Resources

ProFert-Pine - A fertiliser tool for softwood plantations in southern Australia

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ProFert-Pine - A fertiliser tool for softwood plantations in southern Australia

Prepared for

Forest & Wood Products Australia

by

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Executive Summary

This project modified and calibrated an existing fertiliser tool (ProFert 1.0) that had been initially developed for softwood plantations across Tasmania, so that it could be applied to plantations in other regions. Using datasets provided by collaborating plantation growers (HVP, TPPL and Norske Skog) based in Victoria, the Green Triangle and Tasmania and CSIRO together with information from published and unpublished reports, new relationships for predicting responses to N, P and K fertiliser were developed which could be used across the three regions. The model was modified so that it could accept data from the existing growth and yield systems used by plantation growers to calculate growth rates, product yields and values and harvesting and haulage costs. The resultant tool (ProFert 2.0) was tested and validated using independent data sets and compared with other methods used to select stands for fertiliser application. The results demonstrated that the tool could accurately predict growth response and profitability across a range of stands and nutrient limitations and that it provided superior results to existing approaches.

Overview of ProFert

ProFert 1.0 is a decision support tool for assisting plantation growers in predicting growth responses to and financial performance of fertiliser use. To the author’s knowledge, it is the only tool available which provides a complete financial analysis of the profitability of fertiliser use in softwood plantations over an entire rotation. It was developed for use across northern Tasmania for Timberlands Pacific using data from research trials across northern Tasmania provided by Timberlands Pacific and Forestry Tasmania and was based on an earlier model (NP-Opt) which was produced by CSIRO in collaboration with FWPA, and a consortium of forest growers for use in the Green Triangle (May *et al.* 2009a).

The relationships used in the original model (NP-Opt) to predict response to fertiliser were based on results from 16 research trials established in the Green Triangle across South Australia and Victoria. These results included:

- relationships between N and P response and foliar N and P concentrations, leaf area index and indices of soil N and P availability;
- relationships between rate of application for different forms of N and P fertiliser and growth response;
- relationships between time since application and cumulative response for different forms of N and P fertiliser; and
- effects of prior applications of N and P fertiliser on stand nutrient status and subsequent response to N and P fertiliser.

The updated tool developed for Timberlands Pacific included:

- revised relationships for predicting response to N and P for northern Tasmania;
- harvesting and transport costs for logs from different locations;
- product specific wood values;
- an improved user interface and more efficient operation and optimisation; and
- conversion of the model from a series of spreadsheets to VBA code.

The current project further improved the tool by:

- developing more robust response relationships for predicting N and P responses from datasets provided by collaborators;
- developing a K response relationship using data from published studies;
- incorporating the effects of secondary nutrient limitations on predicted response;
- better accounting for the interactions between successive fertiliser applications;
- changing the interface and underlying processes in the model to accept growth, harvest and product breakdown data from the various systems used.

Data provided by collaborators

A critical component of the project was the provision of growth and fertiliser response data by the project collaborators. These datasets were used to develop and test new fertiliser response relationships and enable the tool to use growth and yield data directly from existing systems. Data provided by collaborators included:

- predictive relationships from HVP for stands across Victoria:
    - between response to N fertiliser and foliar N;
    - between response to P fertiliser and foliar P;
- predictive relationships from Norske Skog for stands across the Tasmania:
    - between response to N fertiliser and foliar N;
    - between response to P fertiliser and foliar P;
- treatment responses to fertiliser experiments established in Tasmania and the Green Triangle from CSIRO;
- results from two additional operational fertiliser trials in Victoria established by HVP;
- growth and yield data, harvest and haulage costs and product values from HVP;
- growth estimates and product yields from Norske Skog's growth model; and
- stand growth curves and percentage breakdown of logs of different sizes from TPPL.

Development of relationships predicting fertiliser response

New relationships between response to fertiliser and foliar N and P were developed using datasets from Victoria, Tasmania and the Green Triangle. The N response datasets were modified by minimising potentially confounding factors by:

- removing all results where a nutrient other than N was deficient; and
- removing treatments where urea only was applied.

There were negative linear relationships between % response to N fertiliser pre-treatment and foliar N concentrations for all three regions. However, there were significant differences between the relationships with predicted responses larger for the one based on Victorian data compared with the relationship based on data from the Green Triangle.

Responses to P were significantly related to foliar P concentrations in negative exponential relationships for Victoria and the Green Triangle, but not Tasmania. As with N, the slopes of the relationships differed significantly with predicted responses to P larger for the relationship from Victoria compared with that from the Green Triangle.

The differences in response to N and P fertiliser between the three datasets were attributed to a number of factors including:

- secondary nutrient deficiencies where, for example, P or another nutrient limits the capacity of trees to respond to N fertiliser;
- differences in soil type with stands on clay or loam soils (the predominant types for the Victorian sites) possibly being more responsive to both N and P fertiliser than the sandy soils (the predominant type for Green Triangle sites);
- differences in the rate of N fertiliser applied with 300 kg N/ha used across the Victorian sites compared with 200 kg N/ha across the Green Triangle and Tasmanian sites; and
- The effect of drought, with lower than average rainfall in the Green and Tasmania during part of the measurement period possibly limiting responses in these regions.

Of these possibilities, differences in soil texture appeared to be the most likely cause of differences between the relationships. However, responses across the sites in Tasmania (which were on clay or loam soils) were similar to those for the Green Triangle. Despite this inconsistency, it was assumed that the relationships based on Victorian data applied to clay/loam soils while those from the Green Triangle and Tasmania applied to sandy soils. This is the only effect of soil type on response allowing the user to select which relationship to use by simply changing the soil type for a given site.

In addition to modelling response to N and P fertiliser, results from two research trials in Victoria (Hall and Raupach 1963, Raupach and Hall, 1974) were used to develop a relationship between response to K fertiliser and foliar K.

