsequent response to N fertiliser (Figure. 29). Furthermore, when variation due to differences in temperature were accounted for this index explained 42% of variation in response for sites with a mean max temperature of 18-20 °C (Victorian sites) and 59% of variation in response for sites with a mean max. temperature of > 20 °C (WA sites). Thus, combining NDVI with foliar N increased the % response explained by 13-22% for these two regions. However, as with other variables, there was no significant relationship between the index of canopy N content and response for the 6 Tasmanian sites (max temperature < 18°C).

It is important to note that while the values for NDVI used here are from the controls, they do not strictly cover the period prior to fertiliser application. Because no Sentinel 2 data was available prior to December 2018, the values for all sites are the averages for 2019. Hence, for sites fertilised in 2019 the averages include data collected 2-4 months post-application, while for sites fertilised in 2018, the entire 12-month period is post-application. Due to the observed increase in NDVI over time at some sites, it is likely that pre-fertiliser NDVI values would have been lower than those used here, especially for those sites fertilised in 2018. In the next phase of the project, we will test whether the relationships reported in this study can be improved by examining data from other satellites, such as Landsat, which cover earlier time periods.

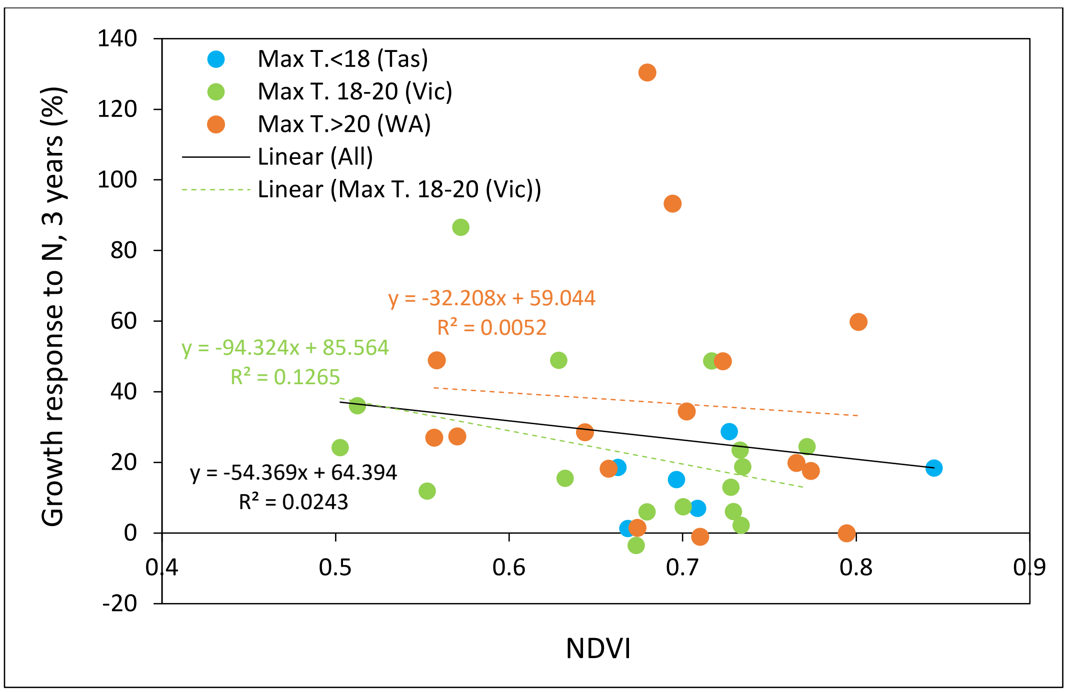


Figure 28. **Relationship between % increase in volume growth and average NDVI measured in 2019 split by mean maximum monthly temperature.**

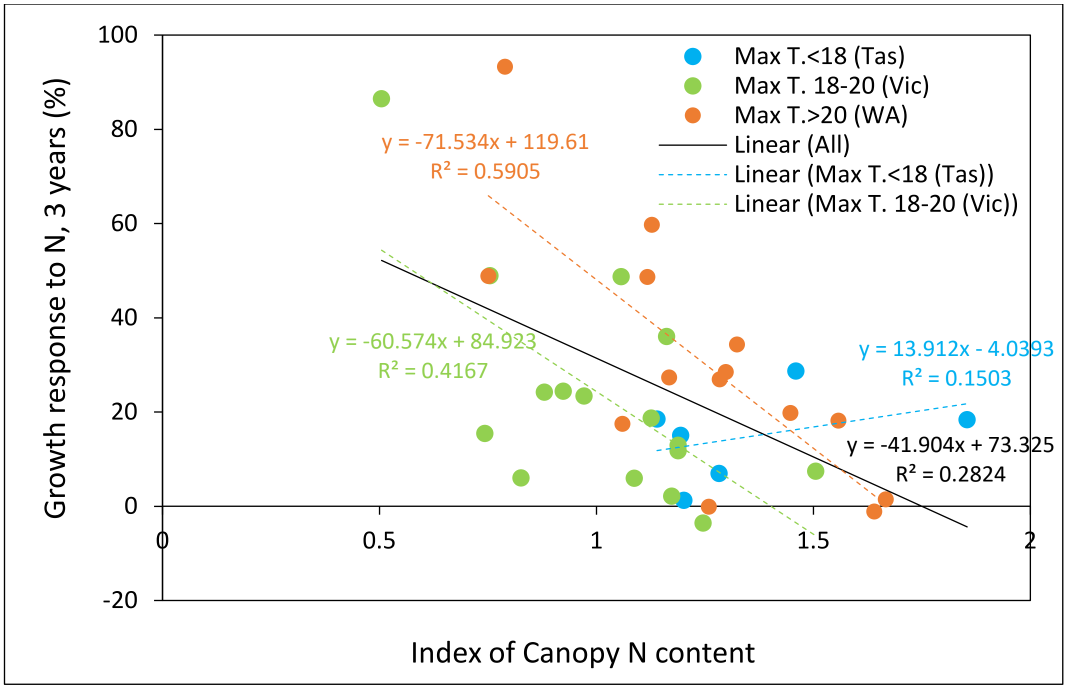


Figure 29. **Relationship between % increase in volume growth and average Index of Canopy N Content (NDVI x Foliar N) split by mean maximum monthly temperature.**

To evaluate stability of NDVI over time, as well as its sensitivity to fertiliser, the time course of NDVI was analysed over the 3 years since fertiliser application for controls and fertilised treatments. The average NDVI values for controls and fertilised treatments over the 3 years for each of the sites are shown in Tables 10a and 10b. Charts of time course NDVI data for selected sites are shown in Figures 30 - 32.

There was a strong seasonal trend in NDVI at most sites with it tending to peak in June each year and falling to a minimum in December. There was also a significant difference in NDVI between fertilised treatments (N400P100) and the control (N0P0) at many sites in the years following fertiliser application with average differences over 3 years ranging from -2.5% at Hays to 14.1% at Lake Jasper 19. Student T tests indicated that these differences were significant ($P < 0.05$) at 19 of the 37 sites and marginal ($P < 0.1$) at a further 8 sites (Tables 10a and 10b). While the relative differences in NDVI between the treatments appear small, it should be noted that the baseline for NDVI for these sites will be greater than zero (i.e. where there are no trees, NDVI may be around 0.1-0.2). Therefore, the relative difference is likely to be much smaller than the actual change in canopy cover and greenness. It is likely that the NDVI measurements in this study include background "greenness" from grasses and understory species, which vary seasonally. Investigation of the reasons for the variation in NDVI is required to assess whether issues such as seasonal growth in the interrow and sun angle influence NDVI measurements.

The charts for NDVI data over time illustrate the temporal patterns of NDVI and show the impact of fertilization over the 3 years following fertilization for different sites. There were no significant NDVI responses at any of the Tasmanian sites (Table 10). The Erriba site showed a 1.3% growth response and a 2.5% NDVI response to fertiliser which was not significant (Figure 30). These latter results were likely influenced by a steep decline in NDVI for the control treatment in December 2021 which can be attributed to residual noise in the data.

Table 10. **Average NDVI values for controls and N400P100 treatments across the 23 fertiliser responsiveness trials and 14 rates trials over the 3 years post fertiliser application. For the rates trials the values are averages for controls (treatments 1 &2) and N400P100 (treatments 9&10). Dark green highlights indicate differences between treatments at P < 0.05 and light green at P < 0.10.**

Site	Trial Type	Region	Avg.		Std. Dev.		Rel. Diff	P(Diff)
			N0P0	N400P100	N0P0	N400P100	%	
Erriba	Response	Tas	0.669	0.682	0.141	0.050	1.9	0.862
Preston	Response	Tas	0.842	0.841	0.006	0.004	0.0	0.925
Railton 1	Response	Tas	0.801	0.784	0.045	0.031	-2.1	0.543
Railton 2	Response	Tas	0.833	0.824	0.012	0.032	-1.1	0.588
Annadale	Response	Vic	0.748	0.782	0.028	0.018	4.5	0.046
Convey	Response	Vic	0.834	0.863	0.016	0.012	3.5	0.004
Cowland	Response	Vic	0.757	0.800	0.009	0.008	5.7	0.000
Danyenah 1	Response	Vic	0.766	0.796	0.020	0.006	3.8	0.005
Gumbough	Response	Vic	0.771	0.793	0.026	0.034	2.9	0.288
Lindsay	Response	Vic	0.674	0.751	0.017	0.037	11.4	0.000
Meade	Response	VIC	0.774	0.834	0.021	0.009	7.8	0.000
Pepper	Response	Vic	0.728	0.784	0.008	0.010	7.7	0.000
Smith	Response	Vic	0.694	0.771	0.015	0.026	11.0	0.000
The Springs	Response	Vic	0.787	0.816	0.024	0.010	3.7	0.025
Dingup 18	Response	WA	0.791	0.802	0.012	0.019	1.4	0.439
Dingup 19	Response	WA	0.812	0.831	0.005	0.008	2.3	0.059
Greville 18	Response	WA	0.805	0.824	0.009	0.010	2.4	0.100
Greville 19	Response	WA	0.816	0.841	0.013	0.007	3.0	0.084
Lake Jasper 18	Response	WA	0.725	0.825	0.026	0.009	13.8	0.019
Lake Jasper 19	Response	WA	0.749	0.855	0.024	0.008	14.1	0.013
Ocallaghan	Response	WA	0.786	0.838	0.015	0.019	6.7	0.050
Triangulee	Response	WA	0.685	0.771	0.036	0.019	12.4	0.052
Wisbey	Response	WA	0.824	0.861	0.016	0.015	4.4	0.077
Hays	Rate	Tas	0.810	0.790	0.038	0.030	-2.5	0.363
Myrtle Bank	Rate	Tas	0.809	0.802	0.023	0.019	-0.9	0.572
Andrews	Rate	Vic	0.735	0.772	0.029	0.024	5.0	0.075
Danyenah 2	Rate	Vic	0.770	0.787	0.005	0.008	2.3	0.010
Henke	Rate	Vic	0.796	0.830	0.011	0.012	4.2	0.007
Karlinski	Rate	Vic	0.832	0.849	0.020	0.019	2.1	0.196
Moorabinda	Rate	Vic	0.740	0.787	0.019	0.034	6.3	0.041
Wallabadah	Rate	Vic	0.733	0.753	0.008	0.019	2.7	0.076
Burrell	Rate	WA	0.675	0.715	0.027	0.012	6.0	0.027
Fagan	Rate	WA	0.751	0.797	0.019	0.011	6.1	0.007
Jones	Rate	WA	0.720	0.758	0.011	0.015	5.3	0.007
Lake Jasper	Rate	WA	0.775	0.814	0.016	0.012	5.0	0.008
Lyons	Rate	WA	0.759	0.759	0.028	0.030	0.0	0.995
Parola	Rate	WA	0.738	0.765	0.011	0.011	3.8	0.012

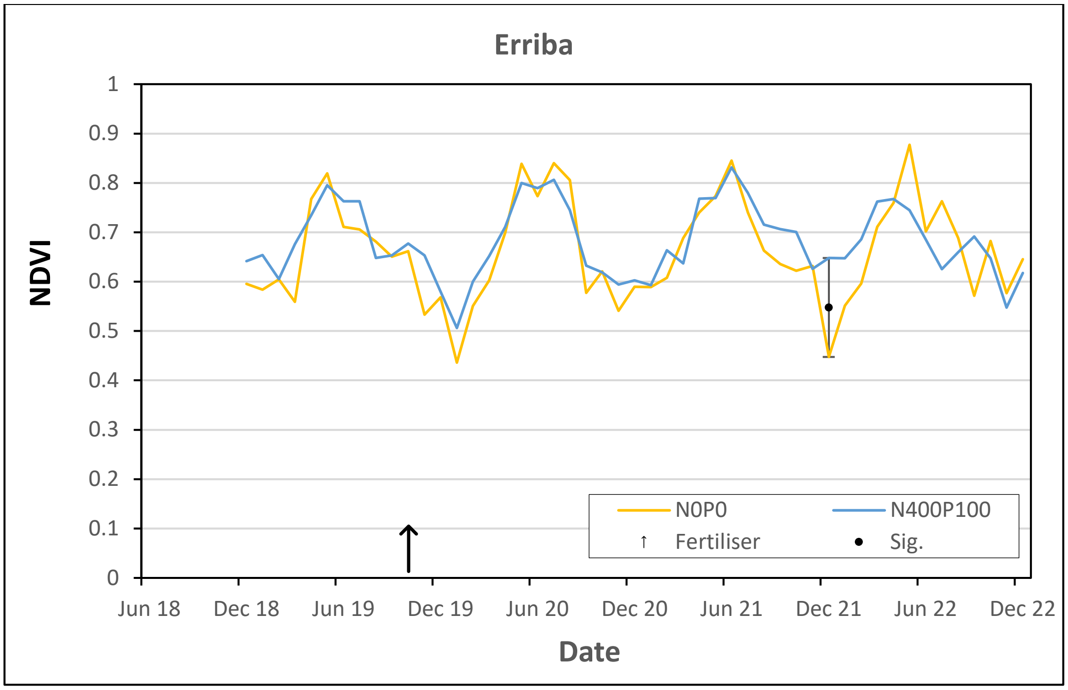
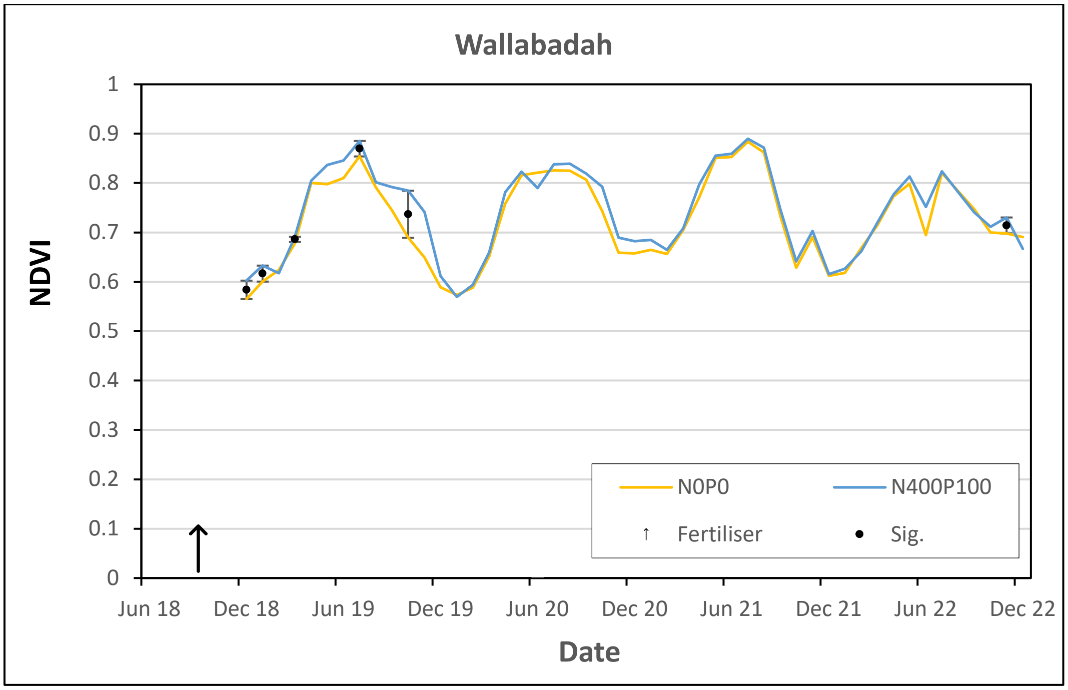


Figure 30. **Influence of season and fertilization on NDVI for a non-responsive Tasmanian site: Erriba. Note: the arrow indicates the time of fertiliser application while the error bars indicates the date when the differences between reflectance of the fertilised and unfertilisd treatments were significant.**

The NDVI trends over the three-year period at Wallabadah, a non-responsive site, and Lindsay, a responsive site in Victoria, exhibited the same distinct seasonal pattern evident at the Erriba site with maximum values in winter and minimum values in summer (Fig. 31a and 31b). Despite a 3% increase in NDVI and a 6% increase in volume growth at Wallabadah, neither of these changes were statistically significant. It is worth noting that the growth of trees in response to nitrogen was initially significant, as was the increase in NDVI in the first year following fertilizer application. However, this response diminished over time, and by the third year, there was no significant difference in cumulative growth for the different treatments, indicating the disappearance of any response to fertilization. At Wallabadah the CWI for the growing seasons in the three years post fertilization averaged 0.42 indicating that water was likely a more limiting factor for tree growth there compared to other sites. Therefore, the initial increase in canopy cover was probably unsustainable, limiting the longer-term response to fertilizer.

In contrast to the Wallabadah site, the NDVI response to fertilizer at the Lindsay site gradually increased over time, peaking at approximately 15% in the second year while the average growth of the fertilised trees was 87% greater than the control. The CWI for the period was 0.54 at this site, compared to 0.42 at Wallabadah, indicating that water was less limiting to growth.

a)



b)

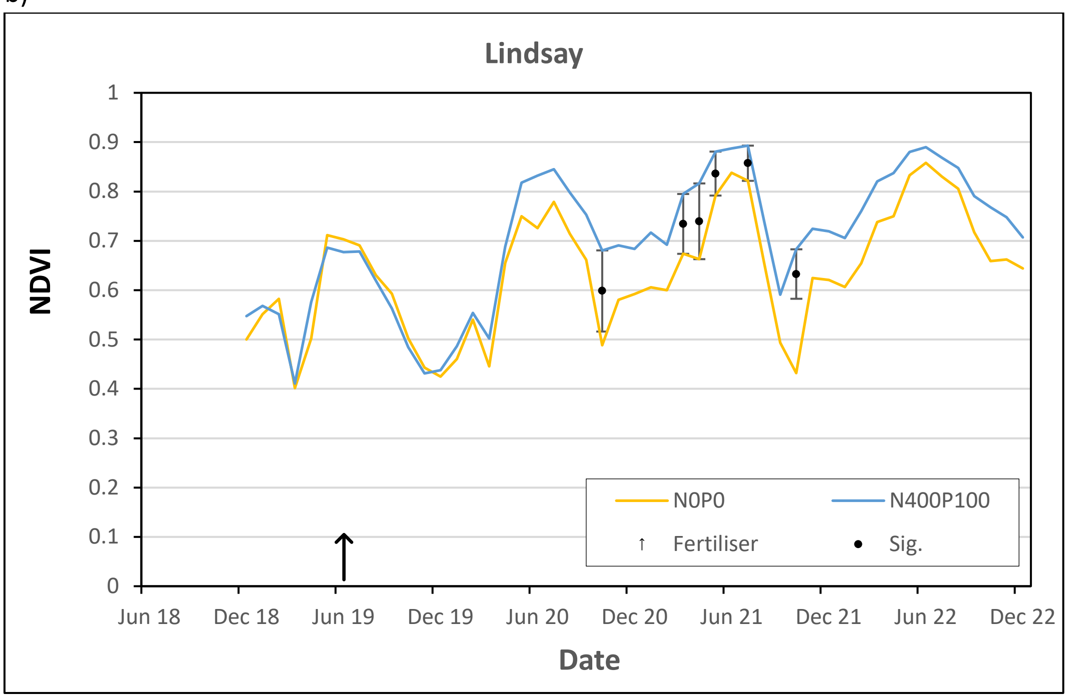
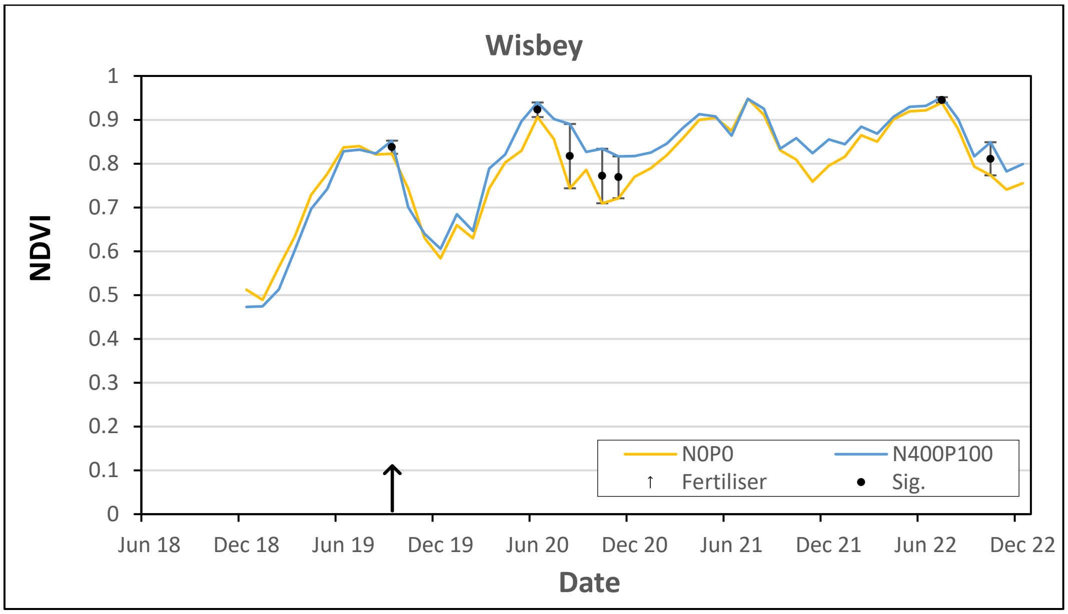


Figure 31. **Influence of season and fertilization on NDVI for a) a non-responsive site: Wallabadah and b) responsive site: Lindsay, in Victoria. Note: the arrow indicates the time of fertiliser application while the black points with error bars indicate the dates when the differences between reflectance of the fertilised and unfertilisd treatments were significant.**

In WA, the seasonal trend in NDVI in the first year was similar to that at the Victorian and Tasmanian sites (Figs. 32a and 32b). Subsequently, the magnitude of the seasonal variation appeared less than observed in the southeastern sites. At both the unresponsive Wisbey site (Fig. 32a) and the highly responsive Lake Jasper 19 site (Fig. 32b), there was a significant increase in NDVI with time, from an average of around 0.7 in 2019 at both sites to around 0.85 at Wisbey and around 0.8 at Lake Jasper in 2021 after which it appeared to stabilize.

a)



b)

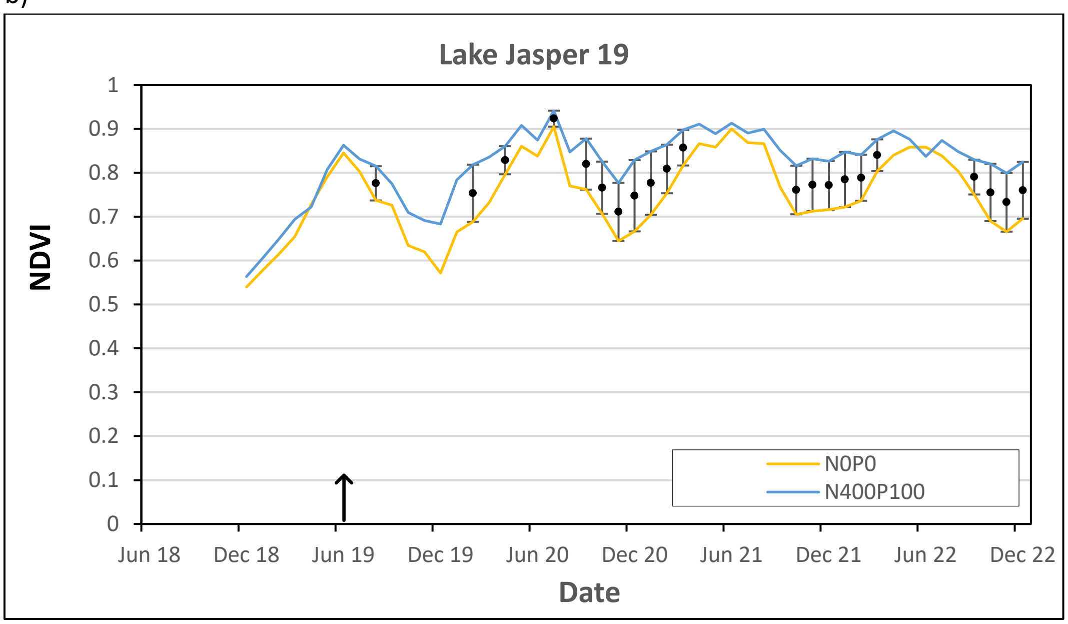


Figure 32. **Influence of season and fertilization on NDVI for a) a non-responsive site: Wisbey and b) responsive site: Lake Jasper 19, in WA. Note: the arrow indicates the time of fertiliser application while the black points with error bars indicate the dates when the differences between reflectance of the fertilised and unfertilised treatments were significant.**

Predicting fertilizer responses

The second component of the analysis of the response data was the identification of relationships between environmental and treatment impacts that enable site-specific prediction of the responses to fertilizer and the rates required to achieve the predicted responses. This focussed on identifying the responses to nitrogen as there was little evidence that potassium and phosphorus were limiting plantation growth.

Multivariate regression was used to combine the identified environmental variables into systems that provided predictive models of the observed responses and can potentially be used to predict the responses to applied nitrogen in hardwood plantations across southern Australia.

Multiple regressions

A series of multiple regressions were constructed to test the combined impact of climate, stand condition (NDVI) and nutrition variables in assessing the potential response to applied nitrogen. These analyses indicate that water availability, temperature, the supply of nitrogen (soil and foliar N) and stand condition (NDVI) influence the response to applied N. These preliminary analyses indicate that foliar N has greater predictive capacity than soil nitrogen. This contrasts with previous work with eucalypts which demonstrated that soil N provided stronger predictions of responses to N application at establishment than foliar N collected from trees one year after the initial treatment (Szota et al. 2014).

We have developed a series of multiple regressions between the growth over 3 years for the unfertilized controls, the optimum fertilizer applications (N400, P100, K100) and the percentage response to the optimum fertilizer application.

Multiple Regressions were constructed between the environmental variables and:

- Growth of the controls (average of treatments 1 and 2) for all sites,
- Growth of N+P treatments (average of treatments 9 and 10) for all sites,
- Vol% responses to N+P for: all except Meade and Greville 18.

All sites were used for the relationships between growth of the controls and N+P treatments and stand and site factors. Two sites were excluded from the relationships with Vol% responses:

- Meade: excluded due to uncertainty about the implementation of the fertilizer treatments,
- Greville 18: excluded due to absence of any response compared with Greville 19 which was on the same site and which provided a 50% response.

The Lake Jasper 18 site was also excluded initially due to the much higher foliar N concentrations for plots comprising this site (2.2% which were sampled in November) compared with the adjacent plots which comprised Lake Jasper 19 (1.2% which were sampled in June, similar to most other sites) which was discussed earlier (see section on Integrating the influences of site and fertility on productivity and response to fertilizer). However, removing this site resulted in only a small improvement to the relationship (+2% increase in r2), so it was decided to retain it.

As explained in the Methodology, to minimize the risk of including randomly correlated variables in the regressions the following constraints were placed on the fitting process:

- No more than 4 variables were included in any regression to ensure the ratio of independent variables to observations was around 1:10,

- Only those variables where there was some clear logical association with growth or response to fertiliser were included,
- Only variables with significant parameters (i.e., Pr <0.05) were included,
- The regressions with the best fit were selected on the basis on lowest MSE (Mean Square Error), highest adjusted r^2 and most normally distributed residuals.

The parameters and coefficients for the selected regressions are shown in Tables 11 and 12 and the relationships between actual versus predicted growth or response to fertiliser are shown in Figures 33 to 37. Most of the selected regressions included a total of 4 independent (i.e. x) variables except for numbers 3, 8 and 9 in which 3 variables were used. In these latter regressions a C/N ratio (which is an indicator of N availability) was used instead of soil N and soil C concentrations resulting in a similar proportion of the variation being explained with a smaller number of variables giving a slightly higher adjusted r^2 and lower MSE (Tables 13a and b).

The prediction of growth in the control treatment (Equations 1 and 2, Figures 33 and 34) used the water related variables (CWI, rainfall and evaporation) and soil C/N ratio. Substituting NDVI for soil C/N increased the regression strength from R^2 of 0.35 to 0.57. This indicated that the water related variables and nitrogen supply (measured as foliar N) or NDVI strongly influenced the growth of the unfertilised treatments. NDVI is related to soil N supply as the higher N availability increased canopy area as shown by the effects of N fertiliser on NDVI.

***Table 11*. Dependent and independent variables for a range of multiple regressions.**

Dependent (Predicted) variable y	Parameters (x variables)				R^2	Adj. R^2	P	SE
	x1	x2	x3	x4				
1. Vol Gth (Control)	CWI Lim	Ann. R	Ann. E	Soil C/N	0.358	0.278	0.0056	6.0
2. Vol Gth (Control)	CWI Lim	Ann. R	Ann. E	NDVI	0.543	0.486	0.0000	5.1
3. Vol Gth (N+P)	CWI Lim	Ann. R	Ann. E	Avg. Rad	0.520	0.460	0.0001	20.0
4. Vol % Gth Resp (N+P)	Foliar N	NDVI	CWI Lim	Max T^0	0.428	0.352	0.0017	22.7
5. Vol % Gth Resp (N+P)	Foliar N	NDVI	CWI Lim 2008-18	Max T^0. 2008-18	0.526	0.463	0.0001	20.7
6. Vol % Gth Resp (N+P)	Soil N	SOC	CWI Lim	Max T^0	0.301	0.208	0.0257	25.1
7. Vol % Gth Resp (N+P)	Soil N	SOC	CWI Lim 2008-18	Max T^0 2008-18	0.369	0.285	0.0138	23.9
8. Vol % Gth Resp (N+P)	Soil C/N	CWI Lim	Max T^0		0.300	0.233	0.0105	24.7
9. Vol % Gth Resp (N+P)	Soil C/N	CWI Lim 2008-18	Max T^0 2008-18		0.365	0.304	0.0044	23.6

Note: Climate data are based on the 3-year period following fertiliser application with the exception of regressions 5, 7 and 9 in which average data for the period 2008-2018 were used. R=rain, E = evaporation., CWI =R/E, CWI Lim is where CWI limited to a maximum value of 1.1, T0 = maximum monthly temperature, SOC = soil organic carbon, C/N = Soil C/N ratio, Avg. Rad = average monthly radiation.

Table 12. **Coefficients for the multiple regressions.**

Dependent (Predicted) variable y	**Coefficients for parameters**				
	x1	x2	x3	x4	constant
1. Vol Gth (Control)	112	-0.0662	0.0579	-0.573	-64.8
2. Vol Gth (Control)	83.3	-0.0491	0.0453	42.3	-80.48
3. Vol Gth (N+P)	413	-0.238	0.1461	14.9	-382.4
4. Vol % Gth Resp (N+P)	-29.5	-116	88.1	10.8	-106.11
5. Vol % Gth Resp (N+P)	-28.7	-121	116	13.4	-177.59
6. Vol % Gth Resp (N+P)	-117	13.8	56.0	6.64	-150.78
7. Vol % Gth Resp (N+P)	-101	11.6	79.7	9.24	-216.8
8. Vol % Gth Resp (N+P)	4.07	50.9	6.33		-178.1
9. Vol % Gth Resp (N+P)	3.39	74.9	9.04		-240.7

The inclusion of rain and evaporation together with CWI in these regressions indicate that the relationship between growth and CWI across the 3 regions is complex and that there appear to be underlying interactions between rainfall and evaporation that were not picked up by CWI alone. There are strong differences in the seasonality of the rainfall distributions between the regions with, for example, an almost uniform rainfall distribution in Tasmania compared to the strongly seasonal rainfall in the WA Mediterranean climate. It is likely that water availability is influenced by factors other than the ratio between rain and evaporation.

For the optimally fertilized treatments, the climate parameters (CWI, rain, radiation, evaporation) were influential in determining the growth of the plantations (Equation 3 Table 13a, Figure 35). Importantly, the productivity of fertilized plantations was not influenced by N supply measured as either soil or foliar N. This indicates that the level of fertilizer applied in the trials likely eliminated any potential deficiency of N as was intended with the high rates of N applied.

Regressions based on foliar N and NDVI (Equations 4 and 5 in Table 13b; Figures 36, 37) were superior to soil N or soil C/N ratio for predicting response (Equations 6-9 in Table 13b; Figures 38, 39). Including foliar N, NDVI, CWI and maximum monthly temperature in the three-year monitoring period explained 43% of variation in the relative growth responses (Equation 4, Table 13b, Figure 36). When the climate data for the 10 years prior to the trials being established (2008-18) was used, the R^2 increased to 0.53 (Equation 5, Tables 13b, Figure 37). We are unsure why the earlier period provided a stronger relationship.

For sites which are planned to be fertilised in the future, only prior climate data will be available for growth and response projections. Therefore, it is important that a representative period is used to predict the future temperature, evaporation and rainfall. Since there have been significant changes in these indicators over the past 50 years in most regions as a result of climate change and natural variability, it is suggested that the average for the most recent 10-year period is used rather than longer term data.

***Table 13*. Summary of the multiple regressions explaining the most variation in a) underlying volume growth of the controls and b) growth response to N+P fertiliser, showing parameters (x variables) used, values of coefficients and significance of each parameter and R2 values (r2), adjusted r2 values (Adj. r2), significance (P) and standard errors (SE) of the overall relationships.**

a)

Regression	Parameters (x variables)				R^2	Adj. R^2	Pr	SE
1	**CWI Lim**	**Rainfall**	**Evaporation**	**Soil C/N**	0.358	0.278	0.006	6.0
Coeff	112.3	-0.1	0.1	-0.6				
Pr	0.0024	0.0098	0.0007	0.2641				
2	**CWI Lim**	**Rainfall**	**Evaporation**	**NDVI**	0.543	0.486	0.000	5.1
Coeff	42.3	83.3	0.0	0.0				
Pr	0.0005	0.0053	0.0164	0.0006				
3	**CWI Lim**	**Rainfall**	**Evaporation**	**Avg. Rad**	0.520	0.460	0.000	20.0
Coeff	412.6	-0.2	14.9	0.1				
Pr	0.0008	0.0050	0.0024	0.0055				

b)

Regression	Parameters (x variables)				R^2	Adj. R^2	Pr	SE
4	**Foliar N**	**NDVI**	**CWI Lim**	**Max T^0**	0.428	0.352	0.002	22.7
Coeff	-29.5	-116.1	88.1	10.8				
Pr	0.0051	0.0405	0.0068	0.0004				
5	**Foliar N**	**NDVI**	**CWI Lim$_{2008-18}$**	**Max $T^0_{2008-18}$**	0.526	0.463	0.000	20.7
Coeff	-28.7	-120.5	116.4	13.4				
Pr	0.0028	0.0185	0.0003	0.0000				
6	**Soil N**	**SOC**	**CWI Lim**	**Max T^0**	0.301	0.208	0.026	25.1
Coeff	-117.0	13.8	56.0	6.6				
Pr	0.0887	0.0661	0.0904	0.0371				
7	**Soil N**	**SOC**	**CWI Lim$_{2008-18}$**	**Max $T^0_{2008-18}$**	0.369	0.285	0.014	24.9
Coeff	-100.5	11.6	79.7	9.2				
Pr	0.1248	0.1042	0.0183	0.0086				
8	**Soil C/N**	**CWI Lim**	**Max T^0**		0.300	0.233	0.011	24.7
Coeff	4.1	50.9	6.3					
Pr	0.0580	0.0929	0.0463					
9	**Soil C/N**	**CWI Lim**	**Max $T^0_{2008-18}$**		0.365	0.304	0.004	24.4
Coeff	3.4	74.9	9.0					
Pr	0.1003	0.0176	0.0102					

Note: Rainfall = annual rainfall (mm), Evaporation = annual pan evaporation (mm), CWI Lim = annual rainfall/annual pan evaporation with CWI limited to a maximum value of 1.1, T^0 = average maximum monthly temperature (^{o}C), Avg. Rad = average monthly radiation (MJ/m^2), Foliar N = foliar N concentration (%) , NDVI is the normalised difference vegetation index derived from satellite data, Soil N is the concentration of total nitrogen (mg/g), SOC is the concentration of organic carbon (mg/g) and Soil C/N = soil C/N ratio. Climate data are averaged for the 3-year period following fertiliser application with the exception of regressions 5, 7 and 9 which used the average for the 10-year period from 2008-18 (prior to fertiliser application). Foliar soil and NDVI data are means of all plots prior to fertiliser application.

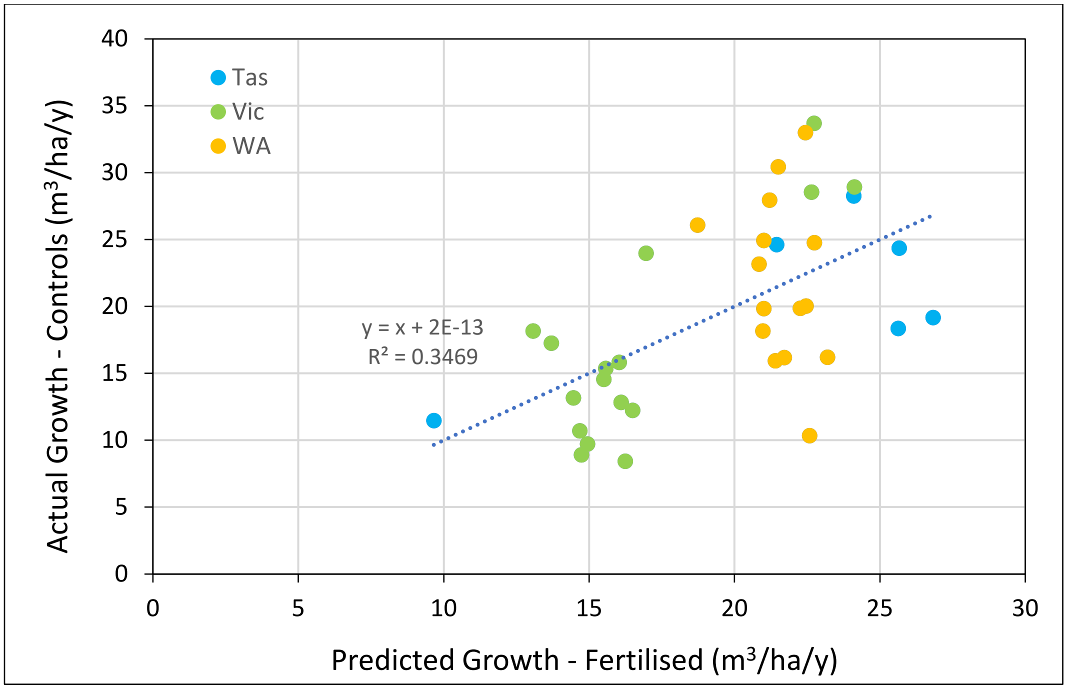


Figure 33. **Actual versus predicted growth for control treatments for Equation 1, Control volume growth using climate predictors and soil C/N).**

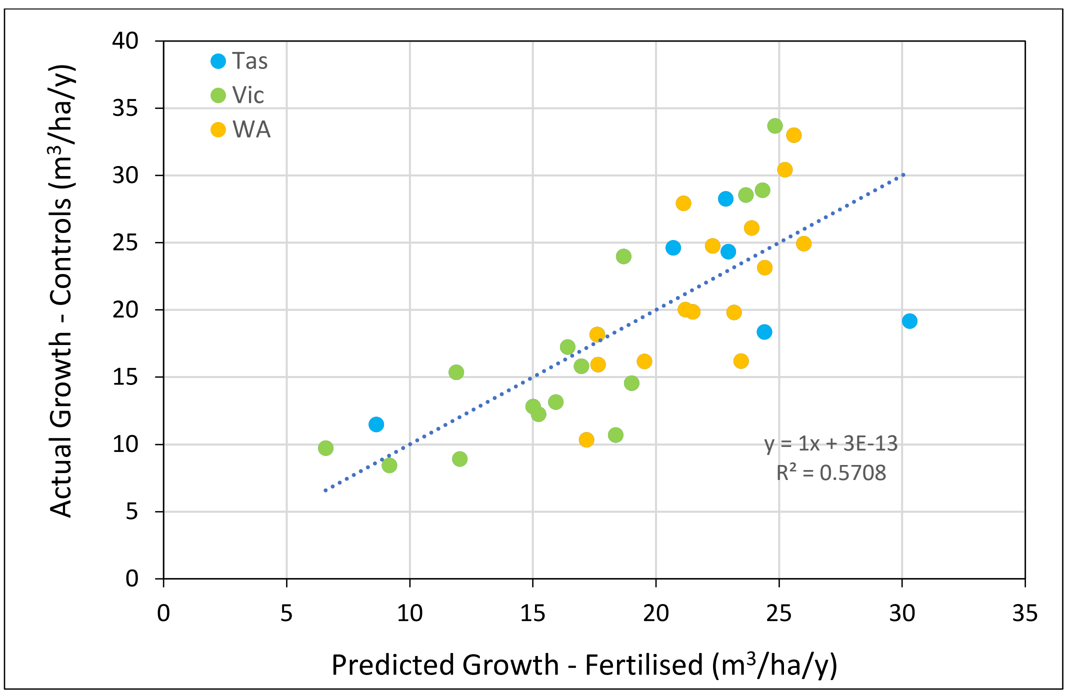


Figure 34. **Actual versus predicted growth for control treatments for Equation 2, Control volume growth using NDVI and climate predictors.**

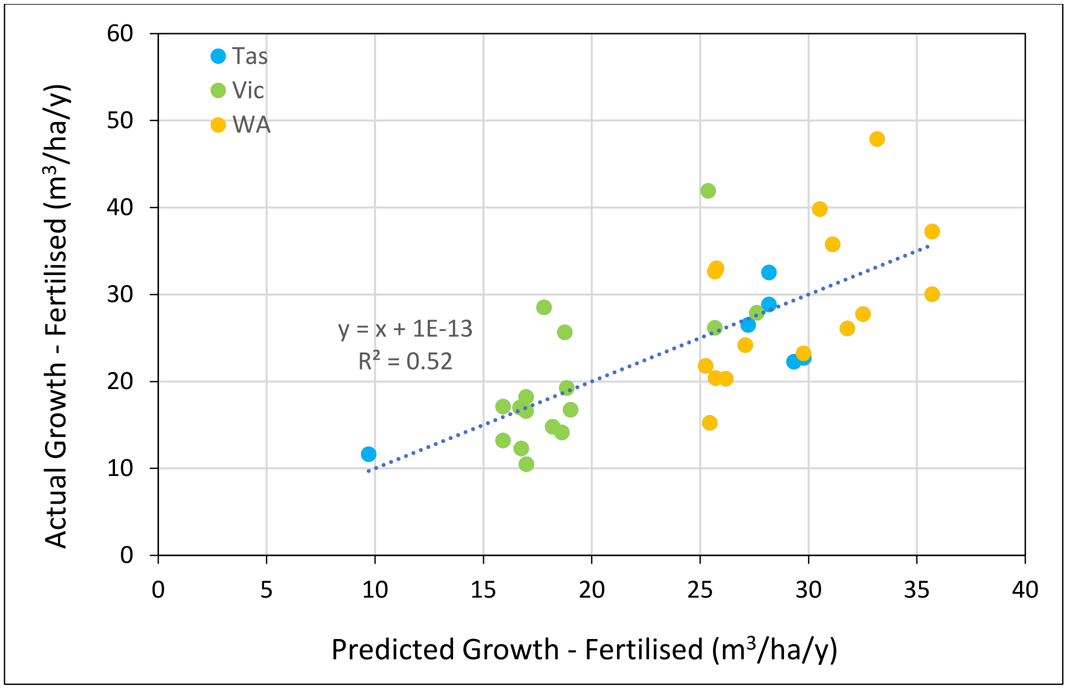


Figure 35. **Actual versus predicted growth for fertilized treatments for Equation 3, Fertilized Volume growth using climate predictors, water and radiation.**

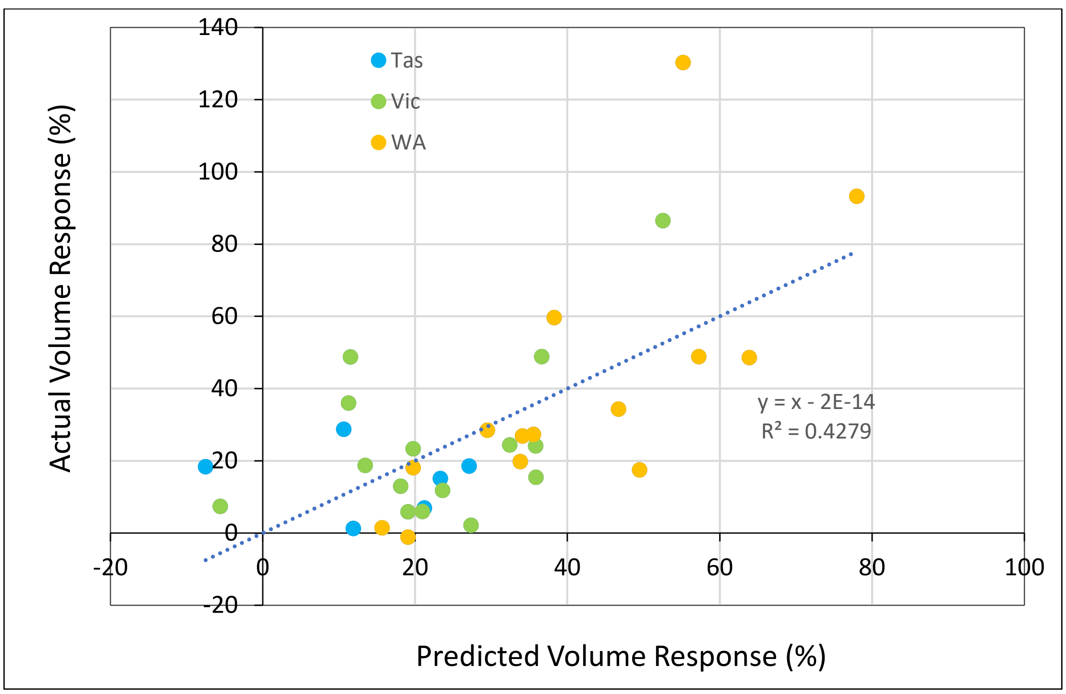


Figure 36. **Actual versus predicted percentage response to fertilizer over three years for Equation 4, using NDVI, foliar N and 3-year climate predictors.**

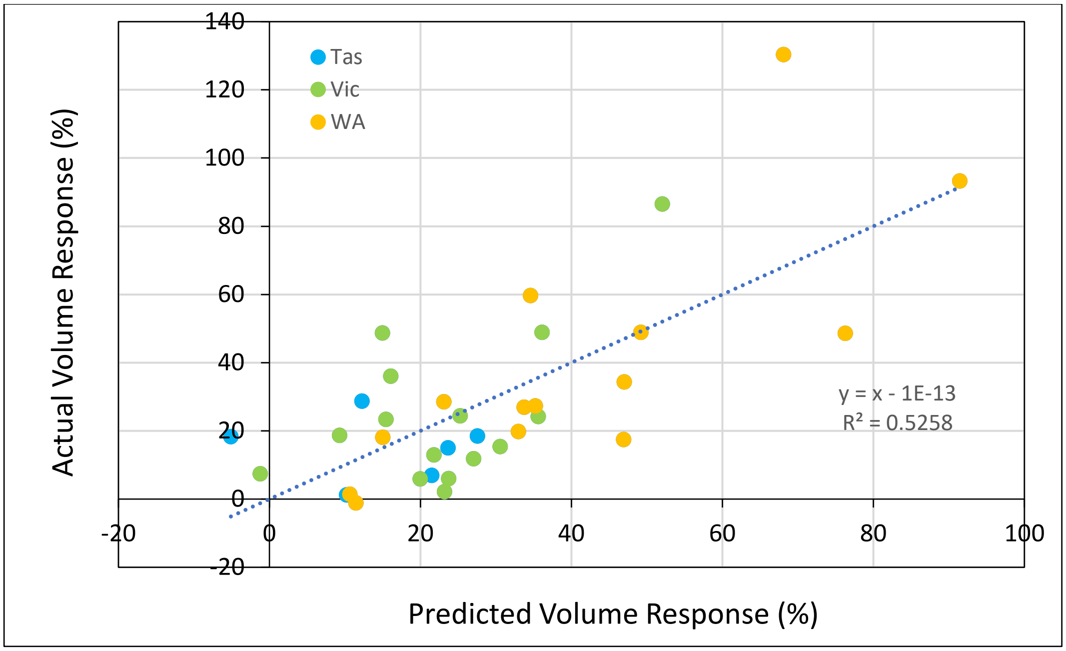


Figure 37. **Actual versus predicted percentage response to fertilizer over three years for Equation 5, using NDVI, foliar N and pre-treatment climate predictors.**

Using soil N or soil C/N ratios provided weaker relationships than the foliar and NDVI relationships with an r^2 for the relationships of 0.30 (Equations 6 and 8 in Table 13b; Figures 38 and 39). All the variables in the relationships were significant ($P < 0.05$) apart from soil N, soil C and soil C/N which were marginally significant $0.05 < P < 0.10$).

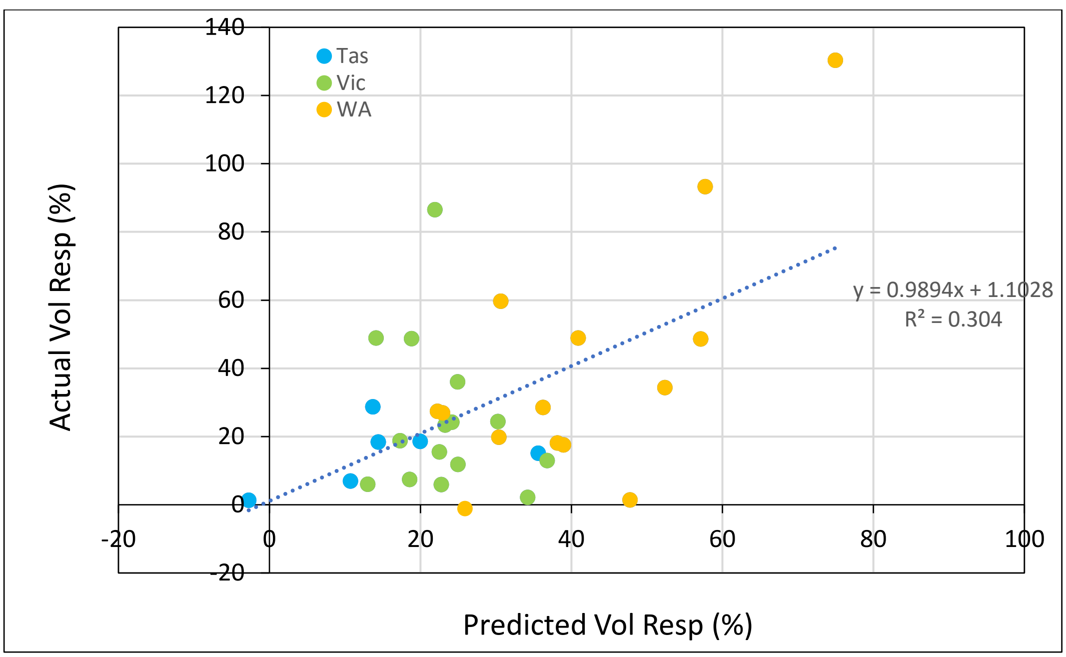


Figure 38. **Actual versus predicted percentage response to fertilizer for Equation 6, using soil C/N ratio and 3-year climate predictors.**

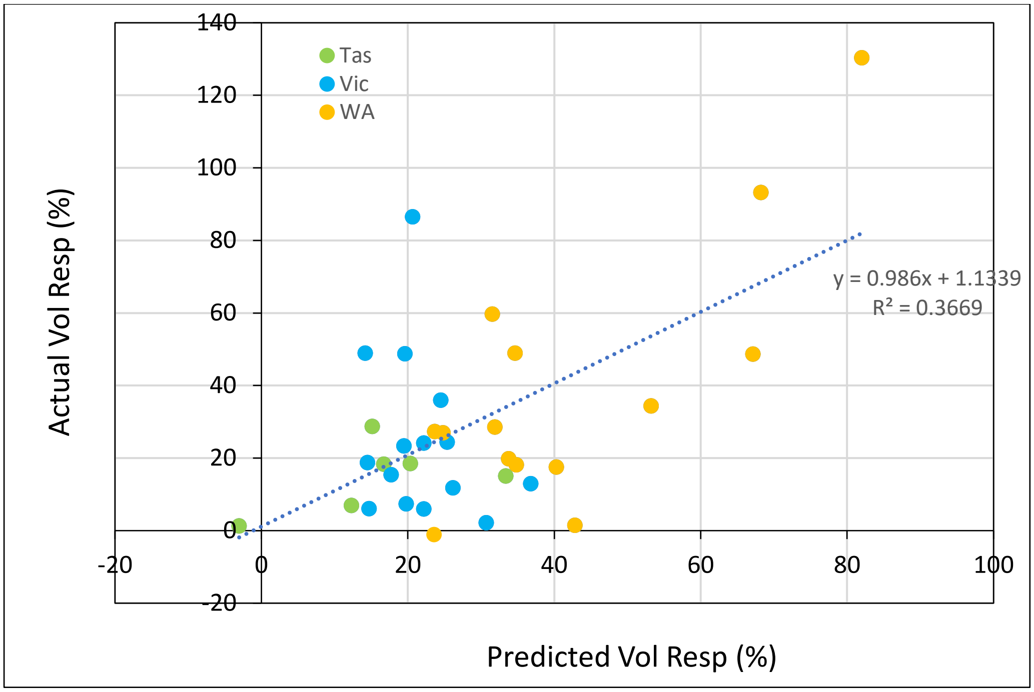


Figure 39. **Actual versus predicted percentage response to fertilizer for Equation 7, using soil C/N ratio and pre-treatment climate predictors.**

The standard errors for the regressions provide an indication of the potential confidence in the predictions. For example, for the relationship using foliar N and NDVI plus the 3-year climate data with a standard error of 22.7 we could expect around 68% of predicted responses for individual sites to be within +/- 23% of the actual response achieved. While this indicates significant unexplained variation, it likely provides plantation managers with a more accurate method for predicting N responses than is currently available.

The substantial proportion of unexplained variability in the multiple regressions is probably a result of the wide range of sites across varied climatic zones and soil types that have only been partially characterised. As yet, no attempt has been made to assess the soil physical and topographic attributes that may contribute to the variability. In a study of the relationship between growth, wood properties and climate for *E. nitens* in north-western Tasmania similar regression analyses explained 27% of the variation in growth and up to 51% of the variation in wood density (Rocha-Sepulveda et al. 2022), indicating the difficulty in identifying all the contributions to variation in such studies.

It is important to note that, at this stage, the relationships remain speculative in that they have not been validated against an independent dataset. Importantly, we are not recommending that forest growers rely on the relationships between climate, soil and or NDVI values to predict the absolute growth of stands. Rather, they indicate that the climate and soil or foliar variables used to predict the relative increase in growth (i.e. CWI, temperature and foliar N and DVI or soil C/N ratios) have a physiological basis for their inclusion in these relationships.

Furthermore, while the relationships predicting relative response to fertiliser are promising, there are some important considerations that need to be noted regarding their operational use. These include:

- The NDVI values used to develop the relationships are for the period January-December 2019 and so do not strictly cover the period prior to fertiliser application. Operationally, NDVI values will probably be collected for the 12 months ending in June prior to fertiliser application to allow sufficient time to identify responsive sites and order fertiliser. Due to the gradual increase in NDVI over time this could result in site responsiveness being overpredicted (i.e. by around 6%) based on the maximum expected difference in NDVI (0.05) and the current parameter for NDVI (116, Equation. 4 Table 13b). Additionally the influence of weeds and understory were not accounted for and will need further investigation.
- The foliar nutrient concentrations are for foliage collected around the time of fertiliser application. Foliage will typically be collected the year prior to fertilising to allow sufficient time for chemical analysis as well as ordering fertiliser. Foliar N tends to decrease rapidly in the first 1-3 years (O'Brien et al. 2003, confidential unpublished report) and so foliar N concentrations will likely be greater than those used here. This could result in response being underpredicted slightly (again by around 6% based on the maximum expected difference (0.2%) and the foliar N parameter in the relationship 29.5). In other words, it is possible that the expected difference in predicted response due to higher foliar N concentrations could largely offset the overprediction associated with the smaller NDVI values.
- Due to the seasonal variation in foliar nutrients (O'Brien et al. 2003, confidential unpublished report) it is important that foliar samples are collected around the same time as that used to develop the current regressions for all sites. In the current study, most samples were collected between July and September. It is therefore recommended that foliar sampling be undertaken in August the year prior to fertiliser application. Additional work with *E. globulus* and *E. nitens* is required to understand the seasonal variation in foliar nutrient concentrations so that there is a firm basis for predicting the nutrient status of plantations.
- While the primary relationships (i.e. Equations 4 and 8, Figs. 36 and 38) were constructed using actual climate data for the period over which growth responses were measured, operationally average climate data will be used. The fact that the 10-year climate data appeared to fit the relationships at least as well as the actual climate data indicates that this should not impact the accuracy of the predictions. However, it is important that representative data is used (i.e. average data for the past 10 years rather than data from the past 20 or 30 years) due to the effects of climate change.

The issues regarding variation in foliar N and NDVI identified above will aim to be addressed in the next phase of the project through:

- Accessing NDVI datasets for the period prior to fertiliser application and using this data to refine the relationships.
- Reviewing existing literature on changes in foliar N in the first few years of growth to determine the likely difference in foliar N resulting from sampling one year prior to fertiliser application.
- Attempting to quantify the influence of weeds and understory growth on NDVI values seasonally and annually.

- Using the above data to characterise the seasonal variation in foliar N and NDVI and assess the likely impact of this variation on the predicted response.