Accounting for secondary nutrient deficiencies

To allow ProFert to account for interactions between different nutrients, a novel process was developed which modelled the effects of secondary nutrient deficiencies. Secondary nutrients are any nutrients which are not included in the fertiliser being applied. These can limit responses to fertiliser and can result in significant interactions between different fertiliser types.

To account for secondary nutrient limitations it was assumed that:

- Where a secondary nutrient is below adequate it will reduce the response to fertiliser;
- The degree of reduction increases linearly as the concentration of the secondary nutrient decreases so that it reaches 50% when the secondary nutrient is deficient;
- The degree of reduction is calculated from the most limiting nutrient;
- Where a secondary nutrient is included in the fertiliser mix, the degree of the reduction declines based on the rate applied using the same relationship used to predict response to different fertiliser forms and rates (see below).

Accounting for effect of fertiliser form and rate

Relationships between rate of application and growth response for different N fertiliser forms were based on results from fertiliser experiments established in the Green Triangle and Victoria. Previous work from the Green Triangle had demonstrated that responses to N applied as urea were less than those to other N forms as a result of N volatilisation losses. The results from Victoria were consistent with these findings with a relationship between response to N and foliar N significantly different for urea alone compared one based on N applied as ammonium sulphate or urea + P. Average predictions from the two relationships indicated that the response to urea alone was 25% less compared with the other N forms which was very close to average reduction (27%) reported for sites in the Green Triangle.

To account for observed responses to different rates of N and P application on clay/loam soils The N form x rate relationships and P form x rate relationships were modified as follows:

- the response to urea alone was assumed to be 25% less than that to other N forms for both clay/loam and sandy soils;
- the response to 300 kg N/ha was assumed to be 25% greater for clay/loam soil and 5% greater for sandy soil compared with 200 kg N/ha;
- where P was applied together with urea, it was assumed that volatile losses of N were negligible and there was no reduction in response; and
- the response to P fertiliser applied at a rate of 160 kg P/ha was assumed to be 13% greater on both sandy and clay/ loam soils compared with 80kg P/ha.

In addition a new rate response curve was developed for K based on results from a study by Hall and Raupach (1963).

Calculating long term growth responses

Long term growth responses to N and P fertiliser were estimated from average responses from 10 experiments in the Green Triangle measured over 10 years. The results were re-analysed by fitting curves to the cumulative responses to improve the prediction of long term responses. Key assumptions included:

- the annual response to N reached a maximum two years after application, decreased to less than zero at 6 years and returned to zero at 11 years;
- the annual response to P reached a maximum five years after application before gradually decreasing to zero, 20 years after application; and
- the annual response to N+P reached a maximum two years after application before gradually decreasing to zero 10 years after application.

The temporal response to K fertiliser was assumed to follow the same pattern as that for N.

Accounting for effects of multiple fertiliser applications

The experiments in the Green Triangle indicated that prior applications of N and P fertiliser could increase or decrease the response to future applications by changing the stand’s nutrient status. In the previous version of the model (ProFert 1.0), this effect was accounted for empirically by adjusting the expected response to N or P up or down depending on the number of years since the previous fertiliser application and the amount of fertiliser applied.

In contrast, in ProFert 2.0, the effects of past fertiliser applications (including N, P, K and S) are accounted for using the assumed changes in foliar nutrient concentrations from which responses to future fertiliser applications are predicted. Relative changes in foliar nutrients over time were estimated using results of foliar monitoring over 10 years across the 10 stands used to estimate long term growth responses. These showed that foliar N increased then fell rapidly in the first three years after N fertiliser application but foliar P remained elevated for at least 10 years after P fertiliser application, elevating responses to subsequent N fertiliser. This approach is more robust and flexible than the empirical approach used in previous versions of the model.

Calculating Growth and Product Yields

To calculate total increase in wood volume and the volume of individual products harvested, underlying growth, harvest regime and product yields must be estimated. Previous versions of ProFert used default growth curves, based on site quality or height index, combined with estimates of product yields for different stem volumes. As part of the project, the tool was modified so that it could use estimates from operational growth and yield systems.

Each collaborator used a different growth and yield system. HVP used YTGen, TPPL used a combination of YTGen and default growth curves and Norske Skog used their own growth and yield model. ProFert was redesigned to be able to accept the type of growth data used by each organization. This ensured that the outputs of the tool were consistent with each company's growth and yield estimates for individual stands.

In addition, default growth curves and product yields based on data from the Green Triangle were included in the model to allow it to be used in the absence of other data. These curves are based on the site quality system used in the Green Triangle which ranks stands from 1 (highest productivity) to 7 (lowest productivity) limiting their application in other regions. Therefore, a procedure was developed to enable ProFert to select the appropriate site quality for a stand based on total standing and harvested volume at a given age.

Economic analysis and optimization procedures

ProFert includes a detailed analysis of the economics of fertiliser applications including outputting discounted costs of fertiliser, revenue from harvested wood, net present value, internal rate of return and the volume of wood produced per $ spent. The economic analysis in the ProFert 2.0 was improved by:

- including actual mill door product values input by the user or from the growth and yield system rather than modelled estimates;
- incorporating results from the user's growth and yield model to estimate the recovery of different products;
- accounting for the differing harvest costs for different harvest operations; and
- accounting for the transport costs for different products, stand locations and destinations.

The optimization procedure was also improved to make it faster and more accurate. This included:

- improving the efficiency of optimal fertiliser treatment selection;
- including the option for the user to fix certain fertiliser treatments to remove key nutrient limitations; and
- providing additional outputs including charts and tabular outputs of responses to all fertiliser treatments tested for individual sites.

Testing and validation

ProFert 2.0 was tested and validated using results from the original Green Triangle dataset as well and additional operational trials in Victoria provided by HVP. The Green Triangle datasets used included:

- results from core fertiliser treatments, some of which were used to develop the original response relationships to check that predicted relative and absolute increases in wood volume and NPV were accurate and unbiased;
- results from additional treatments not used in the predictive relationships including different forms and rates of N and P fertiliser; and
- responses to fertiliser treatments applied after third thinning to plots previously fertilised with N, P, N+P or left unfertilised after 2nd thinning;

The results of the comparisons with the Green Triangle data sets indicated that ProFert 2.0 could accurately predict both growth responses and profitability of a range of fertiliser treatments across different stands and a variety of nutritional limitations with no evidence of significant positive or negative bias. The results, in terms of percent variation explained for each analysis, were as follows:

- Core treatments: relative response 74%, absolute response 60%, NPV 61%;
- Addition fertiliser form x rate treatments: relative response 58%, absolute response 62%, NPV 67%;
- Repeat fertiliser applications (with 1 replicate per treatment): relative response 42%, absolute response 30%.

The additional Victorian data provided by HVP included five treatments applied operationally across two sites. Relative responses only could be calculated as there was no data from which underlying growth rates could be predicted. ProFert was able to explain 73% of the variation in response across the treatments.

Performance compared with other approaches

Comparison of the performance of ProFert with that of alternative approaches used to select sites for fertiliser application demonstrated that it was superior. For the comparison, the 16 sites in the Green Triangle were used as these were the only sites for which detailed nutrition and growth measurements were available. Increases in wood volume and value at time of clearfell across the sites were estimated based on measured responses at the final measurement (3-6 years after fertiliser application) and regional growth curves, product break-downs and product values.

The criteria used to select the sites together with the outcomes in terms of average NPV per ha, total NPV (assuming each stand covered 100 ha) and internal rate of return were:

- ProFert:
    - NPV > 0 (for a 10% discount rate): + $344/ha, + $241,000, 20%;
    - IRR > 15%: + $356/ha. + $178,000, 27%
- Alternative approaches
    - All sites fertilised: - $369/ha, - $958,000, 1%
    - Growth > 25% less than expected: + $89/ha, + $36,000, 11%
    - Moderate growth (site quality 3 to 5): - $359/ha, - 456,000, 1%
    - Older stands (> 20 years): - $240/ha, - 408,000, 5%
    - Low foliar N (13 mg/g) or P (< 1.1 mg/g): - $129/ha, - $232,000, - 4%

The outcome of decisions based on ProFert were substantially more profitable (with an average NPV of $344/ha where stands were selected on the basis of NPV) compared with - $370/ha to $90/ha for the five alternative approaches which were considered. ProFert also more than doubled the rate of return on investment (with an IRR of 27% compared with - 4% to 11% for others) and increased the total return from fertilising the stands by more than six fold.

Conclusion and Recommendations

The newly calibrated and improved version of ProFert provides a means for forest managers to predict the effects on both total wood production and financial performance of applying fertiliser to softwood stands. The response relationships on which the predictions are based have been derived from independent datasets covering a wide range of sites across the Green Triangle, Victoria and Tasmania. It is also the first model to account for secondary nutrient limitations as well as the effects of current fertiliser treatments on responses to subsequent applications. Validation of the tool demonstrated that the predictions are unbiased and accurately predict increases in wood production and profitability across the sites covered.

While every effort has been made to ensure the predictions from ProFert are accurate, uncertainty remains regarding differences in relationships used to predict responses to N and P fertiliser from different regions as well as a number assumptions used in the model. Predicted responses to N fertiliser were around 40% less based on the relationship from sites in the Green Triangle and Tasmania compared with that from Victorian sites. Similarly, predicted responses to P fertiliser were around three times greater for the relationship based on sites in Victoria compared with that based on sites in the Green Triangle. These differences may be due to differences in fertiliser treatments, soil type, rainfall, other nutrient limitations or a combination of factors.

Comparisons of actual and predicted responses for other sites will help validate the model and can be used to further improve its accuracy. It is recommended that:

- existing data from fertiliser experiments across Australia be made available by plantation growers and research organisations to further validate the models predictions and test its applicability to other regions and for other species;
- additional fertiliser experiments be established across Victoria, South Australia and Tasmania using the same fertiliser treatments and measurement protocols to better understand potential causes of differences in responses for the different regions and provide more robust relationships for predicting response to N, P and K fertiliser;
- operational fertiliser trials be established by plantation growers to test the accuracy of model predictions and provide further data for validating response relationships; and
- additional fertiliser experiments be established in other regions, younger stands and in different species to test and calibrate ProFert for use in these environments.

New results and relationships can be readily integrated into the existing structure of ProFert. Including data from a wider range of studies and regions into the model will reduce uncertainty associated with its outputs and ensure that it can be used with confidence across a wider range of regions and plantation types.

Regardless of the remaining uncertainties, ProFert represents a major improvement in terms of increasing the capacity of plantation managers to predict increases in wood production and the expected profitability of fertiliser application. It is expected that ProFert will improve the profitability of fertiliser use in softwood plantations managed by the collaborators involved in the study as well as other softwood plantation owners across south-eastern Australia. Adoption of the model is expected to:

- enable forest managers to achieve positive outcomes for a larger proportion of stands by reducing the risk of fertilising non-responsive stands or failing to fertilise responsive stands;
- reduce the risk of adverse environmental impacts from inefficient fertiliser use;
- boost plantation productivity, reducing the amount of land required.

Uptake of the outcomes of this project will be measured by monitoring the use of ProFert, both by the companies directly involved in the project as well as other plantation owners across Australia. TreeMod will continue to liaise with HVP, TPPL and Norske Skog after the completion of the project to ensure that the tool is functioning as desired and that staff are familiar with its operation and are able to use it efficiently. We will also actively promote the tool with other plantation managers, consultants and research institutions. Already there have been expressions of interest in ProFert from both Australia and overseas. It is anticipated that uptake of the model will continue as its benefits are realised making it a key decision support tool used by plantation growers.