COMPONENT 3: ESTABLISHMENT TRIALS

Background

Harvest residue and litter layers (harvest residue) can contain considerable amounts of nutrients that become available to trees during the next rotation. This source of nutrients, if conserved on-site, could potentially alleviate or partially replace the need for fertiliser applications, but this interactive effect of harvest residue and fertiliser management has not been quantified in Australian eucalypt plantations and will be critical for optimising plantation growth and profitability. As well as covering an appropriate range of soil and climate, these experiments also need to cover the wide range of harvest residue management use in hardwood plantations across Australia. Because harvest residue management was designed to cope with the wide range of harvesting and other site preparation operations used, the amounts and evenness of distribution of harvest residue vary greatly, which in-turn could be expected to affect the need for fertiliser.

Materials and methods

The current set of trials aimed to quantify the main effects and interactions of harvest residue and fertiliser management on tree growth during establishment of eucalypt plantations in temperate Australia. Eight establishment trials (Table 14, Figure 40) were installed across sites with a range of fertilities. However, the range of nitrogen supply was quite narrow with only one trial (Landells 0.18%N) having a soil N value below 0.25% N**.** All trials were planted rather than coppiced. These experiments explored the tree growth response to different rates of combination fertilisers containing nitrogen, phosphorus and potassium, with and without operationally retained harvest residue (harvest residue). The 8 experiments were established across three regions by six organisations as summarised in Tables 14-15 and Figure. 40.

Site descriptions

***Table 14*. Location and site descriptions.**

State	Site name	Month/year planted	Coordinates		Soil type	Mean rainfall	Elevation (m)
			Lat.	Long.			
Tas	Takone	6/11/2019	-41.1658	145.619	Basalt	1452.3	508
TAS	Hazelbrook Farm	1/10/2019	-41.2250	145.8184	Red Brown Clay	1384	228
VIC	Karoo	1/06/2019	-38.2894	142.9668	Clay loam/clay	800	121
Vic	Smokey Valley	1/06/2019	-37.9196	141.6362	Sandy Loam	680	87
WA	Landells	31/07/2018	-34.2400	115.1580	Deep Sand	1050	42
WA	Dilkes	29/07/2019	-33.8450	116.1330	Sandy loam	750	277
WA	Allison	1/07/2019	-34.6254	117.2352	Sandy Loam	714	220
WA	Homestead	1/07/2019	-34.8632	118.1798	Sandy Loam	711	93

***Figure 40.* Location of establishment trials.**

Trial design

Each trial had 18 plots, consisting of 3 replicates of nil, standard and high fertiliser applications within 2 x harvest residue regimes (retained or removed, Table 16). Other treatments were included at some sites (in-kind) according to industrial partner needs. The trials had a split-plot design at each site. Main-plot treatments were 2 un-replicated harvest residue management treatments (retained or removed), i.e. each site had one main-plot of each harvest residue treatment. Within each main-plot, sub-plots were 3 levels of fertilization (nil, standard, high) with 3 replicate measurement plots of each arranged in a randomized block design. Hence, there were 18 plots per site. Optional treatments could be included at the discretion of each company, e.g. controlled release fertilizer. However, these optional treatments are mostly not reported here. As harvest residue retention was not replicated within sites, its effect can only be reliably assessed in a multi-site analysis using 8 blocks (sites).

Harvest residue management treatments

There were two harvest residue management treatments, i.e. retained and removed. The methods used to achieve those treatments varied between sites as described in Tables 16 and 17.

***Table 15*. Installation details.**

State	Site name	Month/year planted	Date soil sampled	Initial measureme nt date	Date treatments applied
Tas	Takone	6/11/2019	11/09/2019	23/10/2019	23/10/2019
TAS	Hazelbrook Farm	1/10/2019	18/07/2019	5/11/2019	5/11/2019
VIC	Karoo	1/06/2019	1/05/2019	19/11/2019	24/09/2019
Vic	Smokey Valley	1/06/2019	7/06/2019	18/09/2019	28/06/2019
WA	Landells	31/07/2018	8/08/2018	31/07/2018	19/09/2018
WA	Dilkes	29/07/2019	17/07/2019	30/07/2019	29/07/2019
WA	Allison	1/07/2019	11/07/2019	9/11/2019	18/07/2019
WA	Homestead	1/07/2019	7/07/2019	10/11/2019	1/08/2019

Establishment and measurement details

Annual height measurements commenced when the trees were planted while diameters were also measured from age 2 years (when trees reached sufficient size). Although the trials were established at slightly different times during the first year, the annual measurement times were subsequently aligned to a common month (June). Soil nutrient status was reassessed after 3 years.

Fertiliser treatments

1. Nil
2. Standard (nominally 16g N, 9g P, 25g K per tree)
3. High (nominally 32g N, 18g P, 25g K per tree)

Table 16. **Fertiliser applications and harvest residue management.**

Company	Site	Standard Establishment Fertiliser	Harvest completion Date	Harvest Method	Harvest residue distribution	Harvest residue Removal
PFO	Allison	16g N, 9g P, 25g K per tree, using 150g/tree AgrasCuZn (100):MOP(50)	14/12/18	IFC	Clumps redistributed by machine	Burnt (poorly)
	Homestead		14/6/18			Burnt
	Smokey valley					Pushed
Wapres	Landells	16g N, 9g P, 25g K per tree seedling. This is obtained using 150g/tree AgrasCuZn (100):MOP(50) (2:1)	30/9/2017	CTL	From harvesting + chopper rolled	Burnt
	Dilkes		18/4/18	CTL	From harvesting + chopper rolled	Pushed along inter-rows. Some harvest residue remained along the planting line.
Forico	Takone	16g N, 9g P, 25g K per tree or 35g Urea, 102g SSP, 50g MOP.	April 2019	CTL	From harvesting	Pushed
Midway	Karoo	17.2g N, 45g P, 50g K per tree (blended urea/DAP/MoP)	2018	CTL	From harvesting	Pushed to windrows
RFF	Hazelbrook Farm	20 grams Hafia Multicote 8	July 2018	CTL	From harvesting	Minimal debris, pushed to windrows

CTL = Cut to length, IFC = In field chipped, MOP – Muriate of Potash (KCl), DAP – Di Ammonium Phosphate

No standard type of fertiliser was recommended, as products vary across suppliers in each state, and it was therefore at the discretion of each company, provided the elemental rates matched closely the prescribed rates in the core treatments. Details for each company are provided Table 17.

***Table 17*. Comments on harvest residue management techniques.**

State	Site	Company	Harvest*	Harvest residue management/Comments
WA	Allison	PFO	IFC	Retained by return with forwarders/skidders, distribution clumpy, uneven content of clumps. Removal by burning was very patchy and incomplete.
WA	Dilkes	WAPRES	CTL	Retained harvest residue fairly evenly distributed and chopper-rolled. Removal by pushing with frontend loader. Some debris remained on the planting line.
Tas	Hazelbrook	RFF	CTL	Retained harvest residue light unevenly distributed and redistributed. Removal by mechanical grabbing plus pushing and some burning.
WA	Homestead	PFO	IFC	Retained by return with forwarders/skidders, distribution clumpy, uneven content of clumps. Removal by burning (approx.. 90%)
Vic	Karoo	Midway	CTL	Retained harvest residue evenly distributed. Removal by windrowing outside of trial area, reasonably complete.
WA	Landells	WAPRES	CTL	Retained harvest residue evenly distributed and chopper-rolled. Removal by burning.
Vic	Smokey V.	PFO	IFC	Retained by return with forwarders/skidders, distributed in every second row in large clumps. Removal by pushing
Tas	Takone	FORICO	CTL	Retained harvest residue evenly distributed. Removal by pushing: grabbing, raking, or blading.

* IFC = In-field chipping at roadside, harvest residue removed; CTL = Cut to length at stump, harvest residue retained

Fertiliser was hand applied by burying it near the base of each tree. Fertiliser included various combinations of urea, DAP, MoP, SSP, Multicote 8, and AgrasCuZn. Controlled release fertilizer was applied in the bottom of the planting hole immediately before tree planting.

Plots were installed with approximately 30 trees each (variation was 20-40 trees/plot) and the internal measurement plot dimensions varied to accommodate the various plantation configurations and plantation densities available. A 2-row buffer around all sides of the internal measurement plots was used at all sites to separate the measurement plots from adjacent treatments.

Treatment plots were pegged on all 4 corners, and trees in the internal measurement plots were marked when sufficiently large. Pegs were placed on the tree row rather than between the rows so that future vehicle access would not be compromised (e.g. for weed control). The plot areas were measured to the midpoint between tree rows and between trees within -rows for both the external and measurement plots.

Tree measurements: Height was measured on a subsample of trees to obtain a mean initial height at each site. Heights of all trees and diameters at breast height (1.3 m) over bark (DBHOB) were measured annually in June in each plot when trees were tall enough.

Soil sampling: A bulked surface soil sample (0-10 cm) from within the inter-row area of each measurement plot was taken. Sampling dates are shown in (Table 15). Soil analysis methods were as for the rate and responsiveness trials.

Results and discussion

Initial tree measurements and soil analyses

Based on initial soil analyses, the eight sites were expected to provide a wide range of soil chemical conditions including nutrient availability (Table 18). Available P ranged from 44 mg/kg at Takone to 15 mg/kg at Smokey Valley. Total N ranged from 0.56% at Homestead to 0.18 at Landells. Takone and Hazelbrook Farm appeared to be the most fertile sites having relatively high available P, available K and total N while Landells and Smokey Valley appeared to be the least fertile.

***Table 18*. Initial soil analysis: Means of soil analyses by site and treatment.**

Site	Available P (Colwell) mg/kg	Available K (Colwell) mg/kg	Sulfur mg/kg	Organic C %	Conductivity dS/m	pH ($CaCl_2$)	pH (H2O)	P Buffer Index	Total N %
Takone	43.6	134	13.6	4.92	0.067	4.16	4.79		0.481
Hazelbrook Farm	43.4	200		4.67	0.065	4.32			0.487
Karoo	18.7	89		4.10	0.139	4.21	4.87		0.305
Smokey valley	14.7	71	5.2	3.30	0.052	4.09	5.19	72	0.254
Landells	15.6	51		2.53		4.06		42	0.181
Dilkes	20.9	139		4.34	0.083	5.50	6.35	359	0.389
Allison	43.0	85	10.6	4.09	0.057	4.32	5.37	214	0.367
Homestead	21.5	81	13.2	4.40	0.094	3.98	4.98	186	0.558

Three-year response data were available for all sites for tree survival (Surv, %), height (Ht, cm), and DBH (cm), and from these conical volume per ha was calculated (Volpha, m^3/ha) for each plot. Stem- and tree-level data were also used to calculate the percentage of single-stem trees. The percentage of single-stem trees at the plot level ranged from 63.3% to 100.0%, but these data were not analysed further as treatment differences were not obvious.

Data were analysed by split-plot ANOVA (P = 0.05) with all sites included. Significant results are presented as graphs of main effects of site, harvest residue or fertiliser with 95% confidence limits of means or two-factor interactions shown together with LSD bars.

Site issues

Smokey Valley – This site experienced insect damage in the first year. These were uneven across the site and not detected until long after the event and were probably the reason for low Surv, Ht, DBH, and Volpha at this site. The insect browsing appeared more severe in the area with harvest residue (A. Muneri, Pers. Com. 2023).

Allison – Harvest residue removal was poor at this site as it was burnt very late in the season resulting in very patchy removal. Where retained, the harvest residue was not very evenly distributed from the initial large clumps. Coppice growth within the planted stems was high and not measured so the impact was not quantified.

Survival

The initial range of stocking at the plot level was 789-1615 tree/ha. There was a significant effect of fertiliser on tree survival and a significant site x harvest residue interaction. Increasing fertiliser rate from nil to high progressively decreased average survival from 89% to 81% (Figure. 41 top). Survival was highest at Takone at 97%, with the differences between harvest residue treatment insignificant at that site (Figure 41 bottom). In contrast, survival was low at Smokey Valley in both harvest residue treatments and at Hazelbrook Farm in the harvest residue retained treatment (71-74%). Harvest residue retention increased survival at Landells, but it decreased it at Hazelbrook Farm and had no significant effect at the other sites. Hence, the effect of harvest residue management on survival was inconsistent across the different sites.

Height

There was a significant main effect of fertiliser on height, and a significant site x harvest residue interaction. Increasing fertiliser rate from nil to standard to high progressively increased average height from 8.0 to 9.0 m (Figure 42, top). Height was greatest at Dilkes at ~10.4 m, with the differences between harvest residue treatment insignificant at that site (Figure 42, bottom). In contrast, height was least at Smokey Valley in both harvest residue treatments (c. 5.6 m). Harvest residue retention significantly increased height at Hazelbrook Farm and Takone, but decreased it at Allison and Karoo. Hence, as with survival, the effect of harvest residue management on height was inconsistent across sites.

Diameter

As with height and survival, there was a significant main effect of fertiliser on diameter (DBHOB), and a significant site x harvest residue interaction. Increasing fertiliser rate from nil to standard to high progressively increased average diameter from 7.3 to 8.1 cm (Figure 43, top). DBH was largest at Dilkes in the harvest residue retained treatment at 10.2 cm (Figure 43, bottom), compared to 8.3 cm in the harvest residue removed treatment, but DBH at Hazelbrook Farm, Takone and Smokey Valley was about half of the largest value. Other sites also showed a positive response to harvest residue retention, but, at Karoo and Hazelbrook Farm, harvest residue retention led to decreased DBH. Hence, the effect of harvest residue management on DBH was inconsistent across sites.

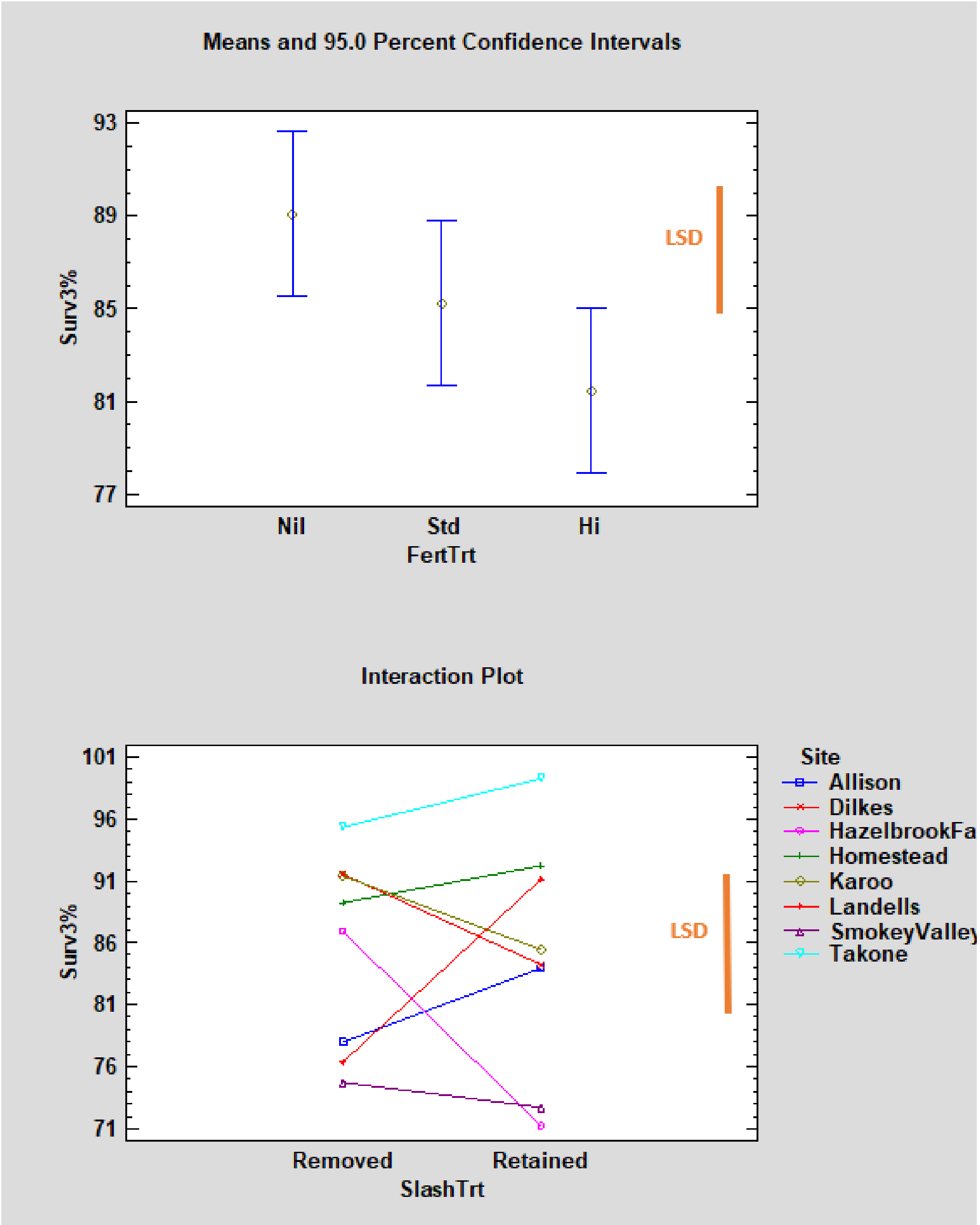


Figure 41. **Main effect of fertiliser (top) and the interaction effects of site and harvest residue (bottom) on tree survival (Surv) at age 3 years.**

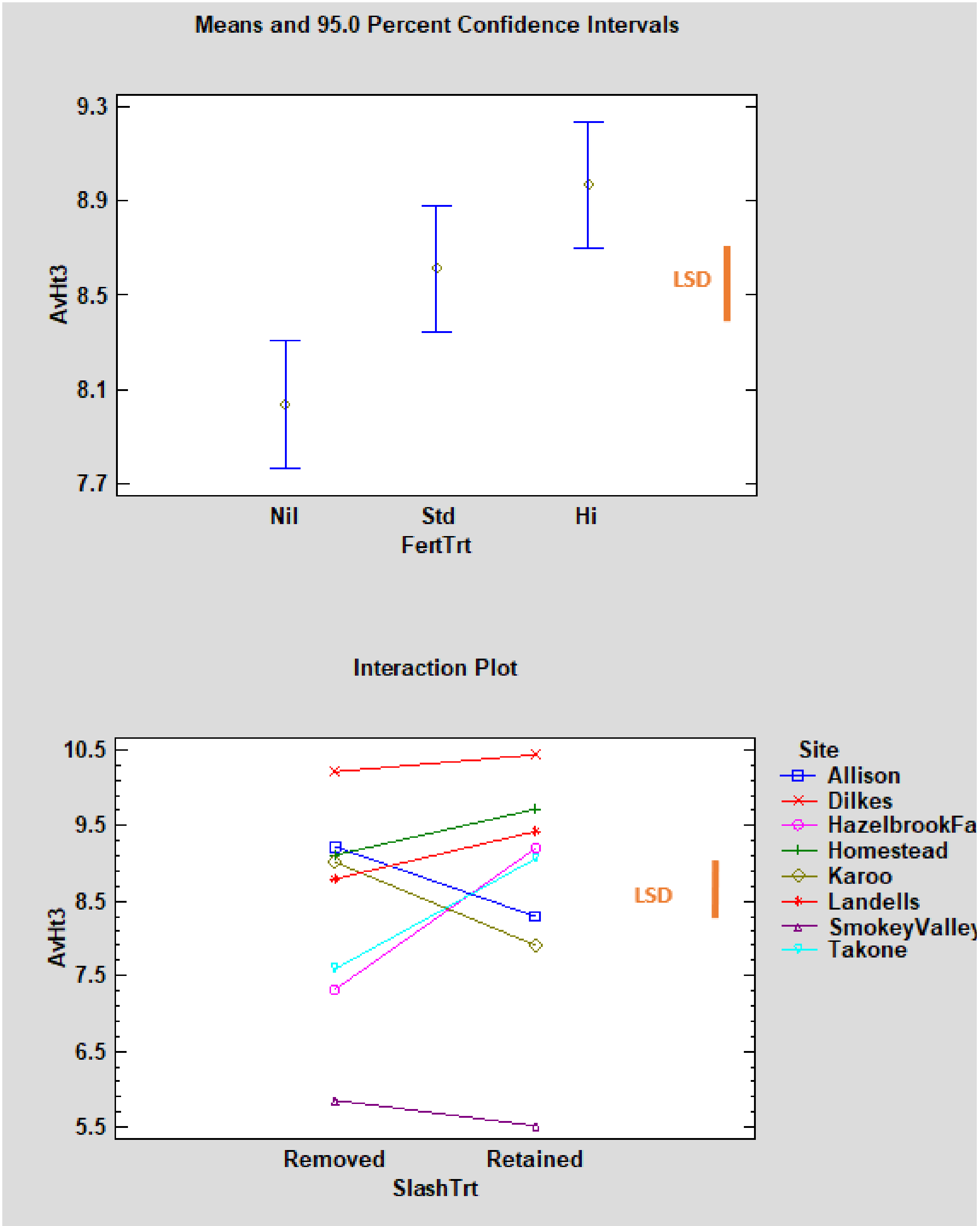


Figure 42. **Main effect of fertiliser (top) and the interaction effects of site and harvest residue (bottom) on tree height (Ht) at age 3 years.**

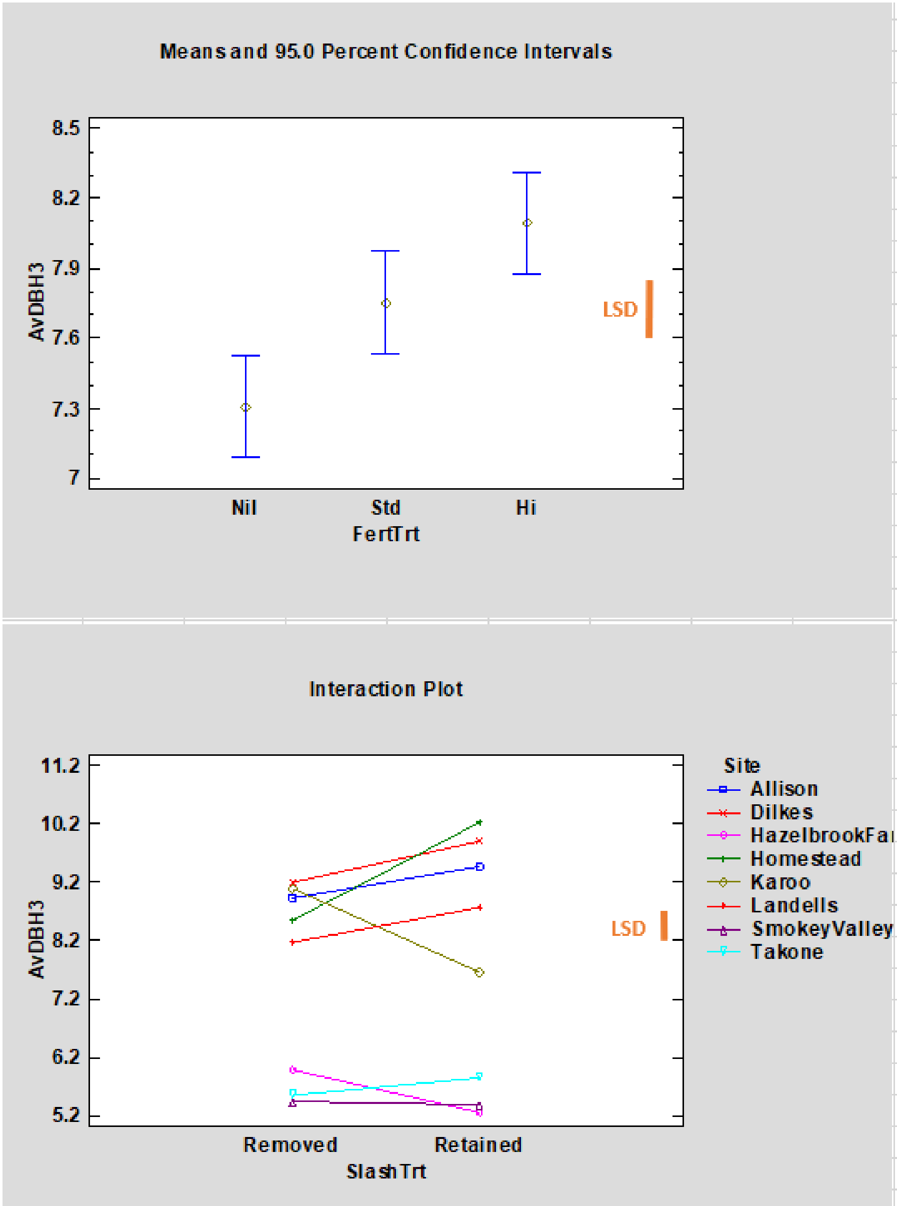


Figure 43. **Main effect of fertiliser (top) and the interaction effects of site and harvest residue (bottom) on tree diameter (DBH) at age 3 years.**

Volume

Because volume responses are shown on a per ha basis, the combined effect of survival and the growth of survivors needs to be considered, which presents complications because of the generally opposing effects of fertiliser on survival and individual tree growth (Ht and DBH), and the inconsistent effects of harvest residue management on these parameters. These effects overall led to a moderated but positive effect of fertiliser on Vol/ha (m^3/ha) for both residue retained and residue removed treatments when averaged across sites (Figure 44, top). Across individual sites, there was no consistent effect of harvest residue management on volume growth (Figure 44, middle) while responses to fertiliser ranged from an increase of 9 m^3/ha over the three years at Dilkes, down to no response at Allison. (Figure 44, bottom).

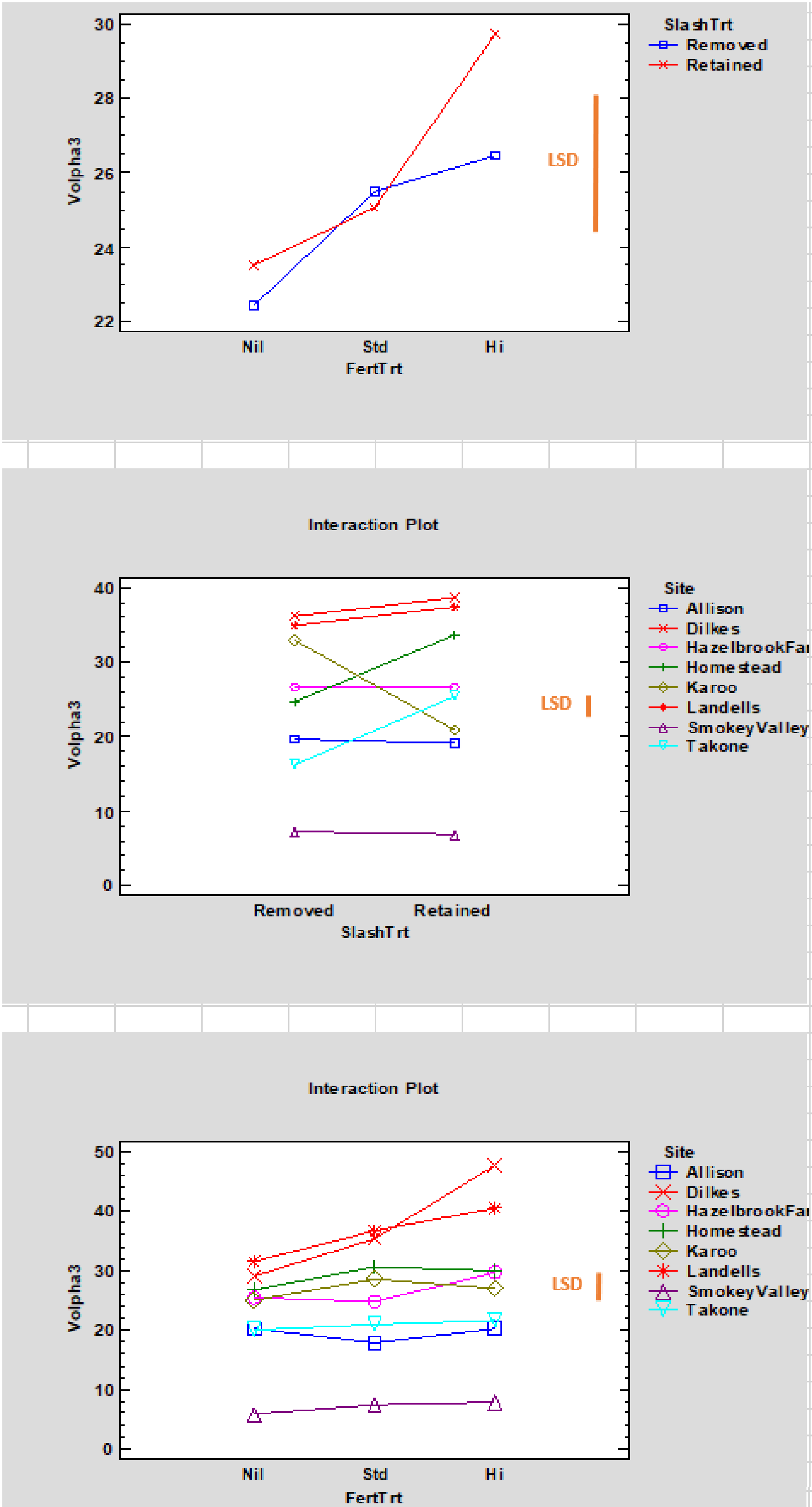


Figure 44. **Interaction effects of harvest residue and fertiliser (top), site and harvest residue (middle), and site and fertiliser (bottom) on stem volume per hectare (Volpha) at age 3 years.**

Further exploration of the harvest residue effect

Interpretation of harvest residue effects is difficult in this study, because (a) harvest residue treatments were not replicated within sites, and (b) they consisted of a range of methods to implement harvest residue retention and removal. An attempt to look for patterns of response was made by describing the methods at each site (Table 19), then grouping sites with similar methods into three different groups (Table 20) and using a one-way ANOVA to test for significant differences between groups. This method was applied to the percentage effect of harvest residue retained compared to harvest residue removed for the parameters of survival, height, diameter and volume/ha, but the effect of harvest residue management group was insignificant in all cases.

***Table 19*. Harvest residue management methods used at each site.**

Site	Harvest residue	
	Removed	**Retained**
Allison	RSP, Bi	FR
Dilkes	GRP	ASP
Hazelbrook Farm	GRP, Bi	ASP
Homestead	RSP	FR
Karoo	Bi	ASP
Landells	Bi	ASP
Smokey Valley	RSP	FR
Takone	GRP	ASP

RSP = roadside processing; Bi = burnt, incomplete; FR = forwarder returned; GRP = grab, rake, push; ASP = at stump processing

***Table 20*. Grouping of sites according to similar harvest residue management treatments.**

RSP-FR	GRP-ASP	Bi-ASP
Allison	Dilkes	Karoo
Homestead	Hazelbrook Farm	Landells
Smokey Valley	Takone	

Soil analyses

Initial and final (3-year) soil analyses were appraised graphically; shown are the graphs for carbon (Figure 45), nitrogen (Figure 46) and Colwell P (Figure 47). Tabulated data (not presented) indicated that time and treatment effects were probably not significant compared to other sources of error. The level of scatter in the data seen in these data is not unexpected. The main source of error was likely to be innate variability within sites that was not fully catered for in the sampling design, which is common for forestry sites. Such variability makes it possible to statistically detect only very large changes in these measures.

Within these data there are a few points to note. If there was no change in a soil analysis value between initial and final sampling, we would expect to see an alignment of points along an imaginary 1:1 line for each type of analysis, which generally is the case. However, for soil C at the Forico Takone site, values increased on average from 5.0 to 7.5%. Such an increase is unrealistic considering the lack of vegetation (trees and weeds) and lack of litter production during the first three years of this plantation. Therefore, sampling or analytical errors are indicated. Similar suspicions arise for soil C at the PFO Smokey Valley site, and for Colwell P at the Forico Takone site, where the initial range of values was much higher than the final range. Resampling and further statistical analysis would be warranted close to the end of the rotation.

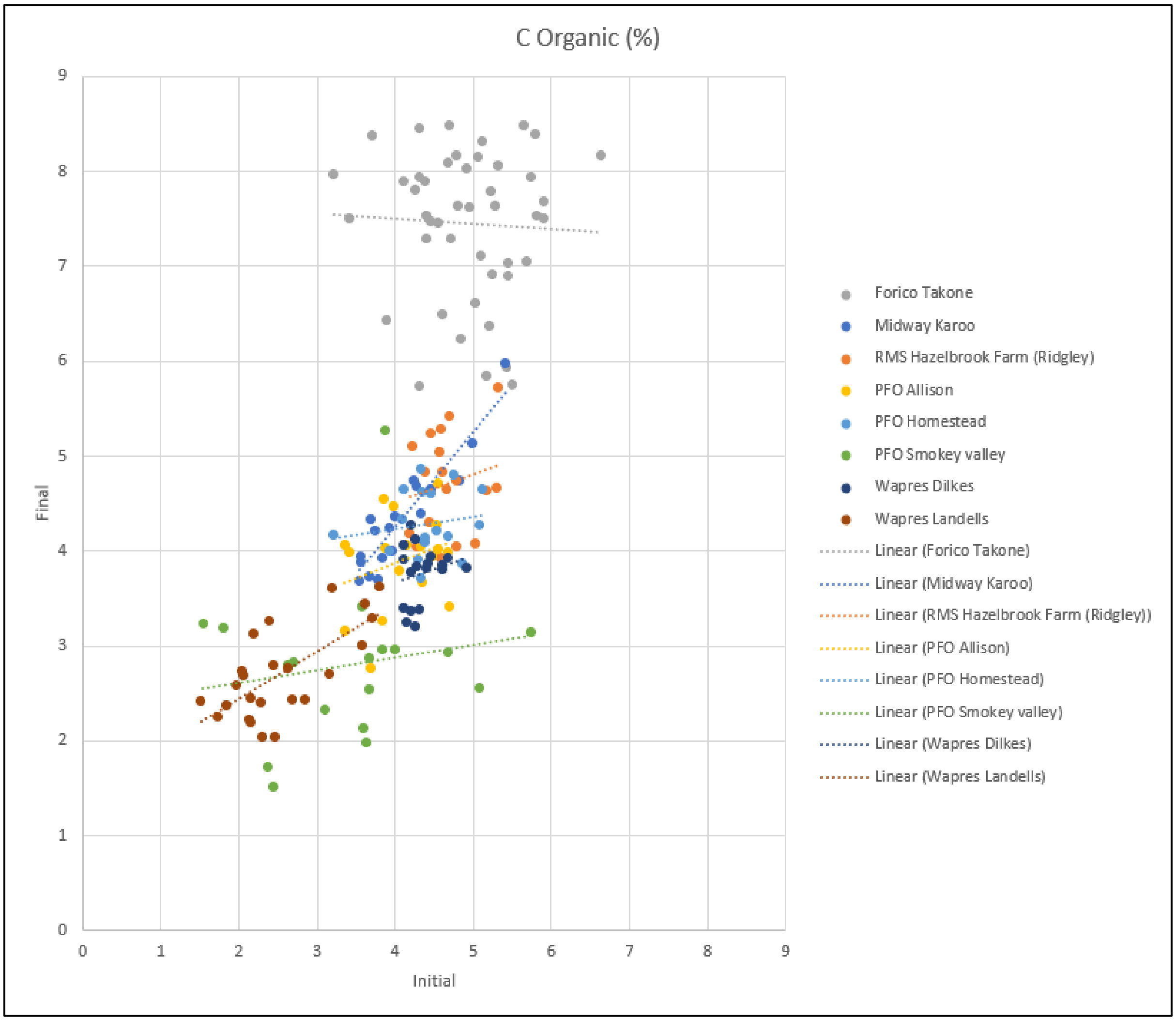


Figure 45. **Comparison of sites for organic C concentrations at the plot level.**

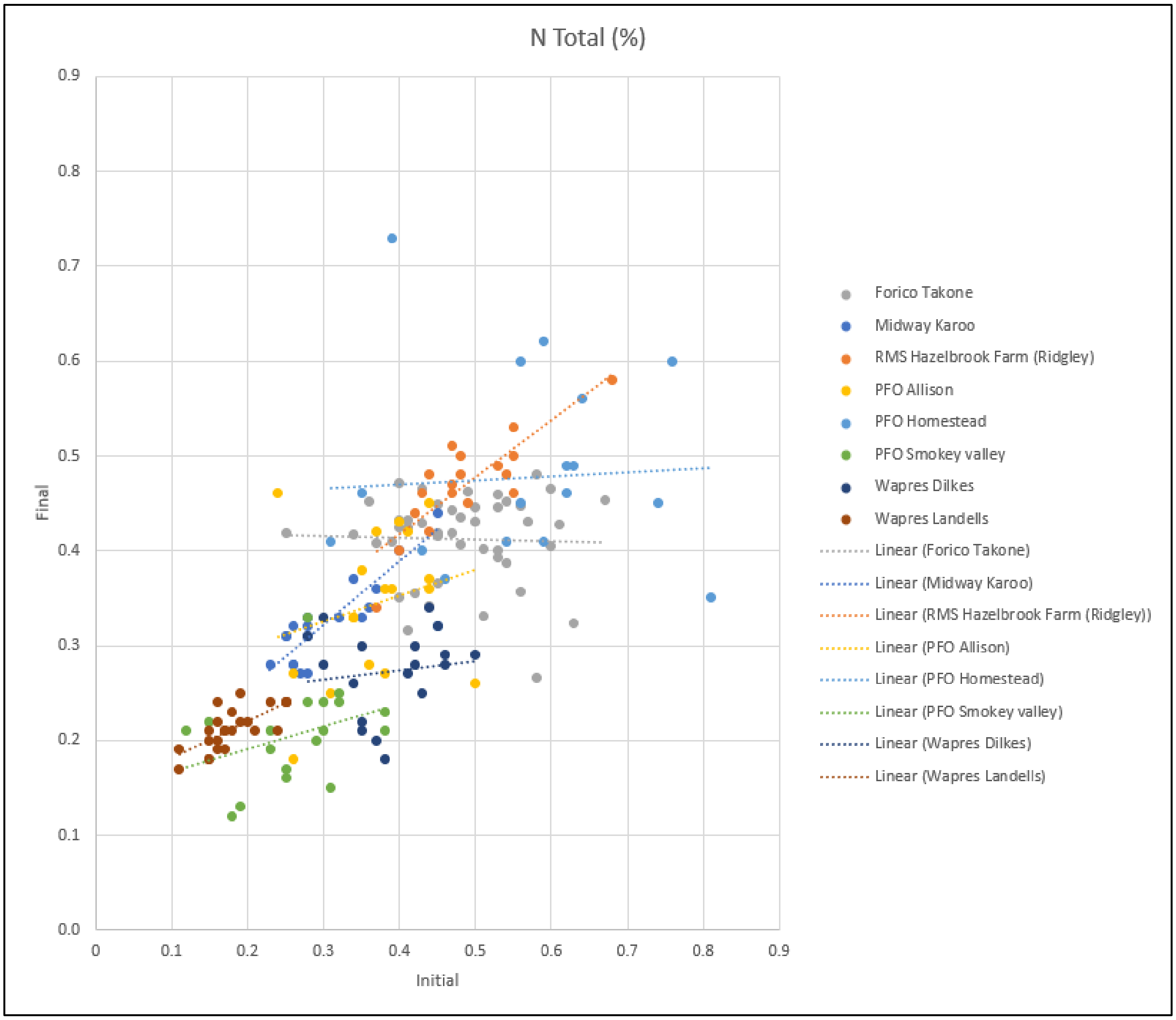


Figure 46. **Comparison of sites for total N concentrations at the plot level. Initial samples were taken in 2019 and final samples in 2022.**

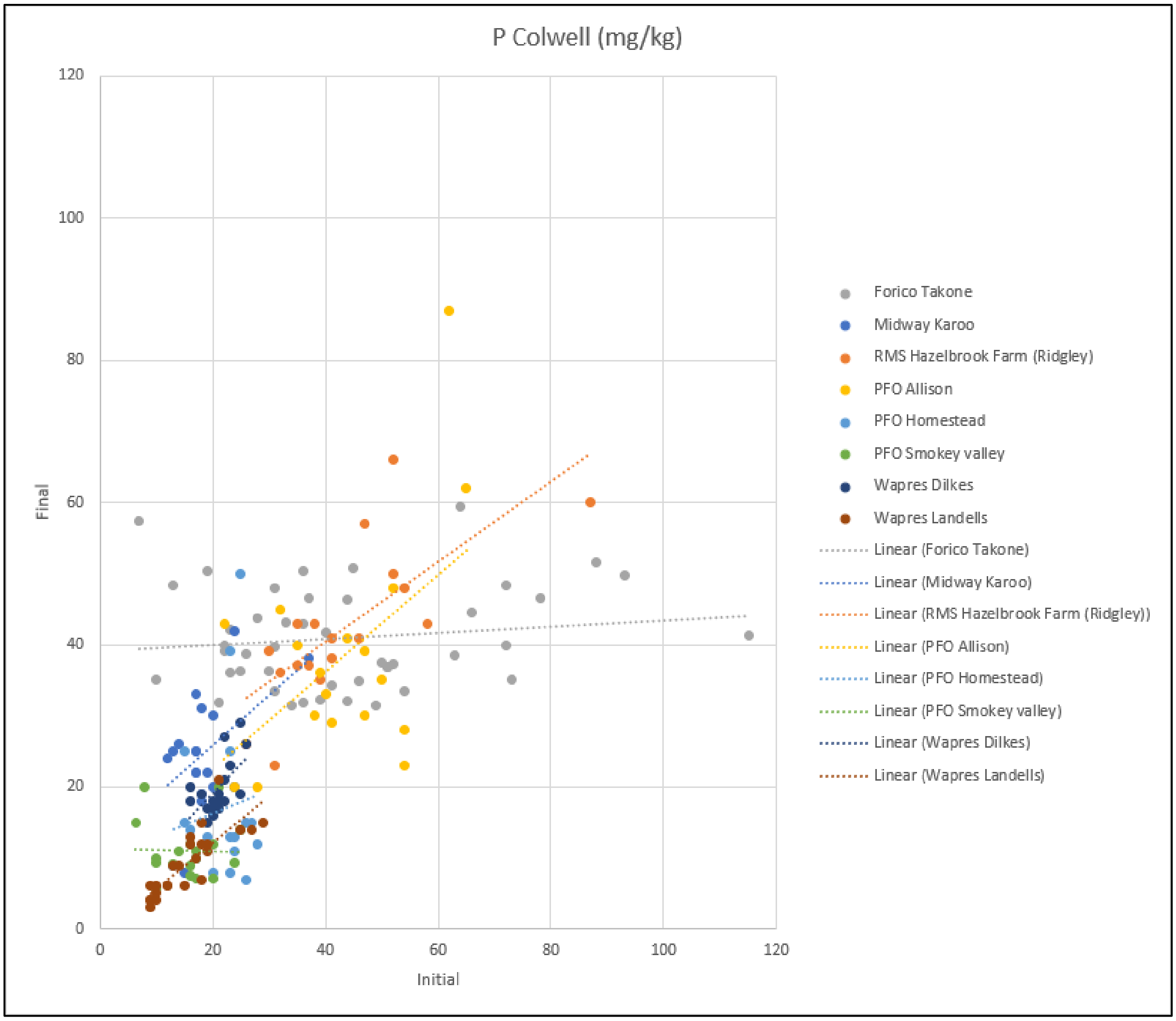


Figure 47. **Comparison of sites for Colwell P (bicarbonate P) concentrations at the plot level. Initial samples were taken in 2019 and final samples in 2022.**

INCORPORATION OF RESULTS FROM FERTILISER EXPERIMENTS INTO PROFERT.

The various results from the fertiliser trials have been incorporated into ProFert to enable it to predict responses to fertiliser applied to young *E. globulus* and *E. nitens* plantations across southern Australia. This section describes the different relationships that have been developed, explains how they have been incorporated into the model and outlines how ProFert operates to predict response and the inputs required to run the model.

The model basically requires five different relationships to predict response. These are:

1) Underlying growth of the stands in the absence of fertiliser;
2) Predicted maximum % response (the base response) to different fertiliser nutrients based on measured stand and site parameters;
3) Accounting for the effect of rate of application on the base fertiliser response;
4) Calculating the variation in annual response with time (i.e. for predicting the long-term response); and
5) Predicting the effect of fertiliser on the stand parameters (measured to predict response) over time (used to estimate responses to subsequent fertiliser applications).

These relationships are used to predict the potential % increase in growth for each year after fertiliser application. This relative annual increase is then multiplied by the underlying growth of the unfertilised stand to estimate the increase in volume over time until the stand is harvested. The final harvest volume is then multiplied by the wood value input for each product (after adjusting for the cost of harvesting and haulage for the particular site). This final value is then discounted to its current value and the cost of fertiliser is deducted to determine the profitability of fertilising the site.

The five relationships outlined above therefore drive the model and are used, together with values and costs input by the user, to determine both the increase in volume and profitability of fertilising different stands with a specific rate and type of fertiliser. The model also includes an optimiser which allows the user to automatically determine the optimum rates and types of fertilisers to apply at selected sites.

The derivation of the various relationships from the results of the study is described below.

Modelling underlying growth of stands in the absence of fertiliser

ProFert is designed to allow easy input by the user of relationships or data for predicting the underlying growth of stands from existing models used by the organisation. A particular site will generally have data available from permanent growth plots or the previous rotation which is used to estimate the growth and harvestable volume.

Where the expected annual growth of a stand is not available, ProFert uses a basic growth model to estimate this from the expected MAI at a given age so that a user can simply input this value. This model uses the tree growth formula used in FullCAM to estimate stem volume growth over time (Roxburgh et al. 2019).

This simple relationship has two parameters (M: the maximum volume for a site and G: the age of maximum growth) and has the following form:

$y = M*e^{(-k/t)}$

where: y is the standing volume at a given age,

M is the maximum volume that can be grown at a site in m^3/ha,

e is Euler's number (i.e. 2.7128),

k is related to the age of maximum growth G (where k = 2*G – 1.25), and

t is the stand age in years

Using stem volume outputs from FullCAM for different regions, this equation was parameterised to be able to match the shape of the growth curve for each region (WA, GT, southern Vic and Tasmania) so that the annual growth could be estimated by FullCAM based on the expected MAI for the stand input by the user. It is important to note that this formula does not enable ProFert to predict the MAI for the stand, simply the shape of the growth curve based on a given MAI.

Examples of growth curves for *E. globulus* for different MAIs (at 10 years of age) for the Green Triangle region are shown in Figure 48.

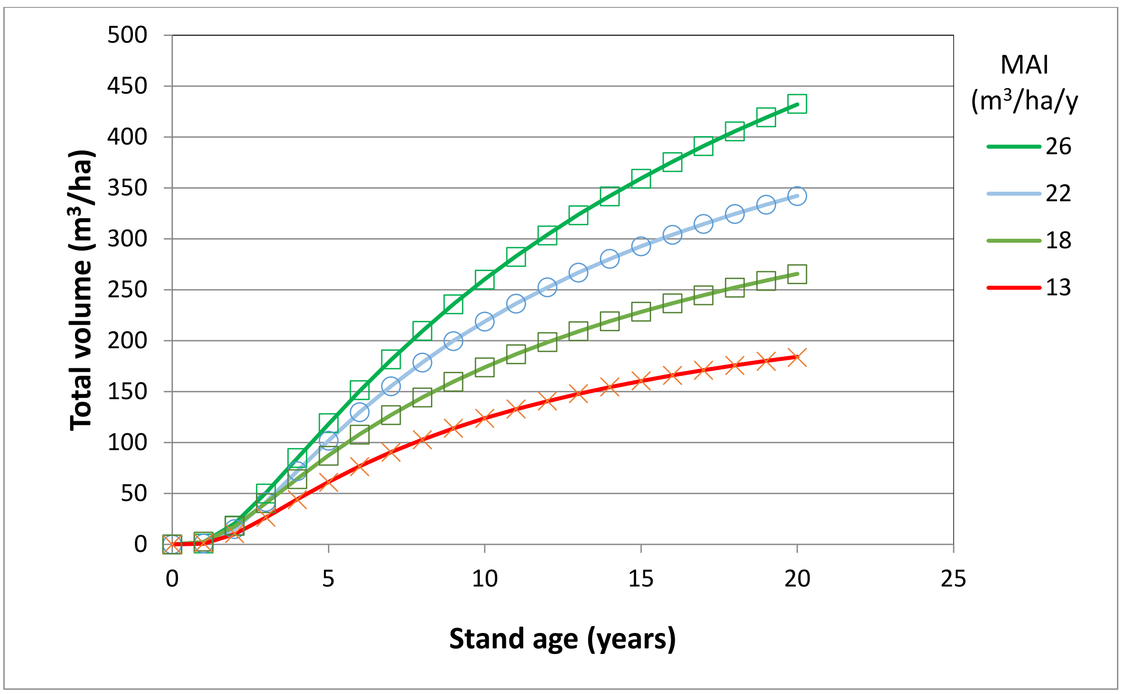


Figure 48. **Actual (markers) and predicted (lines) growth curves for E. globulus stands in the Green Triangle with MAI's ranging from 13 m³/ha/y to 26 m³/ha/y (at 10 years of age).**

Where an MAI is between the values modelled, ProFert estimates the growth curve by linear interpolation between the nearest two curves. Alternatively, where estimated annual growth for a stand is already available, the user can opt to use this rather than ProFert's built in growth curves by selecting the Site-Specific option (see section on running ProFert).

Predicting the base response to fertiliser

The best multiple regression relationships obtained from the project were selected to be used in ProFert to predict the base response to fertiliser. As explained in the section covering multiple regressions, the relationships were chosen based on their logic, strength, consistency and simplicity.

Based on these criteria two relationships were selected, one based on soil-analysis and another based on foliar analysis. These had the following forms:

Foliar relationship (Equation 4 Table 13b):

$$y = -29\mathbf{F_N} - 116\mathbf{NDVI} + 88\mathbf{CWI} + 11\mathbf{T_{Max}} - 106 \qquad r^2 = 0.43,\ \text{Adj } r^2 = 0.35,\ SE = 22.7$$

where:

- y is the 3-year relative cumulative response to N+P fertiliser
- F_N is the average foliar N concentration for the site
- NDVI is the Normalised Difference Vegetation Index for the site
- CWI is the average Climate Wetness Index for the site
- T_{Max} is the average max monthly temperature for the site

Soil relationship (Equation 8, Table 13b):

$$y = 4.07\mathbf{S_{C/N}} + 50.1\mathbf{CWI} + 6.33\mathbf{T_{Max}} - 178 \qquad r^2 = 0.30,\ \text{Adj } r^2 = 0.23,\ SE = 24.8$$

where:

- y is the 3-year relative cumulative response to N+P fertiliser
- $S_{C/N}$ is the average ratio between soil total N and soil total C concentrations for the site
- CWI is the average Climate Wetness Index for the site
- T_{Max} is the average max monthly temperature for the site

The 3-year climate data was used to construct the models as it was important that the growth of plantations and responses to fertilizer were related to the conditions under which they were grown.

It is important to note that while the relationship includes treatments fertilised with both N and P, no significant response to P alone was recorded at any of the 14 sites in the rates trials and the average response to P across the rates trials over 4 years was just 2%. Therefore, while applying N alone could result in a slight (2% on average) reduction in the response, this effect is expected to be very minor based on the 3-year data available. While no significant response to P is expected during this rotation from the current fertiliser treatments, it is possible that as the residual effect of P declines, positive NxP interactions could emerge.

The protocols for foliar and soil sampling as well as NDVI data acquisition are described in the Methods Section. The respective relationships between actual verses predicted % responses to fertiliser based on foliar and soil parameters are shown in Figures 36 and 38.

Effect of N fertiliser rate on response

The effect of rate of N applied on response was calculated from the average results for the N rate study across the 14 rates trials (see Fig. x in relevant section). Four rates of N were applied (0, 100, 200 and 400 kg N/ha) with 7 trials also having a 50 kg N/ha treatment. The responses were standardized by dividing them by the response to the maximum rate (400 kg N/ha). This was the rate used in the relationship to predict the base (maximum) response to fertiliser, so this process allowed the actual response to be calculated by simply multiplying the base response by the standardized factor for the rate of N applied.

A curve was fitted to the results to smooth the data and allow the effect of intermediate rates of fertiliser (i.e. rates not applied in the study) to be calculated by ProFert. An equation commonly used for modelling S shaped curves was used (Kucharavy and Guio 2007). This equation has 3 parameters and has the form:

$$y = ab/(b+(a-b)*e^{(-cR/100)})-b$$

where:

y is the predicted standardized response to N;
R is the rate of N applied,
e is Euler's number (base for natural logarithms), and
a, b and c are parameters for the equation.

The resultant curve is shown in Figure 49. This equation explained 99% of the variation between the points and had a standard error of 0.049 (i.e. +/- 5% of the response to 400 kg N/ha). The values for the parameters were:

a = 1.26021
b = 0.24061
c = 1.61811

To ensure that the calculated response to 400 kg N/ha was consistent with the base response, an adjustment factor was added to make the fitted standardization factor equal to 1 for 400 kg N/ha. This additional parameter had a value of 0.989 and was added as a multiplier for the overall equation as follows:

$$y = (ab/(b+(a-b)*e^{(-cR/100)})-b) * 0.989$$

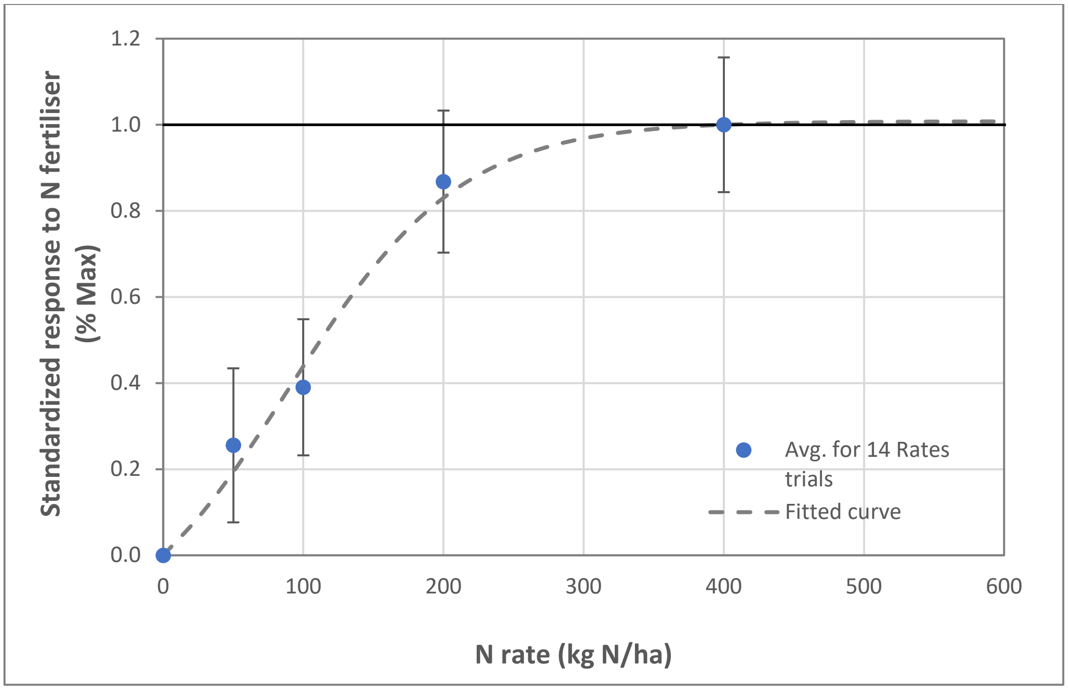


Figure 49. **Relationship between standardized response to N fertilizer (% response divided by the response to the maximum rate of N applied: 400 kg N/ha) and rate of N application. Error bars indicate standard errors of the means.**

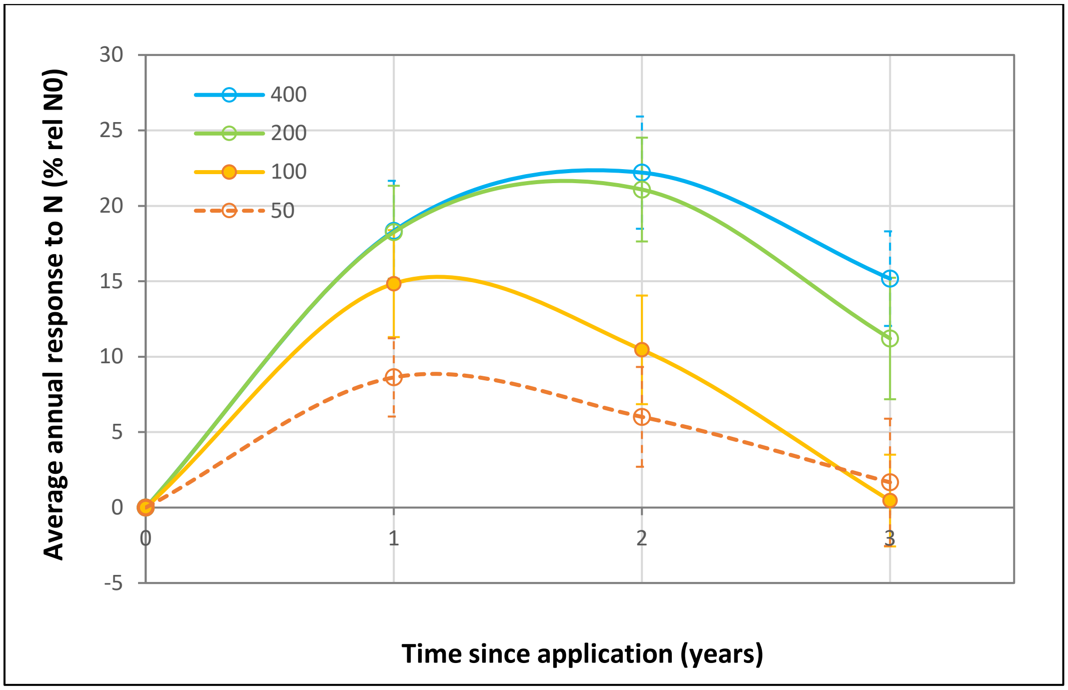
Time course of responses

In order to estimate responses to fertiliser over different time periods, ProFert converts expected cumulative 3-year responses to annual responses for periods of up to 20 years. The raw data for these annual responses was based on results from the N rates trials where 5 rates of N were applied (0, 50, 100, 200 and 400 kg N/ha) with and without P (100 kg P/ha).

The average annual and cumulative % responses for the various N rates over the three years are shown in Figure 50a and 50b (Note these are duplicates of Figures 16a and 16b shown here for convenience). The results for the 100, 200, and 400 kg N/ha rates were based on the averages across all sites while those for 50 kg N/ha were based on results from the 7 PFO sites only as this treatment was not applied at other sites. The values for this treatment were adjusted for the difference between the average annual response to 400 kg N/ha across these 7 sites and compared with that across all 14 sites.