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Introduction

Improvement of productivity of Australia's plantations through the early detection and remediation of forest nutrition issues is a key priority for Australia's plantation forest industries. Previous work by researchers from CSIRO and other organisations has demonstrated that tree growth can be increased by 30-50% over periods of 6 to 12 years by applying the correct nutrients at the correct time within a rotation (May *et al.*2009a, Turner *et al.*2001, Turner *et al.*1996).

However, a large proportion (~50%) of Australia's hardwood and softwood plantations currently receive little or no fertiliser beyond an initial application at planting (May *et al.* 2009b). Despite extensive research into plantation nutrition and responses to fertiliser, forest managers have few tools that they can draw on to assist in making decisions regarding selecting which stands to fertilise, what to apply and how much fertiliser should be used. This has resulted in uncertainty regarding the potential responsiveness of stands and has limited the use of fertiliser to boost growth and improve profitability. In a review of fertiliser use across Australia's plantations May *et al.* (2009b) found that this was a major concern across many companies surveyed.

This project helps address this gap by providing forest managers with a new tool which incorporates the latest scientific discoveries into an easy-to-use, economic model to estimate the increase in wood production and profitability associated with fertiliser use on a stand specific basis. This tool is based on an existing system currently being applied operationally across Northern Tasmanian softwood plantations (ProFert 1.0). This was based on an earlier prototype (NP-Opt available on FWPA's website at http://www.fwpa.com.au/node/177) developed by CSIRO in collaboration with FWPA forest growers in the Green Triangle.

The original version of ProFert used the general framework of NP-Opt, but modified it extensively to allow it to be more flexible and efficient to meet the needs of TPPL for managing its plantations in northern Tasmania. These modifications included:

- development of a user-friendly interface allowing for easier input and output of data;
- conversion of a series of spreadsheet-based formulae into VBA code;
- inclusion of the effect of soil types on fertiliser response;
- more robust and flexible relationships for predicting response to N and P fertiliser;
- incorporation of product types, values and destinations;
- inclusion of product types and transportation costs in the economic analysis;
- adding the capacity to model growth responses for both young and older stands;
- inclusion of a wider range of management regimes including non-commercial thinning; and
- incorporation of uncertainties in the estimates.

These modifications were made in close consultation with Timberlands Pacific to ensure that the end product (ProFert 1.0) met their requirements and assisted its rapid adoption by this organisation. It has now been used to plan fertiliser programs for five years and has assisted in improving the efficiency and effectiveness of fertiliser use by Timberlands Pacific in Northern Tasmania. However, ProFert 1.0 is limited by the fact that it was parameterised specifically for plantation growth, soil types and fertiliser responses within TPPL's estate across this region.

The aim of the current project was to parameterise ProFert so that it could be applied more widely to plantations across southern Australia. Three forestry companies were partnered with plantations covering three separate regions:

- HVP: whole of Victoria,
- Norske Skog: southern Tasmania and
- TPPL: the Green Triangle covering SE South Australia and SW Victoria.

Datasets were provided by each of the companies to enable the model to be modified and parameterised to predict responses to fertiliser, estimate underlying stand growth and incorporate the specific harvesting and management regimes used by each company.

Review of previous work

Across the Green Triangle, CSIRO and ForestrySA have undertaken substantial research into fertiliser deficiencies, the effect of different fertiliser forms and times of application and the size and longevity of responses to N and P fertiliser (e.g. Fife and Nambiar 1999, Raupach *et al.* 1969, May and Carlyle 2005, May *et al.* 2009a). This research complements similar work undertaken in other parts of Australia including Tasmania (Neilsen *et al.* 1981, Neilsen 1992), Victoria (Hopmans *et al.* 1994), NSW (Turner *et al.* 1996, Turner *et al.* 2001), WA (McGrath *et al.* 2003a and 2003b), and Queensland (Simpson and Grant 1991). Results from a series of fertiliser experiments established across the Green Triangle were used to develop a prototype fertiliser decision support system (NP-Opt) to assist forest managers predict growth responses of mid-rotation plantations to alternative fertiliser regimes.

The underlying data and relationship used in the NP-Opt model, its structure and assumptions are fully described in the report available on the FWPA website (May *et al.*2009a). This was the first fertiliser model developed in Australia which allowed the total increase in wood yield and value to be estimated across an entire rotation including up to 4 thinnings and fertiliser applications. It was also the first to incorporate the effects of alternative N forms and interactions between successive fertiliser applications.

Application of this model has been limited due its reliance on detailed nutritional data rather than more generally available soil-type information (J. O'Hehir, ForestrySA Pers. Comm.), difficulties in obtaining the foliar and soil information required and its inability to predict growth responses in young stands (K. Nethercott, Pers. Comm.). However, no suitable alternative off-the-shelf product exists that can accurately predict the response to and profitability of fertiliser application.

ForestrySA developed another tool (EM1888A – young age fertiliser prediction tool, 2010) for the Green Triangle, but this is designed to be used in young stands only, does not provide an economic analysis and does not allow the effects of multiple applications to be modelled. Another tool, FPOS, has been developed by CSIRO in collaboration with FWPA which is a decision support tool for management of hardwood and softwood plantations (Mendham *et al.* 2013). Based on the Cabala growth model, this tool uses climate, soil and species data to predict growth and response to nitrogen fertiliser and provides only a rudimentary means of assessing the profitability of fertiliser use. As a result, it is currently difficult for forest managers to readily account for the complex interactions between soil type, stand characteristics and fertiliser type, amount and timing when selecting stands to fertilise or fertiliser regimes to apply.

This limitation was identified by Timberlands Pacific who contracted TreeMod to develop a new fertiliser tool, based on NP-Opt, but adapted for conditions in Tasmania and improved to allow it to be readily integrated with existing forest management systems.