The trends in the results indicate clear differences in the longevity of the response for the different rates of N applied. For rates of 50 and 100 kg N/ha, the annual response falls to close to zero after just three years, while, for 200 and 400 kg N/ha, the annual response clearly persists beyond this. Currently, four years growth response data is available for only a limited number of sites but the results from those sites support this observation. Previous versions of ProFert assumed that the longevity of the response to a particular nutrient was independent of the rate of application. However, these new results indicate that this assumption could result in the longer-term responses to fertiliser being overestimated for lower rates of N and underestimated for higher rates of N application. Therefore, this addition represents a significant improvement to the model.

a)



b)

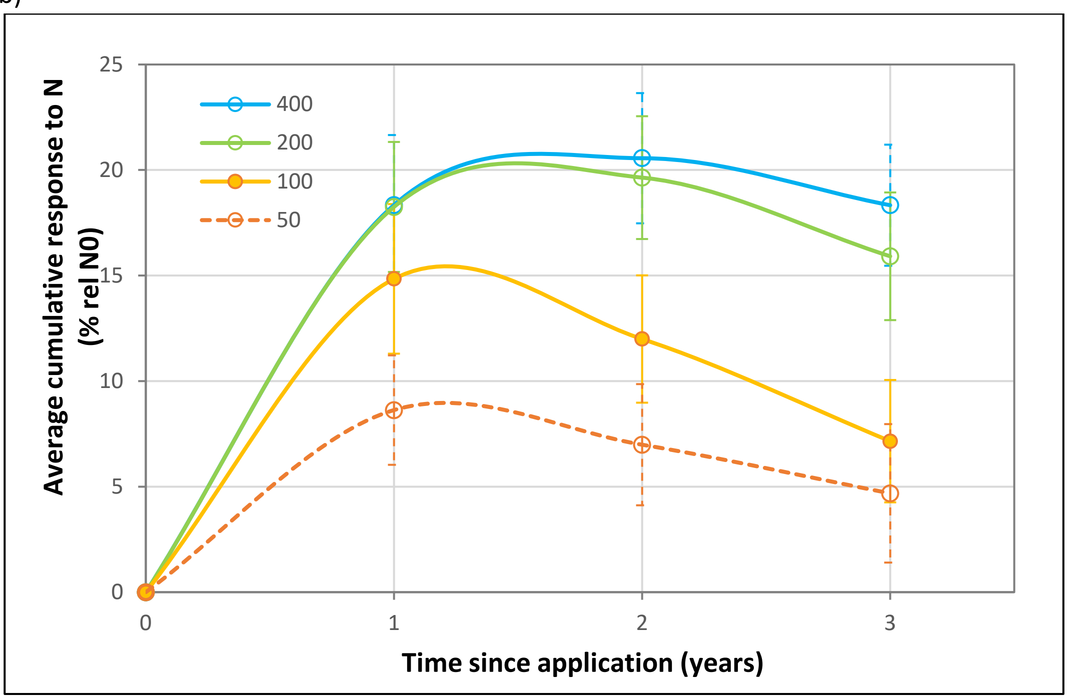


Figure 50. **Variation in average a) annual and b) cumulative % response to different rates of N fertiliser over time (relative to the N0 treatment). Note the curves for rates from 100 – 400 kg N/ha (solid lines) are based on all 14 sites in the Rates trials while that to 50 kg N/ha (dotted orange line) is based on the 7 PFO sites (adjusted for the difference in average response to 400 kg N/ha between the PFO sites and other sites). Points are the averages for the P100 and P0 treatments with K100 applied as a background across all plots.**

To model the effect of rate of N application on the annual response to N, curves were first fitted to the time-course data for each N rate and relationships were then determined between the parameters of each curve and the amount of N applied. Because only 3 years of data was available, a simple third order polynomial relationship with four parameters was fitted to each of the curves. This had the form:

$$y_{Rt} = a_R t^3 + b_R t^2 + c_R t \qquad \text{Equation. 10}$$

where:

y is the relative annual response to N;
R is the rate of N applied in kg N/ha;
t is the number of years after fertiliser was applied; and
a, *b* and *c* and the parameters for the relationship.

Before fitting curves, the temporal annual and cumulative responses were first standardized by dividing them by the average cumulative 3-year response. Standardization of the relationships is required in ProFert because the effect of the rate of fertiliser application on the 3-year cumulative response is already accounted for using the rate response curve shown in Figure 49. The temporal response relationships are then used to distribute this response over each of the prior 3 years and predict the subsequent annual response in future years. The standardized annual response curves therefore show the proportion of the 3-year cumulative response that occurs in any given year after the fertiliser is applied.

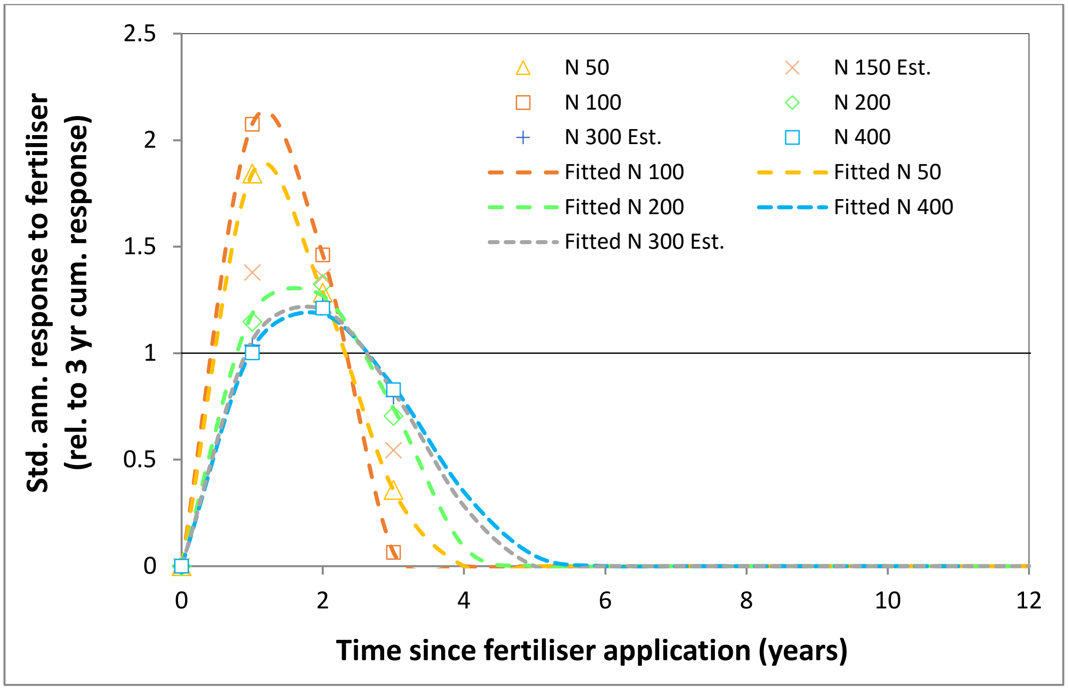
For the four rates of N applied, the cumulative 3-year responses were:

- 50 kg N/ha: 4.7%
- 100 kg N/ha: 7.2%,
- 200 kg N/ha: 15.9%,
- 400 kg N/ha: 18.3 %.

The standardized cumulative and annual responses are shown in (Figures 51a and 51b). It can be seen from these results that the shape of the curve for the 50 kg N/ha rate does not follow the expected pattern based on the curves for 100 kg N/ha and 200 kg N/ha. The former having an apparently longer duration than that for 100 kg N/ha whereas, based on the trend it could be expected to have a similar or shorter duration. This difference could be a result of the 50 kg N/ha rate being based on only half the 14 sites and therefore not being representative of the whole dataset. It is also important to note that neither the average response to 50 kg N/ha nor 100 kg N/ha was significantly greater from zero in the third year (averaging 1.7% for the former and 0.5% for the latter). Therefore, it was decided to exclude the results for the 50 kg N/ha treatment from the next step (finding relationships between the curve parameters and the rate of N applied).

Based on the fitted curves, longevities of the responses to other rates of N application, were consistent with results from other studies. Results from May et al. (2009) and McGrath et al. (2023 in review) for softwood plantations indicated that the maximum duration of the N response to 200 kg N/ha is normally around 5 years, while those from McGrath et al. (2023) indicate that the response to 100 kg N/ha was around 2-3 years while those to 400 kg N/ha are likely to be around 6-8 years. The fitted curves shown here indicate that the longevities of responses for the current study are likely to be around 2, 4 and 5 years for rates of 100, 200 and 400 kg N/ha respectively (Figure 51a).

a)



b)

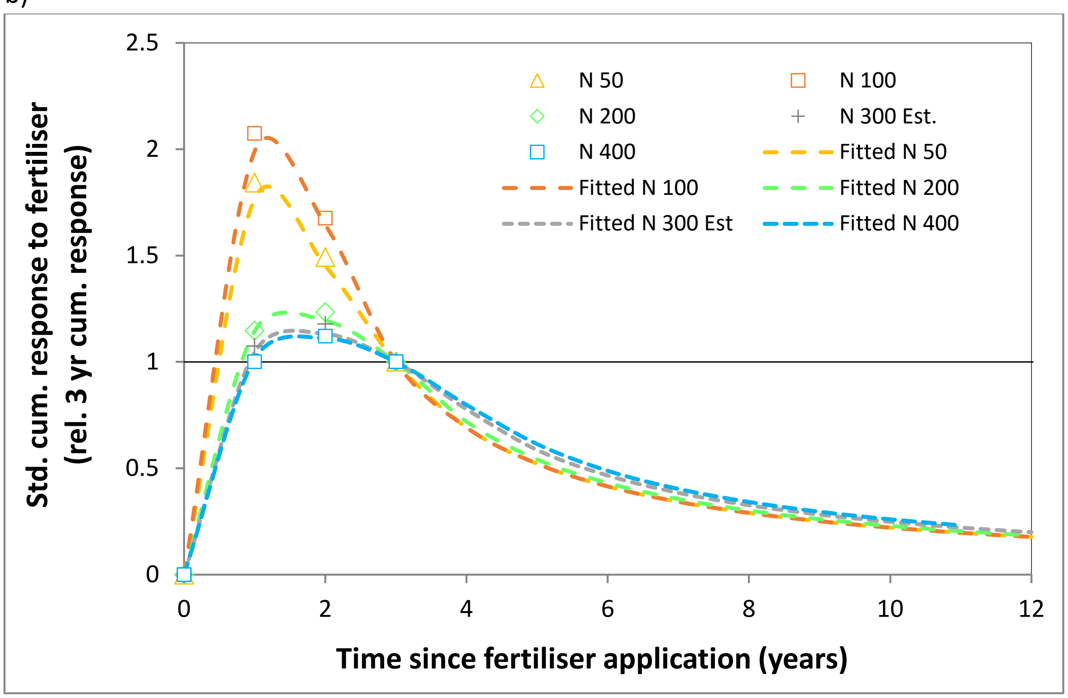


Figure 51. **Standardized a) annual and b) cumulative % responses to different rates of N fertiliser over time (relative to the % cumulative response 3 years after application). Points are average values from the 14 fertiliser rates trials and dotted lines calculated from the fitted curves for the standardized cumulative responses.**

Relationships between parameters a, b and c for the fitted curves and the rate of N applied are shown in Figure 52 together with their equations. In addition, a relationship between the longevity of the response (time in years until the annual response for the fitted curves falls to zero) and rate of N application was determined. This latter relationship was required to ensure that the fitted relationships to the time course response curves were not used past the point where the annual response fell to zero (i.e. past this point the cubic relationships fall below zero and then rise steeply). Inverse power relationships explained over 99.5% of variation for parameters a, b and c while logarithmic relationship explained 99.99% of variation in the response longevity.

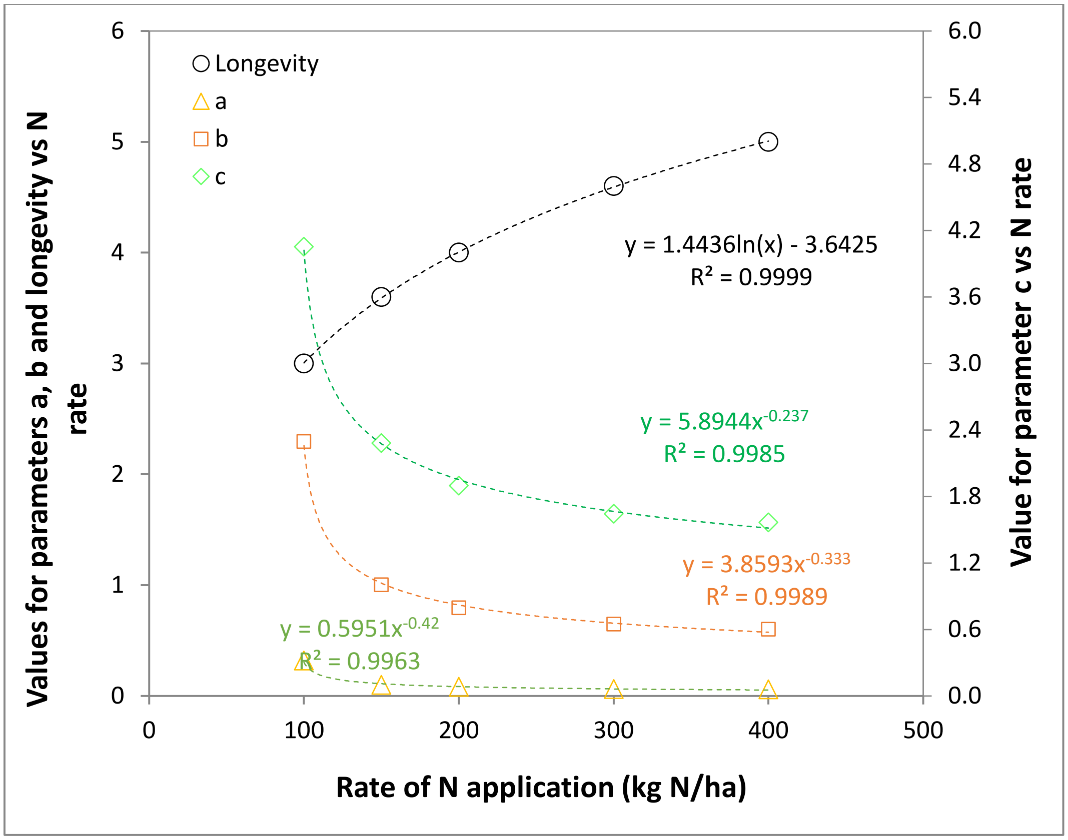


Figure 52. **Relationships between parameter values for the fitted curves for temporal cumulative response relationship and the rate of N applied. (Note the values for parameter a are estimated from the other three parameters and the values for the parameters for 300 kg N/ha were estimated based on interpolation from the other rates).**

The power relationships had the form:

$$p_i = d_i(R-e_i)^{f_i} \qquad \text{Equation 11}$$

where:

p_i is the parameter for the relationship (i.e. *a*, *b* or *c* from Equation 10)
R is the rate of N applied in kg N/ha;
d_i, e_i and f_i are the coefficients for parameters a, b and *c* from Equation 10.

while the logarithmic relationship had the form:

$lg = d_l \ln(R) - e_l$ Equation 12

where:

lg is the longevity of the response;
R is the rate of N applied in kg N/ha; and
d_l, and e_l are the coefficients for the relationship.

The coefficients and equations for estimating the values for the parameter in Equation. 1 are shown in Figure 2 and are given below:

$a = 0.595(R - 95)^{-0.420}$	$r^2 = 0.990$, SE = 0.079	Equation 13
$b = 3.86(R - 95)^{-0.333}$	$r^2 = 0.996$, SE = 0.037	Equation 14
$c = 5.89(R - 95)^{-0.238}$	$r^2 = 0.997$, SE = 0.026	Equation 15
$lg = 1.44\ln(R) - 3.64$	$r^2 = 1.000$, SE = 0.019	Equation 16

The final fitted curves for predicting the time course of standardized annual responses to different rates of N fertiliser are shown in Figure 53. These curves include those for intermediate rates of N (i.e., 150, 250, 300 and 350 kg N/ha) that were not tested as well as a curve for 50 kg N/ha predicted from the equations 13-16 above.

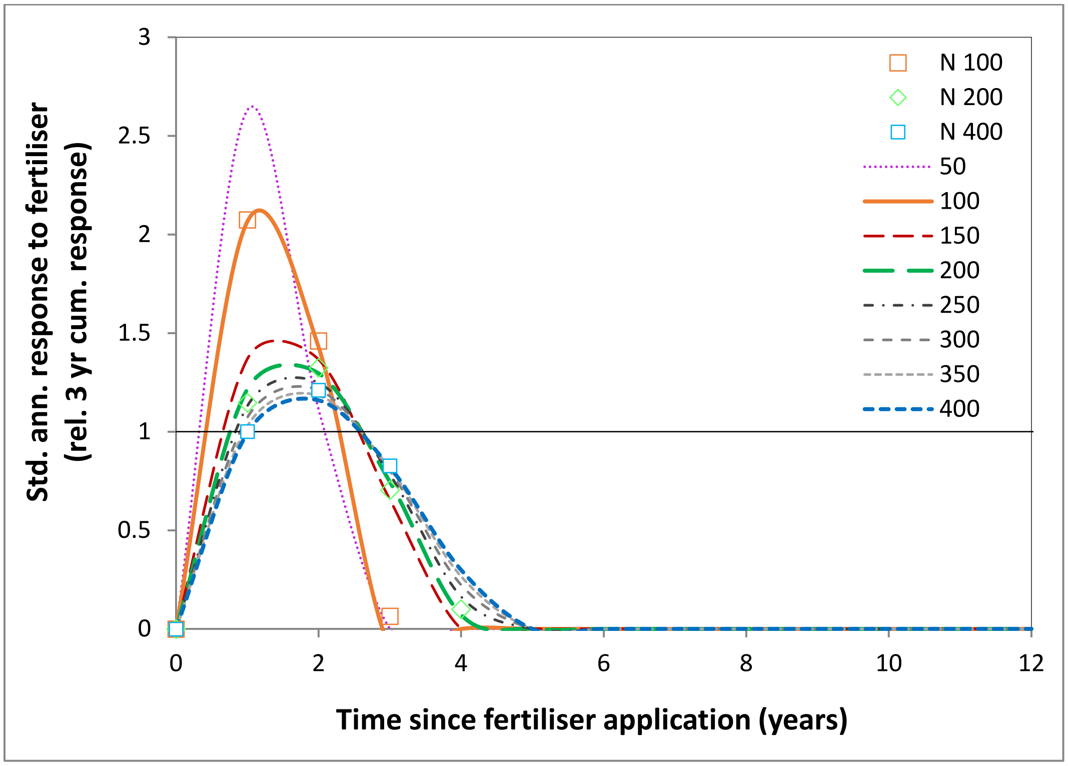


Figure 53. **Modelled standardized annual responses to fertiliser rates ranging from 50 to 400 kg N/ha annual % response to different rates of N fertiliser over time (relative to the % cumulative response 3 years after application). Points are average values from the 14 fertiliser rates trials and dotted lines calculated from the fitted curves for the standardized cumulative responses.**

The pattern of fitted curves appears sound with lower rates tending to have a larger proportion of their response prior to 3 years while higher rates tended to have a larger proportion of the total response occurring after 3 years. The longevity of the responses was also consistent with the 150 kg N/ha rate expected to last around 4 years compared with the 300 kg N/ha rate which was expected to last for 5 years. Whether the predictions are accurate will be determined from measurements of stand growth response to the different N rates over coming years. However, the current model represents the best data available.

The equations for predicting the parameters for the standardized cumulative response curves from N rate were input into ProFert. To prevent extrapolation outside the bounds of the dataset, the upper and lower limits for the effect of N rate on the curves were set to 400 kg N/ha and 50 kg N/ha respectively. The model was then tested to ensure that the predicted results matched the measurements from the various stands.

Effect of fertiliser on response predictors

The response predictors include foliar N and NDVI for the foliar-based relationship and soil N and organic C for the soil-based relationship. Both relationships also include CWI and maximum monthly temperature, but obviously these will not be influenced by the addition of fertiliser.

Total soil N and C are unlikely to change with the application of fertiliser since the applied N will normally only represent a small fraction of the total N in the soil. For example, for a soil with a total N concentration of 0.5%, the total mass of N in the surface 10 cm will be around 7500 kg/ha. Therefore, an application of 400 kg N/ha would only be expected to increase this by around 5% and only then if none of the applied N was taken up by the trees or leached past 10 cm depth. Similarly, soil C is unlikely to change much because of N fertiliser being applied. While fertiliser can increase rates of microbial activity resulting in loss (and gain of C), these effects are expected to be minor compared with the total carbon content of a typical soil (~10-50 t/ha).

As a result, it was assumed that there was unlikely to be substantial variation in soil N and C over time. However, this assumption has the drawback that these parameters will be insensitive to the effect of fertiliser applications and so may be less useful for predicting responses to subsequent applications. Of course, it is possible that the response of the trees may be similar for subsequent fertiliser applications which would validate this approach.

Foliar nutrients can change substantially in the short term in response to fertiliser application. However, these effects tend to be short lived (1-2 years maximum) for N with much of the N taken up used to grow more foliage thus diluting the effect. The effect of P fertiliser, on the other hand, can last for many years. In the current study, only the effect on foliar N is relevant as there was no growth response to P.

Little data is available for the effect of fertiliser on foliar nutrients in *E. globulus* plantations. According to a study by Bennet et al. (1996) and Judd et al. (1996), changes in foliar N and P were observed over a period of 4 years at three different locations in South Gippsland, after applying up to 400 kg N/ha in a series of applications from planting to the age of 2 years. The results from this study were consistent with those for other species indicating that foliar N concentrations were elevated by fertiliser for the first year only and returned to about the same level as the control after 3 years.

A simple model was used to estimate the short-term (1-4 year) impact of fertiliser on foliar N concentrations based on the above results. The formula for the model was:

$$y = f/(1 + \exp(r(t\text{-}m)))$$

where:

y is the absolute change in foliar nutrient concentrations (% dry weight) t years,
f is the initial (maximum) change in concentrations after fertiliser application,
r is the rate of decline in foliar nutrients, and
m is the time of the midpoint of the decline.

The parameters for the relationship were tentatively determined using Solver to fit the relationship to data from Bennet et al (1996) and Judd et al (1996). The final relationship was:

$y = 0.114/(1 + \exp(1.49(t-2.31)))$ $r^2 = 1.00$ MSE = 0.000 Equation 17

N fertilizer increases canopy growth of trees on responsive sites and its effect on NDVI is likely to be pronounced and longer lived than that for foliar N. As part of the current study, NDVI data has been collected and analysed for fertilised and unfertilised treatments across the sites. These results clearly show a small but significant increase in NDVI over the first 3 years post fertiliser application on responsive sites. While it is too early to make any conclusions regarding the longevity of this effect, it appears to be continuing well into the fourth year after application for the sites fertilised in 2018.

The expected change in NDVI in response to N fertiliser was calculated from the above data by calculating the averaging difference in NDVI across all sites for each year after fertiliser application. The form of the relationship was the same as that used for foliar N was then fitted to this data. The final relationship was:

$y = 9.09/(1 + \exp(0.691(t-1.65))$ $r^2 = 0.997$ MSE = 0.118 Equation 18

The longevity (time until the response fell to zero) for the NDVI response was set to 6 years to be consistent with the modelled longevity of the growth response to 400 kg N/ha. The final relationship is shown in Figure 54 together with that for foliar N. As with the relationship predicting the change in foliar N concentrations, the model predicting NDVI response should be considered tentative only at this stage.

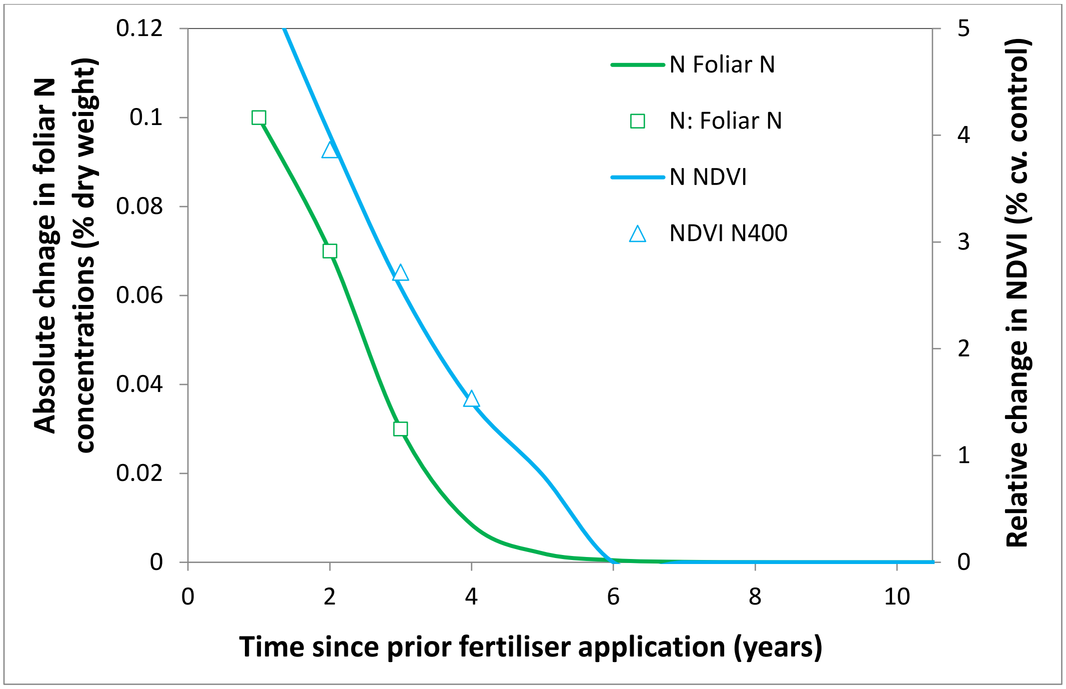


***Figure 54*. Modelled and actual changes in foliar N and NDVI and for the 10 years following fertiliser application for a stand fertilised with 400 kg N/ha. Actual data for foliar N (green squares) are based on results from Bennet et al. (1996) and Judd et al. (1996), while that for NDVI (blue triangles) is based on NDVI data for the 14 rates and 23 response experiments in the current study.**

The outcome of these predicted responses of foliar N and NDVI to N fertiliser is that the responses to subsequent N applications (applied within 3-6 years of the initial application) are expected to be smaller than the initial response provided that other factors (i.e. foliar N concentrations) remain steady.

An important caveat applies to these relationships. They do not consider typical changes in foliar N and NDVI as the stand grows. It is expected that foliar N may continue to decrease over time between ages 1 and 5 (O'Brien et al 2003, confidential unpublished report) while tree canopies will likely expand over the same period until they reach canopy closure. NDVI data is being continually collected for all core treatments across the sites and foliage was resampled from fertilised plots and controls in 2022. This data is currently being analysed and will be used to include the expected changes in both foliar N and NDVI over time with and without fertiliser in ProFert.

Sites were re-fertilised in 2022 and initial growth responses will be available in 2023. These responses will be compared with predictions based on the current relationships to determine whether they need to be modified.

SUMMARY AND RECOMMENDATIONS BASED ON FIRST THREE YEARS OF DATA

Fertilizers

Consistent with the high soil K concentrations at the rates trial sites (Table 5) there was no response to potassium. Furthermore, none of the 14 sites in the rates trial had a significant response to P three years after application. The one site (Burrell, WA) that appeared to demonstrate a significant response to P one and two years after fertilization did not show a significant response three years after fertilization (Figures 10, 11).

There were significant responses to N. In the rates trials, these ranged from 5% up to ~40% for N alone (400 kg N/ha) and from 1% to ~50% where N was applied together with P (100 kg P/ha). In the response trials (where N was applied together with 100 kg P/ha) a similar range of response was found except for the two trials at Scott River where responses of 93% and 130% were recorded. As the rate of N was varied, there was a progressive increase in response up to 200 kg N/ha (equivalent to 435 kg/ha of urea). Based on the trial data, applying 200 kg N/ha will result in an average increase in production of 20% during the first 2 years following fertilization, however this declined to 16% by year three. Importantly, the responses to lower rates of N (50 and 100 kg N/ha) were lower and the responses declined more quickly than when higher applications were used. The 'standard' applications used by the industry partners did not enhance growth significantly. Responses to N fertiliser tended to be greater on infertile (low nitrogen) sites with favourable climatic conditions.

The overall productivity of hardwood plantations and the responses to nitrogen were strongly influenced by temperature and water availability. When nutrient supply was eliminated as a constraint on growth by providing adequate supplies of N, P and K and where water supply was high, the potential productivity of plantations virtually doubled from 20 to 37 m^3/ha/yr as temperature increased from 14^0C to 22^0C. By excluding water stressed sites, the increase across this temperature range was from 20 to 45 m^3/ha/yr. When water supply was limited by rainfall and evaporation the productivity was lower than the potential productivity that was determined by temperature alone.

Soil N concentration appears to provide an indication of the upper limit to the response to applied nitrogen under favourable temperature and water availability. It appears that temperature and water supply constraints influence the responses to N application. Where growth is limited by either low temperature or water supply, responses to N tend to be lower and the soil N concentration that provides a limit to productivity is also appeared to be lower compared with more favourable sites.