The resultant tool (ProFert 1.0) is now used operationally by Timberlands Pacific to select stands for fertilising across Northern Tasmania. After initial testing, it now forms the basis of nutrition management of the company's softwood plantations. ProFert 1.0 was specifically designed so that it could be readily adapted to conditions in other regions of Australia. However, more data from fertiliser experiments from sites in regions other than the Green Triangle and Tasmania was required to allow robust relationships for predicting response to fertiliser to be developed. The current project addressed this issue by acquiring datasets from fertiliser experiments across Victoria and other parts of Tasmania and using these to develop new relationships which could predict response to fertiliser across a wider range of stand and soil conditions.

Methodology

Datasets used

Four separate datasets were used to develop the underlying relationships used to predict response to fertiliser in the model. These datasets were sourced from:

1. HVP: responses to N fertiliser from four sites located in central and western Victoria that were fertilised after first (T1) and second thinning (T2);

2. HVP: responses to P fertiliser from 15 sites located across the whole of Victoria that were fertilised after second thinning;

3. CSIRO: responses to N and P fertiliser across 16 sites located in the Green Triangle (south east SA and southwest Victoria) fertilised after T2 and T3;

4. Norske Skog: responses to N and P fertiliser across 7 sites located in central and southern Tasmania fertilised after T1.

The stands ranged in age from 4 years to 32 years and stand and site variables were related to increases in growth relative to controls over 4 - 15 years. The treatments and relationships derived from each dataset are discussed in more detail below.

Victorian Data

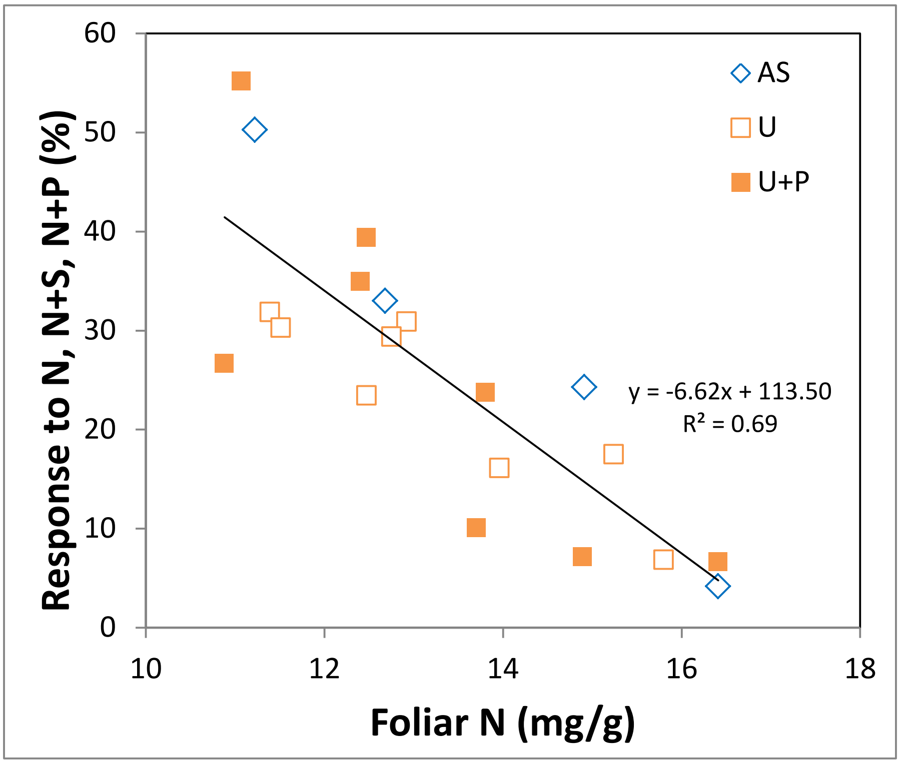
Responses to N fertiliser

HVP provided raw data and associated relationships for responses to N fertiliser and foliar N across four sites located across Victoria. The data was based on four 4 year responses from two separate fertiliser applications (the first after 1st thinning, T1, and the second after second thinning, T2) each with 2 different N treatments including:

- N alone as urea (300 kg N/ha) after both T1 and T2;
- N+P as urea (300 kg N/ha) and triple super phosphate (80 kg P/ha) after T1 only; and
- N + S as ammonium sulphate (300 kg N/ha) after T2 only.

Altogether, there were 20 treatment x site combinations. A relationship between response and pre-treatment foliar N concentrations explained 69% of the variation in relative growth responses (growth of fertilised treatments expressed as a % increase relative to growth of the controls, Figure 1). From this original dataset five sites deficient in P, S or other nutrients were excluded to remove potential confounding limitations from or (in the cases where N was applied in combination with S or P) responses to these nutrients. The modified relationship explained 79% of variation in growth response and was assumed to provide an indication of the relationship between foliar N concentrations response to N alone in the absence of other nutrient limitations.

a)



b)