Based on the responses in the first three years post fertilization we provide the following recommendations:

- Potassium application appears unnecessary on these ex agricultural sites. However, this needs to be monitored as the international experience is that potassium may become more of an issue over multiple rotations.
- Mid-rotation phosphorus application appears unnecessary on these ex agricultural sites; however it is likely that the P supply from prior agricultural fertilization will decline over time and this needs to be monitored.

- Applying 200 kg N/ha (equivalent to ~435 kg/ha urea or 952 kg SOA) will increase plantation productivity. Higher rates did not consistently increase the productivity of the plantations, but the responses may be prolonged with higher applications.
- The strongest responses to nitrogen application were observed on warmer wet sites. Thus, the responses to nitrogen application will likely be greatest on wetter sites in southern WA.
- Conversely the colder Tasmanian sites, which generally had higher soil nitrogen, demonstrated limited responses to applied N.

Harvest residues and fertiliser

There was a clear and substantial positive effect of starter fertiliser on individual tree growth at all sites, which averaged c. 10% increase for height and diameter (DBHOB). This response was not maximised by the rates of fertiliser used in this series of experiments, as there was no evidence of the responses plateauing at the highest rate (double the normal operational rate) applied. In contrast, tree survival was negatively affected, decreasing from an average of 89% without fertiliser to 81% with a high rate of fertiliser. This moderated or negated the potentially positive effects of fertiliser treatments on productivity.

These results suggest that, although growth of individual seedlings was enhanced by addition of N and P, the fertiliser may not have been appropriately applied to all seedlings (i.e. too much might have been placed too close to seedlings in the wrong form at the wrong time). Further, the analysis provided in the earlier Yield Gap project suggests that a survival of 89% with an initial stocking of 789-1615 trees/ha would have been limiting to growth in some plots. Further research is needed to provide more optimal results for establishment fertilisation.

There was no consistent effect of harvest residues on survival or growth of seedlings across the sites. A range of harvest residue management methods were used across the sites, but no significant effects were detected when grouped into similar methods, because of (a) the variability in definition that remained within the groups, and (b) because harvest residue management was not replicated within sites. In addition, insect browsing at least at one site (Smokey Valley) resulted in substantial mortality, reducing growth across all treatments, potentially masking the effects of harvest residue treatments.

These results suggest that the positive effects of harvest residue retention identified in earlier research are not being realised in this series of experiments. We can speculate about the reasons for this result. Harvest residue layers were probably not uniform or deep enough to provide the mulching effects of reduced soil drying and weediness, and to moderate temperature extremes under the adequate rainfall and weed control conditions used. The trees that survived benefited from increased nutrient availability from fertilisers and would have similarly benefited from nutrient release from harvest residue if that was close and timely enough for the trees to access it. In this respect, the nutrient benefits of harvest residue retention might not have yet been fully realised. Given that all these sites are ex-farmland and that, except for a few infertile high rainfall warm sites, the responses to N were generally less than 20%, we were unlikely to detect substantial fertiliser or residue management effects or interactions given the trial designs and implementation methods.

Based on the responses in the first three following establishment we provide the following recommendations:

- Controlling insect browsing is crucial to plantation performance,
- Harvest residue should be retained as a precautionary measure where practical, and
- Fertilizer should continue to be applied to newly planted seedlings at the standard rate. But there is evidence that higher rates can give substantial responses, especially if mortality can be managed.

Future research should be aimed at developing consistent practical methods of removing and retaining harvest residue within and between sites, and avoiding the negative effects of harvest residue retention on survival and growth that were seen at some of the current sites.

Predicting fertilizer responses

Foliar N appeared to be a better predictor of response to N fertiliser than soil N or soil C/N ratios. When combined with NDVI (as a surrogate for leaf area) and climate variables (CWI and average monthly maximum temperature), the relationship explained 43% of the variation in the relative % increase in growth for fertilised treatments compared with controls. In comparison, a relationship including soil C/N, CWI and maximum temperature explained 30% of variation in response. However, due to the dynamic nature of foliar nutrient concentrations within the canopy, between seasons and with age, there will need to be strict guidelines around sampling procedures to ensuring that the technique provides reliable assessments of nutrient status.

These relationships have been incorporated into ProFert together with those modelling the effect of different rates of N on response magnitude and longevity as well as the relationships predicting the effect of fertiliser on foliar N and NDVI (to predict responses to multiple fertiliser applications over the rotation).

The modifications to ProFert enable it to predict responses to N fertiliser across *E. globulus* and *E. nitens* plantations across southern Australia. While there are considerable uncertainties and assumptions in the underlying relationships, the resultant model is expected to provide a useful tool for growers and should represent a major improvement on current methods for identifying potentially responsive young stands to fertiliser and determining the optimum rate of fertiliser to apply. The updated version of ProFert has been provided to growers for testing and will be refined and improved over time based on their feedback. As new results from the next stage of the project become available, these will be incorporated into the model and relationships updated or modified accordingly.

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APPENDIX 1 NUTRITION TRIAL NETWORK SITE CHARACTERISATION REPORT

'Optimising nutrition management of hardwood plantations for sustainable productivity and profitability. *(PNC478-1819)* March 2020

Ian Dumbrell IPMG, John McGrath MFS, Philip Smethurst CSIRO, Barrie May TreeMod, Daniel Mendham CSIRO

Introduction/Background

Declining productivity of successive hardwood rotations has been variously attributed to changes in water availability, pest damage and nutrient availability. Appropriate management of site nutrition has the potential to allow plantation managers to sustainably maintain or improve productivity over successive plantation rotations. Nutrient management may involve site-appropriate management of harvest slash residue and/or application of fertiliser.

At an operational level there is a lack of confidence as to how best to manage nutrition effectively on multi-rotation sites in order to boost or maintain productivity. Management of nutrition across site types and across multiple rotations through improved slash management or fertiliser needs to be informed by evidence.

In the absence of empirical data, hardwood growth responses to nutrition have been modelled using process-based models (e.g. CABALA, FPOS). These models are not routinely used by plantation managers. One of the main cited reasons for the lack of industry take-up is the lack of empirical data across different multi-rotation sites to validate the modelling results and thereby provide confidence with fertiliser decision-making. Alternatively, a new empirical-based model developed for predicting the growth response to and profitability of fertiliser use for softwood plantations (ProFert, May *et al.* 2017) has had good industry uptake and is now being used operationally in softwood plantations. Like all models, ProFert requires data from fertiliser experiments to calibrate its nutrient response predictions for hardwood plantations.

This project will build on the existing hardwood plantation nutrition knowledge by:

1. Establishing a nutrition trial network designed to address the gaps in nutrition response knowledge, specifically in relation to the responsiveness to variations in soil and foliar nutrient concentrations and in relation to soil characteristics and climatic conditions.
2. Using the knowledge from past research and the nutrition trial network to develop tools that allow hardwood plantation managers to better target their fertiliser management on a site specific basis, as follows:

This report addresses 1, which is the first part of milestone 4 of the project. For 2, an assessment of the status of the available tools is presented separately as the second part of Milestone 4.

Objectives of the Project

This project aims to assist plantation managers increase the productivity and profitability of multi-rotation hardwood plantations by developing knowledge and tools that will identify the most responsive sites and optimising nutrient management across sites. This will be done by providing the knowledge that supports economic and sustainable nutrition management decisions for multi-rotation hardwood plantations.

Objectives of the Report

The aim of this report is to describe various components of the three series of trials at the start of project to act as a reference for subsequent analyses of results and model inputs. These components include:

- Experimental design
- Site locations and physical description
- Key experimental establishment dates
- Treatment application methods
- Pre-treatment soil and foliar nutrient status
- Pre-treatment tree measurements
- Any additions or anomalies that may influence future analyses

A photographic record of the majority of sites prior to treatment is stored with the project manager. Some of these photos are included in this report for illustrative purposes.

Project manager

Ian Dumbrell and subsequently Danielle Wiseman (IPMG)

Associated Personnel

Barrie May TreeMod, John McGrath MFS, Daniel Mendham CSIRO, Philip Smethurst CSIRO,

Associated organisations

Forest and Wood Products Australia, WA Plantation Resources, PF Olsen, Australian Bluegum Plantations, FORICO, Reliance Forest Fibre, Midway, SFM

Overall project design

The development of predictive tools to assist decision making by plantation managers will utilize both existing and additional data developed in this project. A network of nutrient response experiments has been established with three components across several states:

- **Component 1. Responsiveness of multi-rotation plantations to nutrient inputs mid-rotation (ages 2-5) -Factorial rate trials** which explore tree growth response to different rates of nitrogen, phosphorus and potassium and/or combinations thereof.
- **Component 2. Responsiveness of multi-rotation plantations to nutrient inputs mid-rotation (ages 2-5) - Diagnostic responsiveness trials.** These experiments will examine the relationships between nutrition diagnostic factors and subsequent tree growth response to fertiliser across a regionally representative set of plantation sites. Key climate, site, soil, and foliar diagnostics will be characterised at each of the sites.
- **Component 3. Responsiveness of multi-rotation plantations to nutrient inputs and/or slash retention at re-establishment.** These experiments will examine the diagnostic factors identifying those sites most likely to be affected by slash removal and most responsive to fertiliser applied at

establishment across a regionally representative set of sites. Key climate, site, soil, and foliar diagnostics will be characterised.

Locations

Forty-two trial sites are located across three states (WA, Vic, Tas) Specific details of the sites are provided in the three sub sections outlining the details of the trial establishment.

Total Trials installed by Industry Partners

Collaborators	WA	GT / VIC	TAS	Total
PF Olsen	8	9	0	**17**
WAPRES	9	0	0	**9**
ABP	2	0	0	**2**
Forico	0	0	4	**4**
RFF	0	0	4	**4**
Midway	0	4	0	**4**
SFM	0	2	0	**2**
Totals	**19**	**15**	**8**	**42**

COMPONENT 2: FACTORIAL RATE TRIALS

Note: The factorial rate trials (Component 2) is presented first in this Appendix as the initial report was configured this way, we have aligned the Components to overcome any confusion between the material in this appendix and in the main report.

Objectives

These trials are designed to assess the tree growth response to different rates of nitrogen, phosphorus and potassium and/or combinations thereof installed across sites with a range of fertility and climate. This will allow the interaction between nutrient supply and climate to be described.

Background

There is an industry perception that much of the research undertaken may only be applicable to particular regions, species, rotation, or site situations. Clearly articulated operational level fertiliser guidelines on the timing and application of nutrients to maximize growth are still mostly lacking. Growth and economic modelling tools such as FPOS and ProFert are not currently deemed to be operationally useful or been adapted for use in hardwood plantations.

Site details

Table 1. **Location and site description**

Company	State	Site name	Trial code	Coordinates		Soil type	Mean rainfall
RFF	Tas	Hays RHYS		-41.4122	146.1459	Loamy/clay	1472
Forico	Tas	Myrtle Bank	TR102B	-41.2915	147.3515	Dermosol	1292
Midway	VIC	Karlinski		-38.5523	143.1554	Clay loam/clay	1000
PFO	VIC	Andrew	0059E	-37.8982	141.0984	Sand	741
PFO	VIC	Henke	0059A	-37.9750	141.1880	Sandy Loam	740
PFO	VIC	Moorabinda	0059F	-37.4419	141.6817	Brown clay loam	658
SFM	Vic	Danyenah	N/A	37.9085	141.8476	clay loam	653
PFO	VIC	Wallabadah	0059D	-37.4140	141.5990	Clay Loam	652
Wapres	WA	Lake Jasper	FT37	-34.3680	115.6780	Deep sand	1050
PFO	WA	Fagan	0065B	-34.9093	117.1289	Sandy Loam	989
ABP	WA	Jones	SSP189/02	-34.6974	117.3300	Sandy Loam	787
ABP	WA	Parola	SSP189/01	-34.7977	117.9600	Sandy Loam	773
PFO	WA	Lyon	0065C	-34.8340	118.0703	Sandy Loam	699
PFO	WA	Burrell	0065A	-34.7106	118.3087	Sandy Loam	614

Trial summary

Each experiment will comprise 30 plots, consisting of 3 replicates x (4 N rates (0, 100, 200, 400 kg N/ha) x 2 P rates (0,100 kg P/ha) + 2 K rates (0,100 kg K/ha). There are 6 trials in WA, 6 in Victoria and 2 in Tasmania.

Table 2. **Summary of Rates trials**

Collaborators	Number of trials			
	WA	GT / VIC	TAS	Total
PF Olsen	3	4		7
WAPRES	1			1
ABP	2			2
Forico			1	1
RFF			1	1
Midway		1		1
SFM		1		1
Totals	**6**	**6**	**2**	**14**

Figure 1. **Location of factorial rates trials**

Key establishment and measurement dates

Table 3 Installation details

Company	State	Site name	Trial code	Planted or Coppice	Month/year planted or harvested	Date soil sampled	Date foliar sampled	Initial measurement date	Date treatments applied
RFF	Tas	Hays RHYS		Planted	Sep-17	16/09/2019	16/09/2019	1/10/2019	31/10/2019
Forico	Tas	Myrtle Bank	TR102B	Planted	2017	16/08/2019	25/10/2019	7/06/2019	17/12/2019
Midway	VIC	Karlinski		Planted	Aug-16	15/05/2019	30/09/2019	mid-Oct	26/09/2019
PFO	VIC	Andrew	0059E	Planted	Jul-18	8/06/2019	19/08/2019	21/08/2019	12/09/2019
PFO	VIC	Henke	0059A	Planted	Jul-17	13/09/2018	13/09/2018	5/09/2018	18/09/2018
PFO	VIC	Moorabinda	0059F	Planted	Jul-18	23/07/2019	19/08/2019	19/08/2019	10/09/2019
SFM	Vic	Danyenah	N/A	Planted	Jul-16	27/05/2019	18/09/2019	16/09/2019	26/09/2019
PFO	VIC	Wallabadah	0059D	Coppice	Mar-15	12/09/2018	12/09/2018	5/09/2018	20/09/2018
Wapres	WA	Lake Jasper	FT37	Planted	June -16	27/09/2018	27/09/2018	5/10/2018	28/09/2018
PFO	WA	Fagan	0065B	Planted	Aug-17	2/05/2019	3/09/2019	17/04/2019	30/10/2019
ABP	WA	Jones	SSP189/02	Planted	Jul-17	22/08/2019	27/08/2019	24/06/2019	6/09/2019
ABP	WA	Parola	SSP189/01	Planted	Aug-17	21/06/2019	22/08/2019	20/06/2019	20/08/2019
PFO	WA	Lyon	0065C	Planted	Aug-17	13/05/2019	21/08/2019	12/05/2019	5/09/2019
PFO	WA	Burrell	0065A	Coppice	Aug-16	22/04/2019	23/08/2019	11/04/2019	29/08/2019

Future assessment program.

- Annual height and diameter measurements will be taken. While the trials were established at slightly different times during the year it is intended to bring the measurement times to a common month (June) so that it is easier to compare the growth and the treatment responses between the sites.

Soil nutrient status will be reassessed at the end of the trial

Trial design

Table 4. **Summary of trial design details,**

(a) Core treatments at all sites (Treatment details in Table 5)

Number of treatments	10 (2 N rates x 2 P rates with basal application of K (8), plus 0N,0P, **0K** and 400N, 100P **0K** (2)
Replicate blocks	3
Total Plots	30
N rates	0, 100, 200, 400 kg/ha
P Rates	0, 100 kg/ha
K rates	0, 100 kg/ha
Internal measurement plots*	Nominally 30 tree plots (0.03 ha), noting that actual plot areas will be used to calculate basal area and volume per ha
External treatment plots*	8 rows x 10 trees (nominal) 25 x 32 m = 0.08. However this varied slightly e.g. PFO trials were 7 rows x 14 trees
Gross area of trial*	~2.4 ha at each site

*Indicative only, the exact plot size between sites based on plantation configuration and status.

(b) Additional treatments installed by industry partners

Site	Additional treatments	Treatments
ABP Jones	3 (9 plots)	133N 23P 0Trace, 133N 23P Plus Trace, 133N 46P
ABP Parola	3 (9 plots)	133N 23P 0Trace, 133N 23P Plus Trace, 133N 46P
Forico	2 (6 plots)	100P, 100N individually
PFO sites	6 (18 plots)	6, with additional 25 and 50 kgP/ha and 50 kgN/ha treatments

Note: *While the additional treatments were installed by the industry participants to address questions related to their specific situations this report focuses on the 10 core treatments across the 14 sites as they form the basis of this component of the project. This Site Characterisation Report will be relevant to the additional work. While some of these treatments may assist in addressing the issues being examined by the overall matrix of trials, the value of including these additional investigations will be evaluated by the Steering Committee and the Research Providers as the project progresses.*

Fertiliser application details

Table 5a. **Treatments and application rates for NxPxK rates interaction trials**

	Elemental nutrients (kg/ha)		
Treatment	**N**	**P**	**K**
1	0	0	0
2	0	0	100
3	0	100	100
4	100	0	100
5	100	100	100
6	200	0	100
7	200	100	100
8	400	0	100
9	400	100	100
10	400	100	0

Table 5b. **Fertilisers used in the rates trials:**

Company	**Rates trials**	
	Fert type	Application
PFO	Sulphate of Ammonia (SOA) AllPhos (TSP) Muriate of Potash (MOP)	Hand applied (broadcast) separately (i.e. not blended)
Wapres	Sulphate of Ammonia (SOA) DiAmmonium Phosphate (DAP) Muriate of Potash (MOP)	Hand applied (broadcast). Products blended
Forico	Agrotain Urea Single Superphosphate (SSP) Muriate of Potash (MOP)	Hand applied (broadcast) separately (i.e. not blended)
Midway	Urea DiAmmonium Phosphate (DAP) Single Superphosphate (SSP) Muriate of Potash (MOP)	Hand applied (broadcast) separately (i.e. not blended)
RFF	Agrotain Urea Triple Superphosphate (TSP) Muriate of Potash (MOP)	Hand applied (broadcast) separately (i.e. not blended)
ABP	Sulphate of Ammonia (SOA) AllPhos (TSP) Muriate of Potash (MOP)	Hand applied (broadcast) separately (i.e. not blended)
SFM	Sulphate of Ammonia (SOA) DiAmmonium Phosphate (DAP) Muriate of Potash (MOP) Pastureking (DSP)	Hand applied (broadcast) separately (i.e. not blended)

Note the additional treatments applied by ABP were applied as Urea, Mono ammonium phosphate (MOP), AllPhos (TSP) and Muriate of potash (MOP).

Method

Details of trial establishment.

1. **Sites were selected** to provide a range of soil and climatic condition (Table 1), including nutrient status (Table 6) in plantations in WA Victoria and Tasmania**.**
2. **Plots were installed** to provide approximately 30 trees and the internal measurement plots dimensions varied to accommodate the various plantation configurations and plantation densities available. A 2-row buffer around all sides of the internal measurement plots was used at all sites to separate the measurement plots from adjacent treatments.
3. **Treatment plots** were pegged on all 4 corners and trees in the internal measurement plots were marked. Pegs have been placed on the tree row rather than between the rows so that future vehicle access is not compromised (e.g. for weed control). The plot areas are measured to the mid rows for both the external and measurement plots.
4. **Measurement:** 30 plots were installed at each site and diameter breast height (1.3 m) over bark (DBHOB) and height were measured on all trees in each plot with the exception of the trials at Midway's Karlinski site and ABP (Jones and Parola). Midway measured the largest 4 trees per plot and ABP measure dominant stems plus a cohort range and apply a H/D relationship that is site specific to extrapolate remaining heights.
5. **Randomisation:** At SFM's Danyenah site initial measurements were used to assess site uniformity and allocate treatments. At all other sites treatments were allocated randomly.
6. **Soils sampling:** A surface soil sample (0-10 cm) consisting of 30 cores taken at 3 places (3x10 =30) within the inter-row area of the measurement plots were taken from each plot. Sampling dates are shown in Table 3
7. **Foliar sampling:** Youngest fully expanded leaves were sampled from the mid- to upper crowns from 8-10 trees in each plot. Sampling dates are shown in Table 3.
8. **Fertiliser applications procedure:**
   The individual fertiliser s (N, P, K) for this trial were measured for each plot and broadcast separately by hand across the treatment plot at the rates prescribed for each treatment.

Soil analysis methods

Plant available phosphorus and potassium were extracted using a soil to solution ratio of 1:100 with a 0.5M sodium bicarbonate solution, adjusted to pH 8.5, for 16 hours. The extract was then acidified and measured colourimetrically for Phosphorus. Potassium was determined using atomic absorption spectroscopy (Colwell 1965).

Phosphorus buffering index was measured by the amount of phosphorus sorbed by the soil when the solution concentration of phosphorus is increased by 100 mg/mL. Soil was extracted using a calcium chloride and sodium dihydrogen phosphate solution and the phosphorus sorption measured colourimetrically using an ammonium molybdate/ammonium metavanadate reagent. Phosphorus buffering index was then calculated using the phosphorus sorption measurement and measurement of Colwell Phosphorus (see above) (Allen and Jeffrey 1990).

Plant available sulfur was determined by extracting soil using a 0.25M potassium chloride solution. The extracts were then analysed by inductively coupled plasma spectroscopy (Blair et al. 1991).

Soil oxidizable carbon was measured using the Walkley-Black method (Walkley and Black 1934).

Conductivity and pH in water were measured in a 1:5 soil/deionised water extract. Calcium chloride was added to the mixture to the equivalent of 0.01M to measure the pH in calcium chloride.

Total soil nitrogen was measured using the Dumas high temperature combustion method (Leco analyser) (Rayment and Lyons 2010).

Plant analysis methods

Total nitrogen was measured using the Dumas high temperature combustion method (Leco analyser). Samples were loaded into a combustion tube at 950°C and flushed with oxygen. Gases generated from this process were measured using a thermal conductivity cell for nitrogen (Rayment and Lyons 2010).

Phosphorus, Potassium, Sulfur, Copper, Zinc, Manganese, Calcium, Magnesium, Sodium, Iron, Boron were measured by inductively coupled plasma (ICP) spectroscopy following digestion of the plant material with hydrogen peroxide and nitric acid (McQuaker et al. 1979)

Site nutrient status

***Table 6.* Initial site mean soil nutrient concentrations in the rates interaction trials**

Trial		mg/kg Col P	mg/kg Col K	mg/kg Sulfur	% Organic Carbon	dS/m Conduct	pH pH Level (CaCl2)	pH pH Level (H2O)	PBI	% Total Nitrogen
RMS Hays (Wilmc	16/09/2019	43.67	381.57	4.49	5.04	0.05	4.77	5.75	897.65	0.58
Forico Myrtle Bar	16/08/2019	20.38	222.47	9.13	4.69	0.10	4.22	4.91		0.49
Midway Karlinski	15/05/2019	52.53	293.00		6.63	0.12	5.02	5.79		0.44
PFO Andrew	8/06/2019	14.82	58.47	8.48	3.15	0.07	3.87	5.11	10.21	0.22
PFO Henke	13/09/2018	10.61	42.80	2.93	4.00	0.04	4.40	5.53	10.72	0.25
PFO Moorabinda	1/08/2019	51.28	153.53	12.19	2.68	0.14	4.96	5.66	120.30	0.23
SFM Danyenah	16/09/2019	19.18	112.97	4.83	2.20	0.10	5.78	6.53	83.40	0.17
PFO Wallabadah	13/09/2018	11.62	122.55	4.14	3.49	0.05	4.41	5.42	127.37	0.29
Wapres Lake Jasp	27/09/18	8.20	31.63	5.60	4.65	0.048	4.31	5.41	134.46	0.32
PFO Fagan	23/04/2019	7.68	59.63	9.22	4.14	0.10	3.36	4.50	6.53	0.27
ABP Jones	8/08/2019	22.97	83.63	9.25	4.28	0.06	4.75	5.64	1810.26	0.28
ABP Parola	20/06/2019	26.67	94.21	5.96	2.60	0.04	5.37	6.34	61.43	0.18
PFO Lyon	14/05/2019	11.95	64.35	3.83	4.03	0.04	3.63	4.96	31.71	0.29
PFO Burrell	18/06/2019	16.48	64.22	5.72	2.76	0.03	4.41	5.62	31.00	0.27
Mean across sites		**22.72**	**127.50**	**6.60**	**3.88**	**0.07**	**4.52**	**5.51**	**277.09**	**0.31**

***Table 7.* Initial site mean foliar nutrient concentrations in the rates interaction trials**

		%	%	%	mg/kg	mg/kg	mg/kg	mg/kg	%	mg/kg	%	%	%
Site	**Date**	**N**	**P**	**K**	**Cu**	**Zn**	**Mn**	**B**	**Ca**	**Fe**	**Mg**	**Na**	**S**
RMS Hays (Wilmott)	16/09/2019	2.07	0.13	0.68	6.26	15.90	931.69	25.50	0.43	33.85	0.10	0.01	0.14
Forico Myrtle Bank	25/10/2019	1.78	0.11	0.54	6.50	16.35	2157.70	25.30	0.58	53.15	0.12	0.03	0.13
Midway Karlinski	30/09/2019	1.58	0.10	0.48	4.31	9.18	166.74	12.98	0.73	50.11	0.17	0.23	0.11
PFO Andrew	19/08/2019	2.39	0.16	0.70	3.85	13.80	345.33	27.23	0.86	48.77	0.18	0.23	0.14
PFO Henke	13/09/2019	1.62	0.13	0.81	4.44	13.07	148.67	31.03	1.24	56.60	0.24	0.27	0.13
PFO Moorabinda	19/08/2019	2.43	0.14	0.67	4.68	14.47	456.00	17.30	0.75	52.07	0.20	0.18	0.14
SFM Danyenah	18/09/2019	1.48	0.11	0.62	4.75	8.01	794.33	27.73	1.02	59.33	0.17	0.22	0.11
PFO Wallabadah	13/09/2018	1.11	0.09	0.49	2.90	8.53	677.67	22.87	1.47	46.63	0.15	0.21	0.09
Wapres Lake Jasper	27/09/2018	1.56	0.11	0.60	6.85	11.50	67.28	23.60	0.99	31.43	0.15	0.20	0.12
PFO Fagan	3/09/2019	1.88	0.18	0.89	9.75	16.98	207.82	21.92	0.75	37.90	0.18	0.19	0.14
ABP Jones	27/08/2019	2.29	0.20	0.84	9.56	19.93	151.34	21.09	0.52	49.69	0.19	0.16	0.16
ABP Parola	22/08/2019	2.48	0.25	1.13	9.84	23.44	125.03	27.28	0.58	49.95	0.22	0.19	0.20
PFO Lyon	16/08/2019	1.98	0.16	0.80	8.91	14.64	96.30	24.10	0.79	43.70	0.19	0.21	0.15
PFO Burrell	20/08/2019	1.38	0.11	0.72	5.88	9.54	190.54	22.50	0.90	38.91	0.19	0.21	0.10
Overall mean		**1.86**	**0.14**	**0.71**	**6.32**	**13.95**	**465.46**	**23.60**	**0.83**	**46.58**	**0.18**	**0.18**	**0.13**

The nutrients that have previously been demonstrated to affect the performance of blue gums on ex-farmland are N and to a lesser extent P. A site level analysis of the data revealed no relationship between soil N and foliar N (Figure 2) and similarly for P there was no relationship between soil P and foliar P (Figure 3). This aligns with previous reviews of blue gum nutrition where foliage nutrient concentrations were not related to growth (Szota et al 2014 and McGrath and Mendham 2018). In contrast growth responses were related to soil N concentrations (McGrath and Mendham 2018). Consistent with numerous studies, there was a significant relationship between soil carbon and soil nitrogen with the significance of the relationship determined by the inclusion of all data vs the exclusion of potential outlier (Figure 4). By excluding the apparent outlier, the C/N ratio is ~10, which again aligns with many studies that have similar C/N ratios.