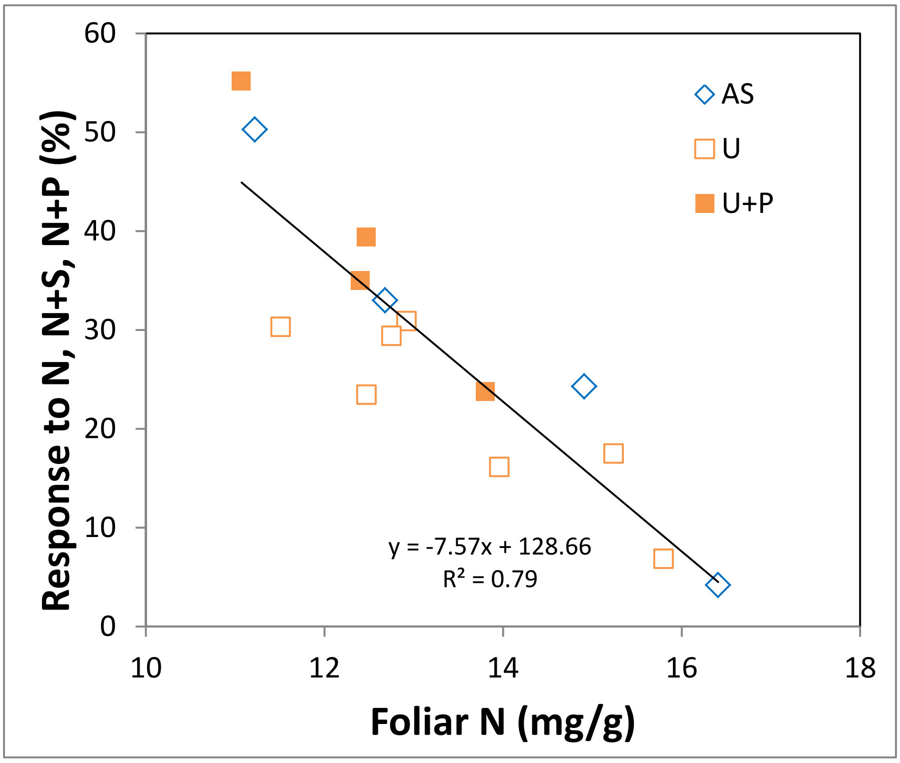


Figure 1: Relationship, based on data from Victoria, between foliar N and 4-yr volume responses to N applied as urea alone (U) or urea + triple superphosphate (U+P) after T1 and as urea alone, urea + triple superphosphate or ammonium sulphate (AS) after T2 for a) all treatments and b) only those treatments where foliar P, Cu or S were not deficient.

Response to P fertiliser

The second dataset and associated relationship provided by HVP included responses to P fertiliser and pre-treatment foliar P concentrations from 15 sites located across Victoria. The stands were aged between 4 and 22 years at the time of fertiliser application and the responses were based on measurements spanning 4 to 12 years depending on the site. All stands were fertilised with P in the form of triple superphosphate. However, the rate varied slightly from 80 kg P/ha, seven at a rate of 100 kg P/ha and one was fertilised at a rate of 120 kg P/ha.

A negative exponential relationship between foliar P and response to P fertiliser explained 85% of variation in relative growth response.

Green Triangle Data

Responses to N fertiliser

The data from the Green Triangle was sourced from a previous report by May *et al.* (2009a) which included 10 sites fertilised in 1995-96 after second thinning (T2) and again in 2002 after third thinning (T3). There were 4 replicates T2 treatments and 4-6 replicates for the T3 treatments. Treatments included:

- N alone as urea (200 kg N/ha) after T2 for 9 sites;
- N+P alone as urea (200 kg N/ha) and triple super phosphate after T2 for 9 sites;
- N alone as ammonium nitrate (200 kg N/ha) after T2 for one site and T3 for 10 sites; and
- N+P as ammonium nitrate (200 kg N ha) and triple super phosphate (80 kg P ha) after T2 for one site and T3 for 10 sites.

The responses after T2 were measured over 6 years while those after T3 were measured over 4 years.

An additional site (Nangwarry) was fertilised with different forms of N fertiliser in after 1st thinning in 2002 including:

- N alone as urea (200 kg N/ha);
- N+P as urea (200 kg N/ha) and triple super phosphate (80 kg P/ha);
- N+P as ammonium nitrate (200 kg N/ha) and triple super phosphate (80 kg P/ha); and
- N+P as ammonium sulphate (200 kg N/ha) and triple super phosphate (80 kg P/ha).

There were 4 replicates per treatment and responses were measured over 6 years.

Five more sites were fertilised with different forms of N and P after T2 in 2003. Treatments included:

- N alone as urea (200 kg N/ha, two sites);
- N alone as ammonium nitrate (200 kg N/ha, five sites);
- N+P as urea (200 kg N/ha) and triple super phosphate (80 kg P/ha, two sites); and
- N+P as ammonium nitrate (200 kg N/ha) and triple super phosphate (80 kg P/ha, five sites).

There were 4 replicates per treatment across these sites and responses were measured over three years.

A relationship based on responses to N+P over 4 years and pre-treatment foliar N concentrations explained 43% of variation between in response after adjusting for differences in the form of N used and prior fertiliser application (Figure 2, May *et al.*, 2009a). However, there was no significant relationship between response to N alone and foliar N ($R^2 = 0.07$). The unadjusted data for all treatments was sourced from CSIRO in order to test the effects of N form and the effect of applying N alone or together with P.