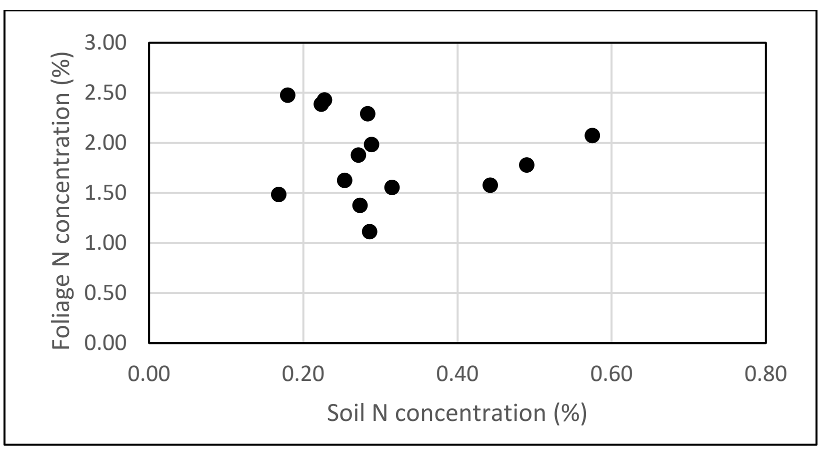


***Figure 2*. Relationship between soil N and foliage N for rates trials**

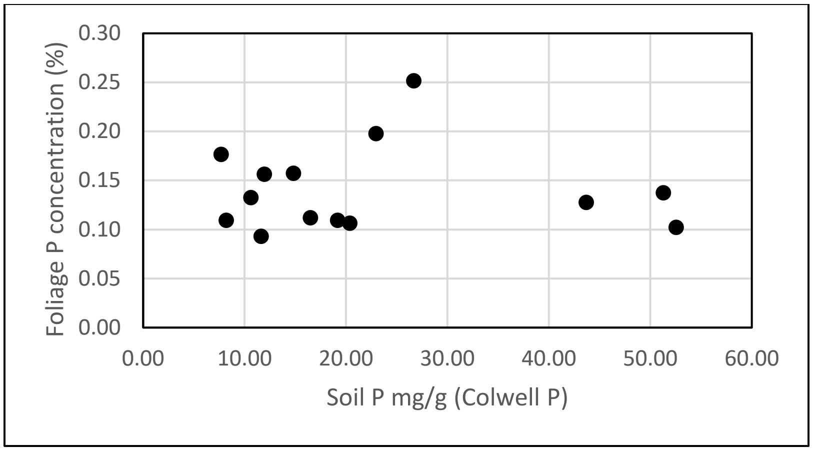


***Figure 3*. Relationship between soil P and foliage P for rates trials**

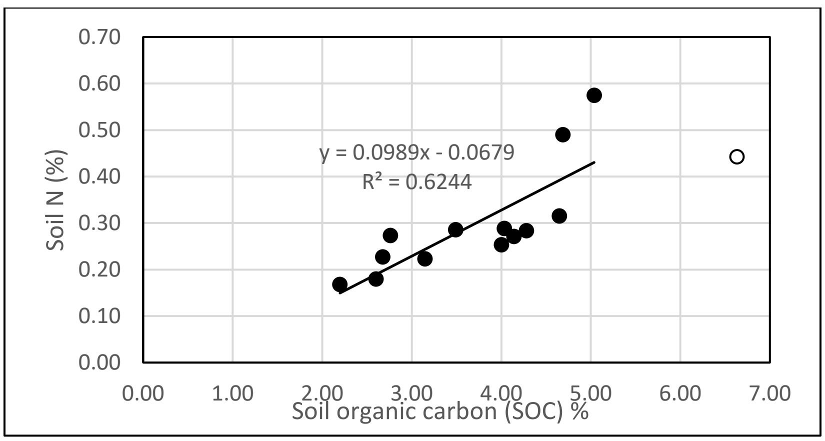


***Figure 4*. Relationship between soil N and soil Organic carbon for rates trials**

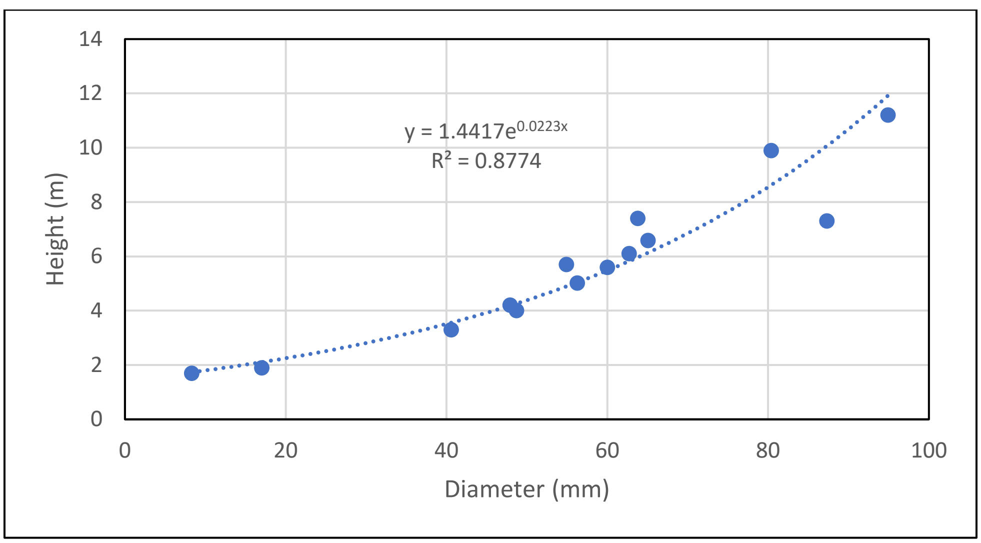
Note: The relationship shown includes data with SOC <5.0% as the open symbol appears to be an outlier.

Tree measurements

Table 8. **Initial site based diameter and height summary**

Site	Date	Age (years) at Establishment	DBHOB (m	Ht (m)
RMS Hays (Wilmott)	1/10/2019	2	48.7	4
Forico Myrtle Bank	7/06/2019	2	47.9	4.2
Midway Karlinski	15/05/2019	3	80.4	9.9
PFO Andrew	21/08/2019	1	17	1.9
PFO Henke	4/09/2018	1	40.6	3.3
PFO Moorabinda	19/08/2019	1	8.3	1.7
SFM Danyenah	16/09/2019	3	87.3	7.3
PFO Wallabadah	5/09/2018	3	94.9	11.2
Wapres Lake Jasper	4/10/2018	2	65.1	6.6
PFO Fagan	23/04/2019	2	62.7	6.1
ABP Jones	20/06/2019	2	56.3	5.0
ABP Parola	20/06/2019	2	60	5.6
PFO Lyon	15/05/2019	2	54.9	5.7
PFO Burrell	18/06/2019	3	63.8	7.4

Figure 5. **Relationship between diameter and height at a plot level**



The initial site level growth data indicates that the sites conform to the strong relationship between diameter (D) and height (H) that has been observed for blue gums (Figure 5). This will be useful in determining which volume and biomass relationships that will be used to estimate these parameters as the trials progress. The coefficient of variation between the treatment means for D and H within the sites was between 0.5 and 2% indicating that within site variation is relatively small. However, if necessary, the initial measurements (D, H) can be used as covariates for subsequent statistical analyses.

Maintenance Schedule

Weed control

The plots will be kept as weed-free as possible using a combination of chemical and mechanical treatments. Rates of herbicide will be determined dependant on weed spectrum and composition. This will be repeated as necessary until it is deemed of no further value to the integrity of the trial.

Future fertiliser strategy

Fertiliser treatments were applied in 2019 with the exception of 2 trials installed by PFO in 2018 (Henke, Wallabadah) and one by Wapres (Lake Jasper) in 2018. The potential for subsequent fertiliser applications, particularly nitrogen could be evaluated at the end of this phase of the trials after 3-4 years of growth and nutrient data has been collected.

Experiment duration

Minimum 4 years –This is the duration of the funding for the project, however the trials could run for the duration of the current rotation which could provide the opportunity for subsequent fertiliser applications.

Additional data

Individual site growth, soils and foliar data are saved in a number of places:

- Company data records
- IPMG records
- Researcher files.

Initial representative photographic records of most sites are also held by the IPMG.

Spatial data:

- IPMG holds individual plot layout data and there are maps showing the location of the trials across Australia.
- IPMG holds individual plot layout data and there are maps showing the location of the trials across Australia.

COMPONENT 1: RESPONSIVENESS TRIALS

Objectives

These experiments will assess the relationships between nutrition diagnostic factors and subsequent tree growth response to fertiliser across a regionally representative set of plantation sites. This will allow the calibration of nutrient responses to assessments of soil fertility. This series of trials will also enhance the available data on the interaction between nutrient supply and climate as outlined in the rates trial series.

Background

As with the rates trial there is a perception that much of the research undertaken may only be applicable to particular regions, species, rotation, or site situations. Clearly articulated operational level fertiliser guidelines on the timing and application of nutrients to maximize growth are still mostly lacking. Growth and economic modelling tools such as FPOS and ProFert are not currently deemed to be operationally useful or been adapted for use in hardwood plantations. These trials will provide the data to improve the prediction of fertiliser responsiveness and hence improve operational fertiliser practice.

Site details

Table 9: Location and Site description

Company	State	Site name	Trial code	Coordinates		Soil type	Mean rainfall
RMS	Tas	Erriba RSN	N/A	-41.4495	146.1164	Loam/claye	1472
RMS	Tas	Preston RI	N/A	-41.2942	146.0546	Loamy/lay	1472
Forico	Tas	Railton 1	RO201F	-41.3522	146.4384	Dermosol	1058
Forico	Tas	Railton 2	RO201F	-41.3522	146.4384	Dermosol	1058
Midway	VIC	Convey		-38.4565	143.1875	Loam/clay	1000
Midway	VIC	Meade		-38.4845	143.3225	Sandy loam/cl	1000
PFO	Vic	Cowland	0060H	-38.0619	142.1083	Sandy Loam	715
PFO	Vic	Smith	0060G	-37.8862	141.6370	Sandy Loam	687
PFO	Vic	Pepper	0060I	-37.8490	141.6763	Clay Loam	680
PFO	Vic	Lindsay	0060J	-37.5221	141.2489	Sand	669
SFM	Vic	Danyenah	N/A	37.9085	141.8476	clay loam	653
Wapres	WA	Lake Jaspe	FT36C	-34.3690	115.6870	Deep sandy	1050
Wapres	WA	Lake Jaspe	FT36C	-34.3690	115.6870	Deep sand	1050
Wapres	WA	Dingup	FT36A	-34.2660	116.2590	Yellow duplex	800
Wapres	WA	Dingup	FT36A	-34.2660	116.2590	Yellow duplex	800
PFO	WA	Trianguleε	0066B	-34.6949	117.4307	Sand	758
PFO	WA	Wisbey	0066C	-34.8926	117.8550	Sand	757
PFO	WA	O'Callagha	0066A	-34.8177	117.6713	Sandy Loam	744
Wapres	WA	Greville	FT36B	-34.1110	116.3060	Yellow duplex	700
Wapres	WA	Greville	FT36B	-34.1110	116.3060	Yellow duplex	700

Trial Summary

The responsiveness of tree growth to uniform rates of nitrogen, phosphorus and potassium that are adequate to optimise tree growth will be measured at a wide range of sites. The trials are operational in scale (strips of 8-10 rows wide and 400-500 m long ≈ 2Ha) and the common treatments include: (1) nil fertiliser, (2) adequate/luxury rates of N, P and K fertiliser (e.g. N400/P100/K100). Plot sizes aimed to provide 30- measurement tree/plot with at least 2 row buffers around the measured internal plot. Other treatments were included (in-kind) at some sites according to industrial partner needs. Key climate, site, soil, and foliar diagnostics will be characterised at each of the sites. There are 9 trial is WA, 7 in Victoria and 4 in Tasmania (Table 10).

Table 10. Summary of Responsiveness Trials

Collaborators	Number of trials			
	WA	GT / VIC	TAS	Total
PF Olsen	3	4		7
WAPRES	6			6
ABP				0
Forico			2	2
RFF			2	2
Midway		2		2
SFM		1		1
Totals	**9**	**7**	**4**	**20**

Figure 6. **Location of responsiveness trials**

Key establishment and initial assessment dates

Table 11 Installation details

Company	State	Site name	Trial code	Planted or Coppice	Month/year planted or harvested	Date soil sampled	Date foliar sampled	Initial measurement date	Date treatments applied
RMS	Tas	Erriba RSMT	N/A	Planted	Sep-17	29/07/2019	29/07/2019	1/10/2019	21/10/2019
RMS	Tas	Preston RPRS	N/A	Planted	Oct-17	29/07/2019	29/07/2019	2/10/2019	21/10/2019
Forico	Tas	Railton 1	RO201F	Planted	Oct-17	14/08/2019	16/10/2019	15/11/2019	22/11/2019
Forico	Tas	Railton 2	RO201F	Planted	Oct-17	14/08/2019	16/10/2019	15/11/2019	22/11/2019
Midway	VIC	Convey		Planted	Aug-16	1/05/2019	30/09/2019	mid-Oct	1/10/2019
Midway	VIC	Meade		Planted	Aug-16	1/05/2019	30/09/2019	mid-Oct	3/10/2019
PFO	VIC	Cowland	0060H	Planted	Jul-18	22/05/2019	24/10/2019	5/09/2019	23/12/2019
PFO	VIC	Smith	0060G	Planted	Jul-17	16/05/2019	22/08/2019	22/08/2019	18/10/2019
PFO	VIC	Pepper	0060I	Coppice	Apr-16	11/06/2019	5/09/2019	4/09/2019	18/10/2019
PFO	VIC	Lindsay	0060J	Coppice	Jan-16	15/06/2019	3/09/2019	3/09/2019	16/10/2019
SFM	Vic	Danyenah	N/A	Planted	Jul-16	27/05/2019	18/09/2019	16/09/2019	26/09/2019
Wapres	WA	Lake Jasper	FT36C	Planted	June -16	17/10/2018	17/10/2018	16/10/2018	5/11/2018
Wapres	WA	Lake Jasper	FT36C	Planted	June -16	28/03/2019	22/05/2019	19/06/2019	24/06/2019
Wapres	WA	Dingup	FT36A	Planted	July -16	7/09/2018	7/09/2018	2/10/2018	13/09/2018
Wapres	WA	Dingup	FT36A	Planted	July -16	28/03/2019	23/05/2019	17/06/2019	19/06/2019
PFO	WA	Triangulee	0066B	Planted	Aug-17	26/04/2019	26/08/2019	2/05/2019	20/09/2019
PFO	WA	Wisbey	0066C	Planted	Aug-17	24/04/2019	26/08/2019	30/04/2019	13/09/2019
PFO	WA	O'Callaghan	0066A	Planted	Aug-17	16/05/2019	26/08/2019	30/04/2019	16/09/2019
Wapres	WA	Greville	FT36B	Coppice	June -16	7/09/2018	6/09/2018	26/09/2018	13/09/2018
Wapres	WA	Greville	FT36B	Coppice	June -16	28/03/2019	24/05/2019	17/06/2019	20/06/2019

Trial design

Table 12. Summary of trial design details,

(a) Core treatments at all sites (Treatment details in Table 12)

Number of treatments	Two core treatments: Nil and Luxury (400N/100P/100K)
Replicate plots	4
Total Plots	8
N rates	0, 400 kg/ha
P Rates	0, 100 kg/ha
K rates	0, 100 kg/ha
Measurement plots within operationally applied strips*	Nominally 30 tree plots (This varied between industry partners with a mean minimum of 36 trees at 2 sites up to 40+and a mean maximum of 48. The number of trees ranged from 15 to 125 trees per plot. There was a relatively uniform number of trees within each trial.
External treatment plots*	8 to 10 rows of trees x 400-500m long (nominal) dependent on site and availability of uniform plantation
Gross area of trial*	5-6 ha nominal

*Indicative only, the exact plot size between sites based on plantation configuration and status.

The trials installed by SFM, RMS, Forico and Midway (7 sites) used the standard two treatment design. The 7 sites installed by PFO and the 6 sites installed by WAPRES included and additional standard operational rate (low/moderate) rate of fertiliser

Note: *While the additional treatments were installed by the industry participants to address questions related to their specific situations this document focuses on the 2 core treatments across the 20 sites as they form the basis of this component of the project. The site characterisation, which this report focuses on, will be relevant to the additional work. While these treatments may assist in addressing the issues being examined by the overall matrix of trials, the value of including these additional lines of investigation will be evaluated by the Steering Committee and the Research Providers as the project progresses.*

Fertiliser application details

Table 13 Treatments and application rates for responsiveness interaction trials

	Elemental nutrients (kg/ha)		
Treatment	**N**	**P**	**K**
1	0	0	0
2	400	100	100

Application – Two treatments in two strips 8-10 rows wide x 400-500m long (2ha)
Measure and Sample - Two treatments x four reps (measurement plots within the strips)

Table 14 Fertilisers used in the responsiveness trials:

Company	Responsiveness trials	
	Fert type	Application

PFO	Sulphate of Ammonia (SOA) AllPhos (TSP) Muriate of Potash (MOP)	Machine applied (broadcast) separately (ie not blended)
Wapres	Sulphate of Ammonia (SOA) DiAmmonium Phosphate (DAP) Muriate of Potash (MOP)	Blended and machine applied SOA:DAP:MOP 68:23:9%
Forico	Agrotain Urea Single Superphosphate (SSP) Muriate of Potash (MOP)	Blended and machine applied (broadcast).
Midway	Urea DiAmmonium Phosphate (DAP) Muriate of Potash (MOP)	Machine applied (broadcast) separately (ie not blended)
RFF	Agrotain Urea Triple Superphosphate (TSP) Muriate of Potash (MOP)	Hand applied (broadcast) separately (ie not blended)
SFM	Sulphate of Ammonia (SOA) DiAmmonium Phosphate (DAP) Muriate of Potash (MOP)	Hand applied (broadcast) separately (ie not blended)

Note the additional treatments applied by ABP were applied as Urea, Mono ammonium phosphate (MOP), AllPhos (TSP) and Muriate of potash (MOP).

Method

Details of trial establishment.

1. Sites were selected to provide a range of soil and climatic condition (Table 9), including nutrient status (Table 14) in plantations in WA, Victoria and Tasmania**.**
2. Plots were installed to provide approximately 30 trees and the internal measurement plots dimensions varied to accommodate the various plantation configurations and plantation densities available. A 2-row buffer around all sides of the internal measurement plots was used at all sites to separate the measurement plots from adjacent treatments.
3. Treatment plots were pegged on all 4 corners and trees in the internal measurement plots were marked. Pegs were placed along tree rows rather than between the rows so that future vehicle access is not compromised (e.g. for weed control). The plot areas were measured to the mid rows for both the external and measurement plots.
4. **Measurement:** 8 plots were installed at each site and diameter breast height (1.3 m) overbark (DBHOB) and height were measured for all trees in each plot with the exception of the trials at Meade and Convey (Midway) where the 4 largest trees per plot were measured.
5. **Soils sampling:** A surface soil sample (0-10 cm) consisting of 30 cores taken at 3 places (3x10 =30) within the inter-row area the measurement plots were taken from each plot. Sampling dates are shown in Table 11. Soil samples – Initial (pre-treatment) and final, one from each measurement plot. 8 plots x 1 sample/plot = 8 per site.
6. **Foliar samples:** Youngest fully expanded leaves were sampled from the mid- to upper crowns from 8-10 trees in each plot and were bulked to give one sample per plot. Sampling dates are shown in Table 11.
7. **Fertiliser application procedure:**
   Fertilisers were broadcast mechanically across the treatment plot at the rates prescribed for each treatment.

Site nutrient status

Table 14 Initial site mean soil nutrient concentrations in the responsiveness trials

Site		Date sampled	mg/kg Col P	mg/kg Col K	mg/kg Sulfur	% Organic Carbon	dS/m Conduct	pH pH Level (CaCl2)	pH pH Level (H2O)	PBI	% Total Nitrogen
RMS Erriba	Tas	29/07/2019	21.88	318.50		5.69	0.05	4.33			0.80
RMS Preston	Tas	29/07/2019	108.63	258.00		5.03	0.05	4.51			0.51
Forico Railton 1	Tas	14/08/2019	12.00	47.50	3.81	2.59	0.05	3.95	4.96		0.17
Forico Railton 2	Tas	14/08/2019	42.88	134.50	7.96	3.52	0.08	4.45	5.29		0.32
Midway Convey	Vic	15/05/2019	54.75	91.50		4.27	0.08	4.66	5.50		0.32
Midway Meade	Vic	15/05/2019	33.13	157.50		3.79	0.08	4.74	5.56		0.27
PFO Cowland	GT	22/05/2019	40.25	70.00	11.53	2.63	0.14	4.50	5.20	61.00	0.20
PFO Smith	GT	16/05/2019	26.63	83.50	5.16	3.65	0.05	4.14	5.03	160.88	0.27
PFO Pepper	GT	11/06/2019	19.75	66.63	4.55	3.69	0.04	4.08	5.08	167.25	0.33
PFO Lindsay	GT	11/06/2019	5.40	64.63	3.44	2.04	0.05	4.68	5.80	2.01	0.15
SFM Danyenah	Vic	16/09/2019	18.03	113.13	3.89	2.81	0.04	4.59	5.70	83.13	0.20
Wapres Lake Jasper 18	WA	7/09/2018	14.78	43.83	10.20	4.62	0.05	4.38	5.46	630.18	0.25
Wapres Lake Jasper 19	WA	7/09/2018	8.19	45.72	8.06	4.95	0.061	3.88	5.14	573.26	0.34
Wapres Dingup 18	WA	7/09/2018	30.92	55.58	7.33	4.41	0.06	5.48	6.30	259.39	0.45
Wapres Dingup 19	WA	28/03/2019	32.00	75.33	10.08	4.75	0.04	5.16	5.98	281.89	0.40
PFO Triangulee	WA	29/04/2019	20.63	37.75	5.19	3.81	0.11	4.11	5.19	97.35	0.36
PFO Wisbey	WA	30/04/2019	17.13	45.88	3.56	2.77	0.06	3.93	5.16	29.71	0.27
PFO O'Callaghan	WA	02/05/2019	13.13	81.25	5.38	3.05	0.04	5.31	6.09	98.68	0.23
Wapres Greville 18	WA	7/09/2018	33.33	84.92	9.03	4.43	0.04	4.75	5.76	1078.48	0.36
Wapres Greville 19	WA	28/03/2019	40.75	93.50	9.45	4.96	0.03	4.35	5.50	1459.55	0.45
Mean			**29.71**	**98.46**	**6.79**	**3.87**	**0.06**	**4.50**	**5.48**	**355.91**	**0.33**
Number			**20**	**20**	**16**	**20**	**20**	**20**	**18**	**14**	**20**

Table 15 Initial site mean foliar nutrient concentrations in the responsiveness trials

Site	Date	% N	% P	% K	mg/kg Cu	mg/kg Zn	mg/kg Mn	mg/kg B	% Ca	mg/kg Fe	% Mg	% Na	% S
RMS Erriba	29/07/2019	1.73	0.10	0.78	7.41	17.65	1163.11	23.83	0.62	53.61	0.13	0.03	0.13
RMS Preston	29/07/2019	2.24	0.15	0.85	7.75	17.42	581.03	36.22	0.71	51.00	0.12	0.03	0.15
Forico Railton 1	14/08/2019	1.73	0.09	0.45		13.88	595.45	3.82	29.96	0.66	55.85	0.10	0.03
Forico Railton 2	14/08/2019	1.78	0.10	0.49		13.02	475.25	3.14	24.44	0.59	58.86	0.10	0.02
Midway Convey	30/09/2019	1.18	0.09	0.44	3.44	10.47	295.42	16.89	0.93	50.33	0.17	0.22	0.09
Midway Meade	30/09/2019	1.70	0.14	0.65	8.18	12.75	403.75	21.16	0.75	52.58	0.19	0.22	0.12
PFO Cowland	24/10/2019	1.38	0.14	0.58	4.73	13.75	555.83	27.33	1.30	155.33	0.26	0.20	0.12
PFO Smith	22/08/2019	1.71	0.12	0.56	5.85	11.67	632.50	21.83	0.97	56.42	0.23	0.21	0.13
PFO Pepper	5/09/2019	1.24	0.09	0.44	3.72	9.13	373.33	20.83	0.75	47.33	0.15	0.18	0.09
PFO Lindsay	3/09/2019	0.88	0.09	0.54	4.71	8.99	176.67	32.58	1.58	46.33	0.15	0.20	0.08
SFM Danyenah	18/09/2019	1.38	0.10	0.60	4.16	8.99	413.75	24.13	11.40	61.00	0.19	0.24	0.10
Wapres Lake Jasper 18	17/10/2018	2.20	0.25	1.43	9.14	18.60	51.42	16.21	0.46	39.00	0.19	0.26	0.16
Wapres Lake Jasper 19	22/05/2019	1.16	0.10	0.79	5.39	12.21	35.08	14.27	0.64	33.61	0.21	0.22	0.09
Wapres Dingup 18	7/09/2018	1.92	0.19	0.91	7.60	19.37	268.92	21.00	0.66	43.42	0.19	0.22	0.17
Wapres Dingup 19	23/05/2019	1.32	0.11	0.78	6.71	10.96	131.42	18.13	0.61	36.92	0.23	0.17	0.11
PFO Triangulee	26/08/2019	1.95	0.17	0.76	8.66	15.59	191.73	16.22	0.65	32.75	0.19	0.15	0.13
PFO Wisbey	26/08/2019	2.31	0.20	0.95	10.69	21.11	91.06	23.19	0.55	43.72	0.16	0.18	0.18
PFO O'Callaghan	26/08/2019	2.27	0.21	1.02	9.88	17.71	111.37	23.18	0.53	37.88	0.19	0.18	0.17
Wapres Greville 18	6/09/2018	1.64	0.14	0.72	5.09	13.16	334.54	21.32	0.83	32.34	0.20	0.20	0.14
Wapres Greville 19	24/05/2019	1.37	0.12	0.81	5.56	11.48	219.83	21.57	0.57	42.17	0.21	0.22	0.11
Overall mean		**1.65**	**0.13**	**0.73**	**6.59**	**13.89**	**355.07**	**20.34**	**3.94**	**45.85**	**5.90**	**0.18**	**0.12**

The nutrients that have previously been demonstrated to affect the performance of blue gums on ex-farmland are N and to a lesser extent P. A site level analysis of the data revealed no relationship between soil N and foliar N (Figure 7) and, similarly for P, there was no relationship between soil P and foliar P (Figure 8). This aligns with previous reviews of blue gum nutrition where foliage nutrient concentrations were not related to growth (Szota et al 2014 and McGrath and Mendham 2018). In contrast growth responses were related to soil N concentrations (McGrath and Mendham 2018). Consistent with numerous studies, there was a significant relationship between soil carbon and soil nitrogen with the significance of the relationship determined by the inclusion of all data vs the exclusion of potential outlier (Figure 9). By excluding the apparent outlier, the C/N ratio was about 10, which again aligns with many studies that have similar C/N ratios.

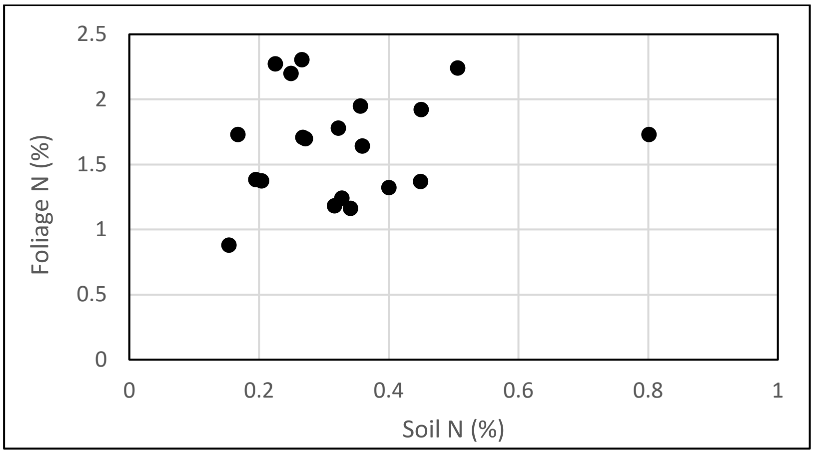


Figure 7. **Relationship between soil N and foliage N for responsiveness trials**

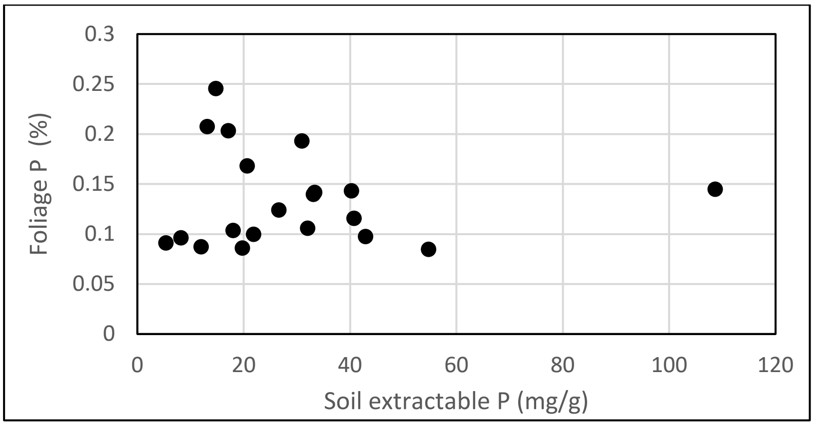


Figure 8. **Relationship between soil P and foliage P for responsiveness trials**

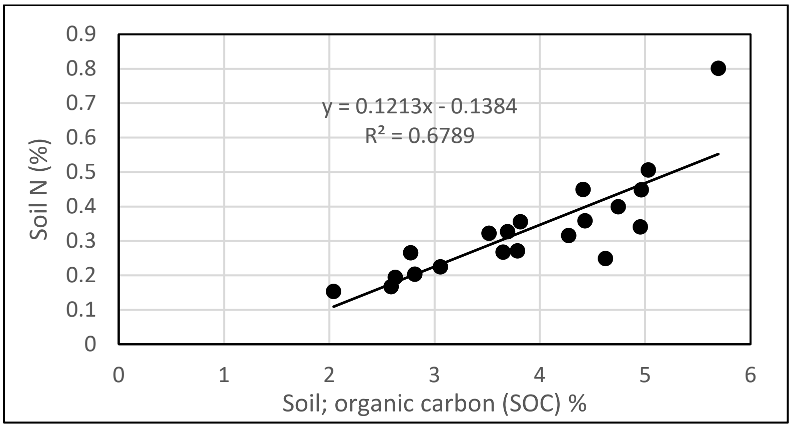


Figure 9. **Relationship between soil N and soil Organic carbon for responsiveness trials**

Table 16. **Initial site based mean diameter and height summary**

Company	State	Site name	Initial measurement date	Age (yrs) at establish.	Mean diam	Mean Ht
RMS	Tas	Erriba RSMT	1/10/2019	2	26.6	2.6

RMS	Tas	Preston RPRS	2/10/2019	2	61.7	4.9
Forico	Tas	Railton 1	15/11/2019	2	73.5	5.4
Forico	Tas	Railton 2	15/11/2019	2	69.2	5.2
Midway	VIC	Convey	mid-Oct	3	93.6	11.4
Midway	VIC	Meade	mid-Oct	3	68.5	7.0
PFO	VIC	Cowland	5/09/2019	1	21.9	2.3
PFO	VIC	Smith	22/08/2019	2	32.9	3.3
PFO	VIC	Pepper	4/09/2019	3	69.6	8.0
PFO	VIC	Lindsay	3/09/2019	3	66.9	7.6
SFM	VIC	Danyenah	16/09/2019	3	81.5	7.1
Wapres	WA	Lake Jasper	16/10/2018	2	59	6.4
Wapres	WA	Lake Jasper	19/06/2019	3	75.7	8.2
Wapres	WA	Dingup 18	2/10/2018	2	68.2	6.9
Wapres	WA	Dingup 19	17/06/2019	3	88.4	9.9
PFO	WA	Triangulee	2/05/2019	2	55.1	5.4
PFO	WA	Wisbey	30/04/2019	2	55.2	5.2
PFO	WA	O'Callaghan	30/04/2019	2	56.9	5.4
Wapres	WA	Greville 18	26/09/2018	2	56.7	7.5
Wapres	WA	Greville 19	17/06/2019	2	64.1	9.0
Mean					62.3	6.4

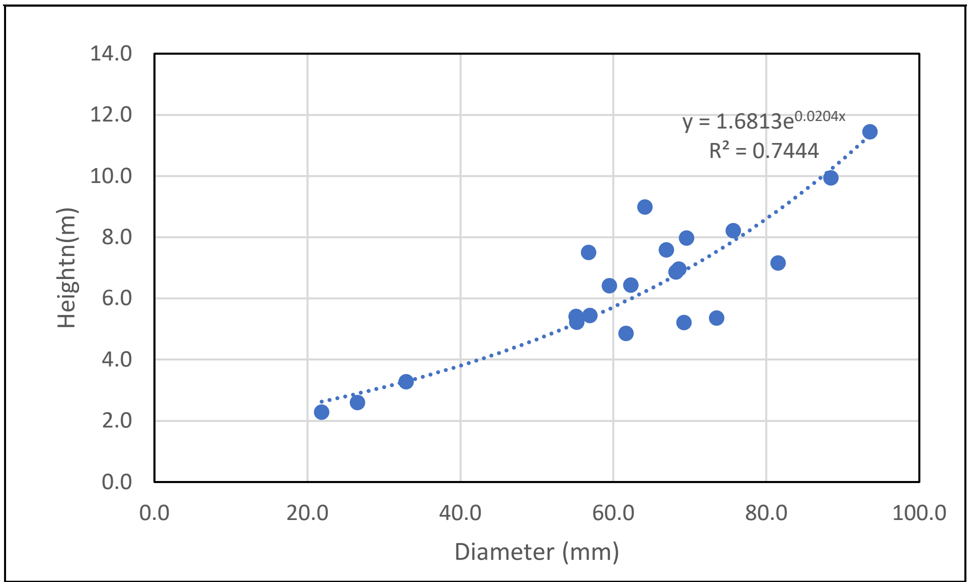


***Figure 10.* Relationship between diameter and height at a plot level**

As with the rates trials, the initial site level growth data indicates that the sites generally conform to the strong relationship between diameter (D) and height (H) that has been observed for blue gums (Figure 10). While the regression coefficients are similar between the two separate series of plots, there is more variation in the relationship for the Responsiveness series relative to the Rates series of trials. As for the Rates Trials, these data will be useful in determining which volume and biomass relationships that will be used to estimate these parameters as the trials progress. The coefficient of variation between the treatment means for D and H within the sites was between 0.5 and 2%

indicating that within site variation is relatively small. However, if necessary the initial measurements (D, H) can be used as covariates for subsequent statistical analyses.