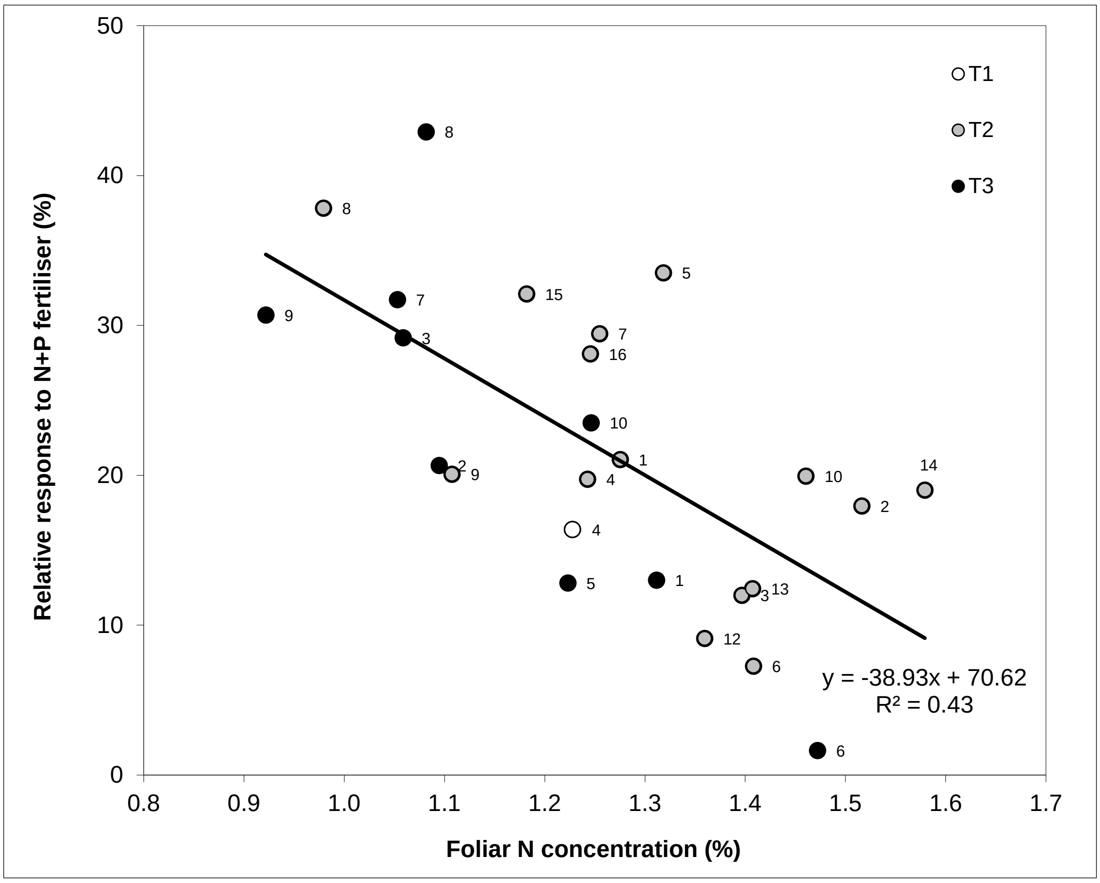


Figure 2: Relationship between response to N and foliar N for treatments fertilised with N+P fertiliser after adjusting for the effects of N form and prior fertiliser treatment for experimental sites across the Green Triangle (May *et al.* 2009a).

In addition, other relationships based on soil and other foliar variables were tested (May et al, 2009a). These relationships included:

- Response to N+P and LAI ($R^2 = 0.42$)
- Response to N+P and LAI x Foliar N ($R^2 = 0.50$)
- Response to N and soil total N ($R^2 = 0.42$)
- Response to N and forest floor N ($R^2 = 0.41$)

Responses to P fertiliser

Data for responses to P fertiliser in the Green Triangle was from the same set of sites as the N response data. A linear relationship between relative responses to P and pre-treatments foliar P concentrations was based on treatments that used P only (applied as triple super phosphate at a rate of 80 kg P/ha). This relationship explained 40% of variation to P fertiliser.

Responses to N and P fertiliser applied at T3 on plots fertilised with N, P or N+P at T2

Fertiliser treatments for the ten stands fertilised with N, P and N+P at T2 and again at T3 were designed in such a way that responses to the various combinations of treatments across the two applications could be calculated (May *et al.*2009a). In this way, residual effects of the T2 fertiliser treatments on stand N and P status and the subsequent response to N, P and N+P treatments applied at T3 could be quantified. For this analysis, there was only one replicate per treatment. Results showed that application of P fertiliser at T2 significantly increased response to N alone applied at T3.

Tasmanian data

Data for fertiliser responses for Tasmanian plantations was provided by Norske Skog (Bruce, 2001). This data included:

- 4 year responses to N fertiliser and 5 year responses to N+P fertiliser and pre-treatment foliar N and foliar P data across 7 sites[a]; and
- 4 year responses to P fertiliser and pre-treatment foliar P concentrations across 6 sites.

N fertiliser was applied at a rate of 200 kg N/ha as urea and P fertiliser was applied at a rate of 80 kg P/ha.

Bruce, 2001 reported a significant relationship between response to N fertiliser and foliar N concentrations which explained 45% of variation in response, but no relationship between response to P and foliar P concentrations.

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[a] Pretreatment foliar P data was available for only six of the seven sites.

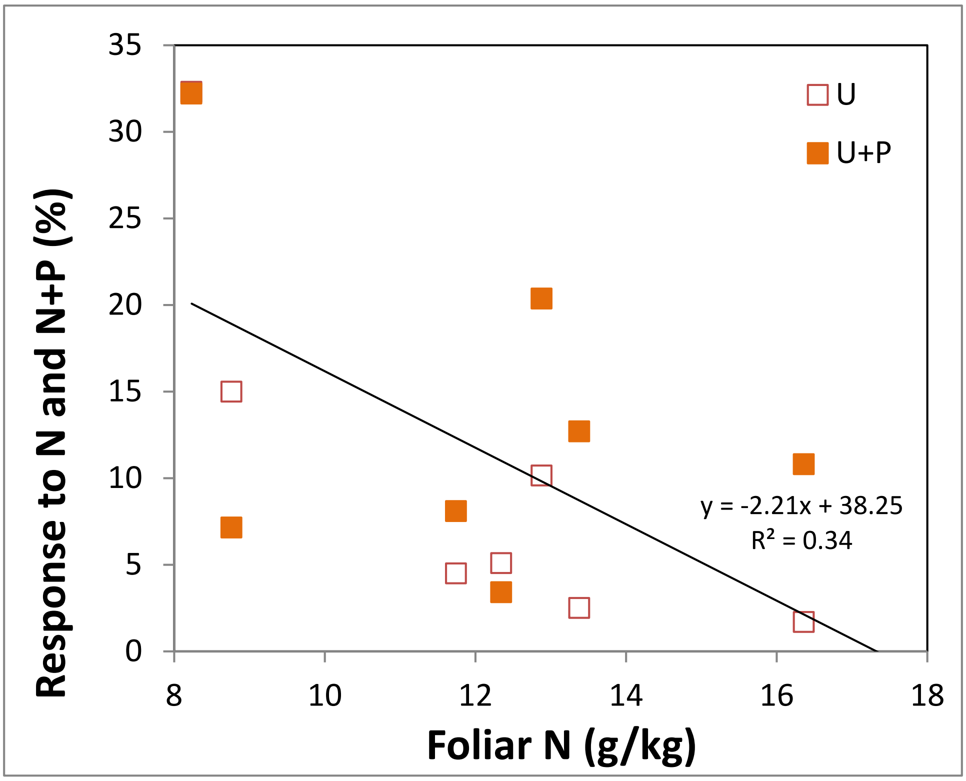


Figure 3: Relationship between response to N and foliar N for treatments fertilised with urea alone (U) or urea + triple super phosphate for experiments across Tasmania (Bruce, 2001).