Maintenance schedule

Weed control

The plots will be kept as weed-free as possible using a combination of chemical and mechanical treatments. Rates of herbicide will be determined dependant on weed spectrum and composition). This will be repeated as necessary until it is deemed of no further value to the integrity of the trial.

Future fertiliser strategy

Fertiliser treatments were applied in 2019 with the exception of 3 trials installed by Wapres in 2018 (Dingup, Greville and Lake Jasper). The potential for subsequent fertiliser applications, particularly nitrogen could be evaluated at the end of this phase of the trials after 3-4 years of growth and nutrient data has been collected.

Experiment duration

Minimum 3 years –This is the duration of the funding for the project, however the trials could run for the duration of the current rotation which could provide the opportunity for subsequent fertiliser applications.

Additional data

Individual site growth, soils and foliar data are saved in a number of places:

- Company data records
- IPMG records
- Researcher files.

Initial representative photographic records of most sites are also held by the IPMG.

Spatial data:

- IPMG holds individual plot layout data and there are maps showing the location of the trials across Australia.

COMPONENT 3: ESTABLISHMENT TRIALS

Objectives

Quantify the main effects and interactions of slash and fertiliser management during establishment of eucalypt plantations in temperate Australia.

Background

Harvest residue (slash) and litter layers can contain considerable amounts of nutrients that become available to trees during the next rotation. This source of nutrients, if conserved on-site, could potentially alleviate or partially replace the need for fertiliser applications, but this interactive effect of slash and fertiliser management has not been quantified in Australian eucalypt plantations and will be critical for optimising plantation growth and profitability. As well as covering an appropriate range of soil and climate, these experiments also need to cover the wide range of slash management use in hardwood plantations across Australia. Because slash management is integrated to the wide range of harvesting and other site preparation operations used, the amounts and evenness of distribution of slash vary greatly, which in-turn could be expected to affect the need for fertiliser.

Trial summary

Eight establishment trials have been installed across sites with a range of fertility**.** These experiments explore the tree growth response to different rates of nitrogen, phosphorus and potassium with and without operationally retained harvest residue (slash). Each experiment comprises 18 plots, consisting of 3 replicates of nil, standard and high fertiliser applications within 2 x slash regimes (retained or removed). Other treatments may be included (in-kind) according to industrial partner needs.

This design aims to quantify the main effects and interactions of slash and fertiliser management on tree growth during establishment of eucalypt plantations in temperate Australia.

The 8 experiments were established across three regions and six organisations as summarised in the following Tables 17-20 and Fig. 11.

Sites

Table 17. **Location and Site descriptio**n

Company	State	Site name	Trial code	Planted or Coppice	Month/year planted or harvested	Coordinates		Soil type	Mean rainfall	Elevation (m)
Forico	Tas	Takone	TK105T	Planted	6/11/2019	-41.1658	145.619	Basalt	1452.3	508
RMS	TAS	Hazelbrook Farm		Planned	1/10/2019	-41.2250	145.8184	Red Brown Clay	1384	228
Midway	VIC	Karoo		Planted	1/06/2019	-38.2894	142.9668	Clay loam/clay	800	121
PFO	Vic	Smokey Valley	0062A	Planted	1/06/2019	-37.91965	141.6362	Sandy Loam	680	87
Wapres	WA	Landells	Sest05	Planted	31/07/2018	-34.2400	115.1580	Deep Sand	1050	42
Wapres	WA	Dilkes	SEst06	Planted	29/07/2019	-33.8450	116.1330	Sandy loam	750	277
PFO	WA	Allison	0067A	Planted	1/07/2019	-34.6254	117.2352	Sandy Loam	714	220
PFO	WA	Homestead	0067B	Planted	1/07/2019	-34.8632	118.1798	Sandy Loam	711	93

Table 18. **Numbers of trials established by company and state**

Collaborators	Number of trials			
	WA	GT / VIC	TAS	Total
PF Olsen	2	1		3
WAPRES	2			2
Forico			1	1
RFF			1	1
Midway		1		1
SFM				0
Totals	**4**	**2**	**2**	**8**

Figure 11. **Location of establishment trials**

Key establishment and measurement dates

Table 19. **Installation details**

Company	State	Site name	Trial code	Planted or Coppice	Month/year planted or harvested	Date soil sampled	Initial measurement date	Date treatments applied
Forico	Tas	Takone	TK105T	Planted	6/11/2019	11/09/2019	23/10/2019	23/10/2019
RMS	TAS	Hazelbrook Farm		Planted	1/10/2019	18/07/2019	5/11/2019	5/11/2019
Midway	VIC	Karoo		Planted	1/06/2019	1/05/2019	19/11/2019	24/09/2019
PFO	GT	Smokey Valley	0062A	Planted	1/06/2019	7/06/2019	18/09/2019	28/06/2019
Wapres	WA	Landells	Sest05	Planted	31/07/2018	8/08/2018	31/07/2019	19/09/2018
Wapres	WA	Dilkes	SEst06	Planted	29/07/2019	17/07/2019	30/07/2019	29/07/2019
PFO	WA	Allison	0067A	Planted	1/07/2019	11/07/2019	9/11/2019	18/07/2019
PFO	WA	Homestead	0067B	Planted	1/07/2019	7/07/2019	1/08/2019	1/08/2019

Future assessment program

- Annual height and diameter measurements (when trees reach sufficient size, most likely age 2), will be taken. While the trials were established at slightly different times during the year, it is intended to bring the measurement times to a common month (June) so that it is easier to compare the growth and the treatment responses between the sites.
- Soil nutrient status will be reassessed at the end of the trial.

Trial design

The trials have a split-plot design at each site. Main-plot treatments are 2 un-replicated slash management options (retained or removed), i.e. each site has one main-plot of each slash treatment. Within each main-plot, sub-plots consisted of 3 levels of fertilization (nil, standard, high) with 3 replicate measurement plots of each arranged in a randomized block design. Hence, there were 18 plots per site. Optional fertiliser treatments could be included at the discretion of each company, e.g. controlled release fertiliser. However, these optional treatments are mostly not reported here. As slash retention was not replicated with-in sites, its effect can only be reliably assessed in a multi-site analysis using 8 blocks (sites).

Slash management

There were two slash management treatments (i.e. retained and removed) but the methods used to achieve those treatments varied between sites as described in Tables 21 and 22. This variability of methods could affect interpretation of results. So, in case we need better descriptions in the future, we request that each company also keep a complete record of what happened at and between harvesting and planting that later might be useful to interpreting tree growth differences between treatments and sites. This record could include dates and descriptions of activities like harvesting, handling of slash, burning, weed control, cultivation, coppice control, and planting.

Fertiliser treatments

4. Nil
5. Standard (nominally 16g N, 9g P, 25g K per tree)
6. High (nominally 32g N, 18g P, 25g K per tree)

Establishment and fertiliser application details

No standard type of fertiliser was recommended, as products vary across suppliers in each state, and it was therefore at the discretion of each company, provided the elemental rates matched closely the prescribed rates in the core treatments. Details for each company are provided in the following table.

Fertiliser was hand applied by burying it near the base of each tree. Fertiliser types differed between companies, and were various combinations of urea, DAP, MoP, SSP, Multicote 8, and AgrasCuZn. Controlled release fertiliser was applied in the bottom of the planting hole immediately before tree planting.

***Table 21.* Fertiliser application details. Further comments on slash management are provided in Table 22.**

<table>
<tr><th>Company</th><th>Site</th><th>Standard Establishment Fertiliser</th><th>Harvest completion Date</th><th>Harvest Method</th><th>Slash distribution</th><th>Slash Removal</th></tr>
<tr><td rowspan="3">PFO</td><td>Allison</td><td rowspan="3">16g N, 9g P, 25g K per tree. This is obtained using 150g/tree AgrasCuZn (100):MOP(50) (2:1)</td><td>14/12/18</td><td rowspan="3">IFC</td><td rowspan="3">Returned by machine Distributed in clumps</td><td>Burnt (poorly)</td></tr>
<tr><td>Homestead</td><td>14/6/18</td><td>Burnt</td></tr>
<tr><td>Smokey valley</td><td></td><td>Pushed</td></tr>
<tr><td rowspan="2">Wapres</td><td>Landells</td><td rowspan="2">16g N, 9g P, 25g K per tree seedling. This is obtained using 150g/tree AgrasCuZn (100):MOP(50) (2:1)</td><td>30/9/2017</td><td>CTL</td><td>From harvesting + chopper rolled</td><td>Burnt</td></tr>
<tr><td>Dilkes</td><td>18/4/18</td><td>CTL</td><td>From harvesting + chopper rolled</td><td>Pushed along inter-rows. Some slash remained along the planting line.</td></tr>
<tr><td>Forico</td><td>Takone</td><td>16g N, 9g P, 25g K per tree or 35g Urea, 102g SSP, 50g MOP.</td><td>April 2019</td><td>CTL</td><td>From harvesting</td><td>Pushed</td></tr>
<tr><td>Midway</td><td>Karoo</td><td>17.2g N, 45g P, 50g K per tree (blended urea/DAP/MoP)</td><td>2018</td><td>CTL</td><td>From harvesting</td><td>Pushed to windrows</td></tr>
<tr><td>RFF</td><td>Hazelbrook Farm</td><td>20 grams Hafia Multi cote 8</td><td>July 2018</td><td>CTL</td><td>From harvesting</td><td>Minimal debris, pushed to windrows</td></tr>
</table>

CTL = Cut to length, IFC = In field chipped
MOP – Muriate of Potash (KCl)
DAP – DiAmmonium Phosphate

***Table 22.* Comments on slash management techniques**

State	Site	Company	Harvest*	Slash management/Comments
WA	Allison	PFO	IFC	Retained by return with forwarders/skidders, distribution clumpy, uneven content of clumps Removal by burning was very patchy and incomplete.
WA	Dilkes	WAPRES	CTL	Retained slash fairly evenly distributed and chopper-rolled. Removal by pushing with frontend loader. Some debris remained on the planting line.
Tas	Hazelbrook	RFF	CTL	Retained slash light unevenly distributed and redistributed. Removal by mechanical grabbing plus pushing and some burning
WA	Homestead	PFO	IFC	Retained by return with forwarders/skidders, distribution clumpy, uneven content of clumps Removal by burning (approx. 90%)
Vic	Karoo	Midway	CTL	Retained slash evenly distributed. Removal by windrowing outside of trial area, reasonably complete
WA	Landells	WAPRES	CTL	Retained slash evenly distributed and chopper-rolled. Removal by burning
Vic	Smokey V.	PFO	IFC	Retained by return with forwarders/skidders, distributed in every second row in large clumps. Removal by pushing
Tas	Takone	FORICO	CTL	Retained slash evenly distributed. Removal by pushing: grabbing, raking, or blading

* IFC = In-field chipping at roadside, slash removed; CTL = Cut to length at stump, slash retained

Method

Further details of trial establishment

1. Sites were selected to cover a range of soil and climatic conditions (Table 17), including nutrient status (Table 24) in plantations in WA, VIC and TAS**.**
2. Plots were installed to provide approximately 30 trees and the internal measurement plots dimensions varied to accommodate the various plantation configurations and plantation densities available. A 2-row buffer around all sides of the internal measurement plots was used at all sites to separate the measurement plots from adjacent treatments.
3. Treatment plots were pegged on all 4 corners, and trees in the internal measurement plots were marked. Pegs have been placed on the tree row rather than between the rows so that future vehicle access is not compromised (e.g. for weed control). The plot areas are measured to the midway between tree rows and between trees within -rows for both the external and measurement plots.
4. **Measurements:** Height was measured on a subsample of trees to obtain a mean initial height. Heights on all trees and diameter breast height (1.3 m) over bark (DBHOB; when trees are tall enough) in each plot will be measured annually in June.
5. **Soil sampling:** A bulked surface soil sample (0-10 cm) from within the inter-row area of each measurement plot was taken. Sampling dates are shown in (Table 19).

Allison

Harvesting: 'In-field-chipping', i.e. above-ground removal to roadside for delimbing, debarking, and stem chipping

Slash removed: as indicated by the harvesting method, plus some stump removal during ripping.

Slash retained: forwarders returned to the experimental area with a large clump of 'slash' that contained a range of proportions of stumps, branches, leaves and bark. An attempt to distribute residues evenly was aided by a drone, but the distribution achieved was somewhat uneven and of non-uniform content. Some burning of slash clumps and chopper-rolling was evident. See above satellite image and following photo.

Site: Allison Treatment: slash retained
Photo date: 17/9/2019
Note: non-uniform slash cover and type

Site: Allison Treatment: slash removed
Photo date: 17/9/2019
Note: cultivation by ripping

Site: Allison Treatment: slash removed

Photo date: 17/9/2019

Note: some ashbeds/poor burn

Dilkes

Harvesting: 'Cut-to-length', i.e. delimbing, debarking, and cut to length near each stump.

Slash removed: mechanically removed by grabbing, raking, or pushing (bucket probably) with a small amount of litter and soil removal but with perhaps 10% of slash left as well. See photo.

Slash retained: as indicated by the harvesting method, but the distribution was somewhat uneven, and it was but it was later redistributed during cultivation. See photo.

Site: Dilkes Treatment: slash retained
Photo date: 17/9/2019
Note: uneven slash cover with 2 inter-rows of light slash load to every 1 row of heavy slash.

Site: Dilkes Treatment: slash removed
Photo date: 17/9/2019
Note: cultivation by ripping

Hazelbrook Farm

Harvesting: 'Cut-to-length', i.e. delimbing, debarking, and cut to length near each stump.

Slash removed: mechanically by grabbing, raking, or blading with a small amount of litter and soil removal but some slash left as well. See photo.

Slash retained: as indicated by the harvesting method, but the distribution was somewhat uneven, and it was later redistributed during cultivation. See photo.

Site: Hazelbrook Treatment: slash retained
Photo date: 10/10/2019
Note: inter-row mounding

Site: Hazelbrook Treatment: slash removed
Photo date: 10/10/2019
Note: slash windrowed; cultivation by mounding

Homestead

Harvesting: 'In-field-chipping', i.e. removal to roadside for delimbing, debarking, and stem chipping

Slash removed: as indicated by the harvesting method

Slash retained: forwarders returned to the experimental area with a large clump of 'slash' that contained a range of proportions of stumps, branches, leaves and bark. An attempt to distribute residues evenly was aided by a drone, but the distribution achieved was somewhat uneven and of non-uniform content. See following photo.

Site: Homestead Treatment: slash retained
Photo date: 18/9/2019
Note: clumped and uneven slash cover; coppice needs controlling; 'tram system' of 3 m and 5 m needs converting to uniform 4 m; chopper rolling

Site: Homestead Treatment: slash removed (burnt)Photo date: 18/9/2019
Note: slash burnt; cultivation by mounding

Karoo

Harvesting: 'cut-to-length'

Slash removed: windrowed

Slash retained: cultivation by mounding

Site: Karoo Treatment: slash retained
Photo date: 7/10/2019
Note: even slash cover; mounding

Site: Karoo Treatment: slash removed
Photo date: 7/10/2019
Note: slash windrowed; cultivation by mounding

Landells

Harvesting: 'Cut-to-length', i.e. delimbing, debarking, and cut to length near each stump.

Slash removed: incomplete burning. See photos.

Slash retained: as indicated by the harvesting method with fairly even distribution. See photos.

Visit notes 2019: (1) spray damage, which might necessitate ignoring one replicate during data analysis (2) acacia pulling needed (3) slash burning here but not at other sites (4) no cultivation.

Site: Landells Treatment: slash retained
Photo date: 17/9/2019
Note: 1 year post planting, slash breaking down and covered by grass

Site: Landells Treatment: slash removed (burnt)
Photo date: 17/9/2019

Smokey Valley

Harvesting: 'In-field-chipping', i.e. above-ground removal to roadside for delimbing, debarking, and stem chipping

Slash removed: as indicated by the harvesting method

Slash retained: forwarders returned to the experimental area with a large clump of 'slash' and distributed along every second inter-row.

Site: Smokey Valley Treatment: slash retained on every second inter-row. Photo date: 7/10/2019
Note: mounding

Site: Smokey Valley Treatment: slash removed
Photo date: 7/10/2019
Note: cultivation by mounding

Takone

Harvesting: 'Cut-to-length', i.e. delimbing, debarking, and cut to length near each stump.

Slash removed: grabbing, raking, or blading with a small amount of litter and soil removal but some slash left as well. See photo.

Slash retained: as indicated by the harvesting method, with a fairly even distribution. See photo.

Site: Takone Treatment: slash retained
Photo date: 10/10/2019
Note: even slash cover; mounding and the planting hole made with the Wilco cultivator

Site: Takone Treatment: slash removed
Photo date: 10/10/2019
Note: slash windrowed (left); cultivation by mounding

Maintenance and measurement program

The annual tree measurement program needs to be maintained, using standard methods that account for branch whorls or swelling at 1.3 m height, multiple stems per tree, and dead or missing trees. Annual photos covering the range of tree and other conditions would be useful.

As weeds can strongly influence tree nutrition, woody and herbaceous weed control needs to be maintained almost completely, e.g. < 5% cover. If weed cover cannot be maintained at low levels, detailed documentation of it will be needed on a per tree and per plot basis. Photos will be useful for documenting the range of weed cover and types at each site.

All activities at each site need to be recorded with a date and description.

Results

Initial tree measurements and soil analyses are summarised in Tables 23 and 24.

Table 23. **Summary of seedling heights within two months of planting**

Site	Mean Height at Planting (cm)
Allison	31
Dilkes	23
Hazelbrook Farm	30
Homestead	45
Karoo	24
Landells	25
Smokey Valley	20
Takone	35
Mean	**29**

Table 24. **Means of soil analyses by site and treatment**

Site	Available P (Colwell) mg/kg	Available K (Colwell) mg/kg	Sulfur mg/kg	Organic C %	Conductivity dS/m	pH ($CaCl_2$)	pH (H2O)	P Buffer Index	Total N %
Takone	43.6	134	13.6	4.92	0.067	4.16	4.79		0.481
Hazelbrook Farm	43.4	200		4.67	0.065	4.32			0.487
Karoo	18.7	89		4.10	0.139	4.21	4.87		0.305
Smokey valley	14.7	71	5.2	3.30	0.052	4.09	5.19	72	0.254
Landells	15.6	51		2.53		4.06		42	0.181
Dilkes	20.9	139		4.34	0.083	5.50	6.35	359	0.389
Allison	43.0	85	10.6	4.09	0.057	4.32	5.37	214	0.367
Homestead	21.5	81	13.2	4.40	0.094	3.98	4.98	186	0.558

Discussion

As is common to these types of experiments, and assuming other aspects of establishment remain favourable, two factors could potentially have a strong effect on our ability to detect significant treatment differences within sites:

- variability in initial tree (seedling) height, and
- variability within sites.

The latter factor can mainly be attributed to soil characteristics, management and weeds. The project anticipated this and took these effects into account by aimed for total weed control and measuring soil characteristics that could be used as covariates in later statistical analyses. There was considerable within-site variability in some of the soil nutrient levels with up to about 100% variation (i.e. double the values) between treatment means, which implies that variability between plots will be even greater.

As already noted, variation in potentially operational slash management methods might confound interpretation of results from this component of the experiment. The important components of variation are: (1) the quality and amounts of nutrients, (2) proximity to a tree, and (3) the rate at which nutrients can be expected to become available for uptake by tree roots. All three of these components vary considerably from tree-to-tree and site-to-site in this series of experiments. Examples of this range are (a) an uneven distribution of stumps removed with some course roots, (b) large piles (c. 1 m^3) of all slash components unevenly distributed, and (c) all components of slash in an approximate even cover around each tree. Slash removal conditions included whole-tree removal, blading and burning, which would variably affect soil conditions. Our general observation was that CTL (Cut to Length) harvesting provided more uniform slash distribution than the IFC (In-Field Chipping) method.

The potential level of nutrient deficiency of individual trees will depend on the gap if any between nutrient demand and supply, which can be met by fertiliser additions which of course will also vary from tree-to-tree. This variation in tree-to-tree, treatment-to-treatment, and site-to-site variation in nutrient supply and demand in relation to slash management is the crux of the interaction with fertiliser responses that will be quantified by this trial series. However, it is too early to speculate on the relative levels of variability in tree growth in relation to slash management, other site factors, and fertilisation.

The potential operational methods of slash retention used in this trial series shows progress during the past 20 years (Smethurst 1998), but it also shows that this issue remains a concern for the industry and therefore justifies the research. This series of experiments and the research of Mendham et al. (2008) is one of the most significant research efforts so far by the Australian industry on slash management methods in hardwood plantations.

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APPENDIX 2 NDVI ESTIMATES FOR RESPONSE AND RATE TRIALS.

NDVI (normalised difference vegetation index) was calculated for fertilised and unfertilised plots at most sites using imagery collected by the Copernicus Sentinel-2 (S2) satellites. NDVI has been positively related to leaf area and productivity of eucalypts and other species in a range of studies in Australia and overseas (Baret, et al. 1995; Carlson and Ripley, 1995, Fang et al. 2019; Kang et al. 2016; Marsden et al, 2010; Xavier et al 2004; Xue et al 2017). It is routinely used to monitor changes in LAI over time at a global scale (e.g. https://earthobservatory.nasa.gov/features/LAI/LAI3.php).

The two polar orbiting Sentinel satellites are located 180° to each other and collect imagery for mid-latitudes once every 2-3 days. They measure reflectance across 13 wavelength bands for each point on the earth's surface about once every 5 days (Table 1). The wavelengths most sensitive to vegetation greenness include the Red and Near Infra-Red (NIR) bands. For the S2 satellites these wavelengths are covered by Bands 4, 5, 6, 7, 8 and 8A which have a spatial resolution of 10-20 m (i.e. producing imagery with pixels with areas of 100-400 m^2).

The spatial resolution of the S2 imagery is finer than earlier satellites such as Landsat which has a resolution of 30 m. This makes it more suitable for examining growth responses of trees in multifactorial fertilizer trials such as those in the rates and responsiveness trials in the current project in which measurement plot sizes were 220 to 340 m^2 (with total treatment areas of 500-700 m^2).

Table 1. **Wavelengths and resolution of each of the bands measured by the Sentinel 2 satellite.**

Sentinel-2 Bands	Central Wavelength (µm)	Resolution (m)
Band 1 - Coastal aerosol	0.443	60
Band 2 - Blue	0.490	10
Band 3 - Green	0.560	10
Band 4 - Red	0.665	10
Band 5 - Vegetation Red Edge	0.705	20
Band 6 - Vegetation Red Edge	0.740	20
Band 7 - Vegetation Red Edge	0.783	20
Band 8 - NIR	0.842	10
Band 8A - Vegetation Red Edge	0.865	20
Band 9 - Water vapour	0.945	60
Band 10 - SWIR - Cirrus	1.375	60
Band 11 - SWIR	1.610	20
Band 12 - SWIR	2.190	20

NDVI was calculated from the Red and Near Infrared bands (bands 4 and 8 for Sentinel data) and averaged for the year prior to fertiliser application:

$$\mathrm{NDVI} = \frac{(\text{Band } 8 - \text{Band } 4)}{(\text{Band } 8 + \text{Band } 4)}$$

Healthy (i.e. green) vegetation tends to reflect less light in the red band (Band 4) and more light in the NIR band (Band 8) and so has an NDVI close to 1, while less healthy vegetation (and bare land) tends to be browner and has an NIR closer to 0 (Figure 1). For vegetation, NDVI generally ranges from 0 to 1. While values as low as -1 are possible, these are generally associated with water.

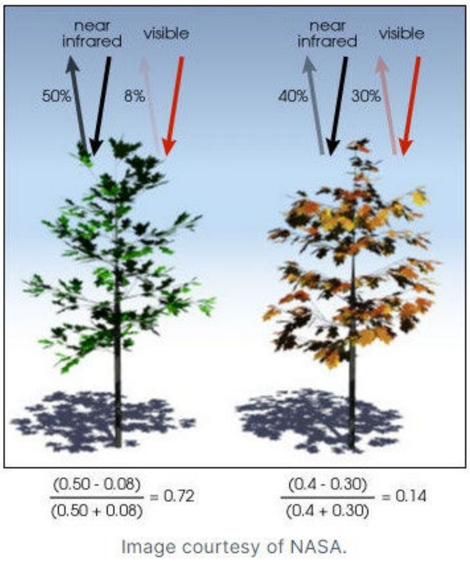

***Figure 1*. Illustration of how vegetation colour contributes to the value of NDVI.**

GPS locations of the centres of all plots were recorded in July-September 2022 for all sites in the Green Triangle and WA, and in Tasmania GPS coordinates were provided for plot corners. Average latitude and longitude for each plot were calculated and used to download S2 imagery for each plot for each site.

Cloud free S2 imagery was collected for the period from December 2018 to January 2023 from Google Earth Engine using code written in Python developed by CSIRO. Initial analysis of this imagery indicated that, despite it being ostensibly cloud free, many outliers still existed indicating that the cloud masking method used for the Sentinel data was suboptimal. The Python code was adapted to identify and remove most remaining outliers (values +/- 0.5 SDs from a running 90-day average) and to output the monthly and yearly averages for each plot at each site.

NDVI values were calculated from average monthly data for each plot and averaged for each treatment. Where there were no cloud-free records for a plot for a given month, NDVI was estimated by interpolation from the two closest months with data. Annual averages were calculated for the period 1st January to 31st December for 2019-2022. Imagery data for the S2 satellites from the Google Earth Engine are available only as far back as December 2018. This means that only up to 7-10 months data is available prior to fertiliser application for those sites fertilised in 2019 and no pre-fertiliser data is available for those sites fertilised in 2018.