Other data

To evaluate responses to other nutrients, published data from other experiments were used. These data included results from Raupach and Hall (1967) and Hall and Raupach (1971) for responses to K fertiliser and results from Kelly and Lambert (1972) indicating the effect of S deficiency on N response.

Data analysis

The relationships sourced from CSIRO, HVP and Norske Skog were reanalysed by removing results influenced by secondary nutrient limitations and accounting for differences in fertiliser types, rates and response periods..

Removal of sites deficient in other nutrients

The Victorian N responses data identified stands deficient in P, S or Cu and included a relationship based only those stands where these were marginal to adequate. A similar procedure was undertaken for the datasets for the Green Triangle and Tasmania. For the Green Triangle experiments, pre-treatment concentrations of P, K and Mg were available for all sites and pre-treatment concentrations of S were available for 11 of the 26 stands. Deficient and adequate nutrient concentrations (in g/kg) were defined as shown in Table 1.

Table 1: Assumed deficient, marginal and adequate concentrations of foliar nutrients and N/S ratios used in development of relationships used in ProFert.

Foliar nutrient	Unit	Deficient	Marginal	Adequate	Source
N	g/kg	10	11	16	Reuter & Robinson (1997)
P	g/kg	1	1.2	1.4	Reuter & Robinson (1997)
K	g/kg	3.5	4.25	6.5	Raupach and Hall (1963)
N/S	ratio	18	15	12	Hopmans Pers. Comm. (2015)

Sites where foliar P or K concentrations were less than or equal to, or foliar N/S ratios were greater than, deficient levels were excluded from the N analysis. Relationships between foliar N and response to N fertiliser were therefore based on the truncated datasets.

Effect of different forms of N

Results from the Green Triangle experiments indicated that the form of N applied can have a significant impact on the response to N fertiliser (May *et al.* 2009a). Responses to urea were significantly less than responses to ammonium sulphate or ammonium nitrate with the reduction in response averaging 35%. This difference was shown to be largely due to loss of N through N volatilisation from urea. The losses were reduced when P, in the form of triple super phosphate, or the volatilisation inhibitor Agrotain was mixed with urea.

To account for the effect of N form on response, the truncated (i.e. with plots deficient in nutrients other than N removed) datasets were split into treatments where N was applied as urea alone, urea plus triple superphosphate, ammonium nitrate or ammonium sulphate. Response to N was related to foliar N for each separate set of treatments and the effect of N form on the slopes and intercepts were compared.

Adjustment of P response relationships

The relationship between response to P fertiliser and foliar P provided by HVP had the form:

$$P\ Response\ =\ a\ \times\ Foliar\ P^{-b}$$

where a and b are constants found by fitting the curve to the data points.

This relationship decreases the response as foliar P concentrations increase. However, the response can never reach zero creating a problem in the case where stands have very high foliar P concentrations and so would not be expected to respond to P fertiliser. Therefore a new relationship was developed with the form:

$$P\ Response\ =\ a\ \times\ Foliar\ P^{-b} - c$$

where c is a constant allowing the relationship to predict a response ≤ 0.

The new curve was fitted to the data points by:

1. transforming the relationship to convert it to a linear relationship (straight line) by taking the logarithms of both the foliar P concentrations and responses to P after adding the constant c as follows:
    - $ln(P\ Response\ +\ c)$;
    - $ln(Foliar\ P)$;
2. setting the constant c to 7 to allow the relationship to cross the x axis at a foliar P concentrations of 1.4 mg/g (indicating adequate levels of P);
3. using the linear regression technique with the transformed variables to find the values for the constants a and b which minimised the Sum of Squares of the residuals:

$$ln(P\ Response\ +\ c) = \ln(a) - \ b\ \times\ ln(Foliar\ P)$$

4. Transforming the relationship back into the original equation using the values from the linear regression for a and b:

This same method was used to develop a relationship between response to P and foliar P concentrations based on data from the Green Triangle. However, to allow the line to pass through the x-axis for a foliar P concentration of 1.4 mg/g the constant c was set to 10.

Relationship between response to K and foliar K

No data on the growth response of plantations to K fertiliser was available from any of the experiments included in the datasets for the Green Triangle, Victoria or Tasmania. Therefore, other published data was used to develop a relationship between K response and foliar K. This data consisted of results from two experiments in young radiata pine stands in Victoria by Hall and Raupach (1963) and Raupach and Hall (1974).

The first of these experiments involved measuring the growth of trees fertilised with five different rates K fertiliser in a 6 year old stand deficient in K (Hall and Raupach, 1963). The authors reported an average 28% increase in growth on K fertilised treatments (>= 125 kg K/ha) relative to controls over 21 months. Data for average tree DBH's for the various treatments indicates that basal area growth tended to increase with rate of application from 36 m^2/ha/y for the controls to 47 m^2/ha/y for 1150 kg K/ha representing an increase of 35% (Figure 4). Foliar sampling indicated that foliar K concentrations increased with rate of fertiliser application from 3.37 g/kg for the controls to 11.26 g/kg for 1150 kg K/ha.

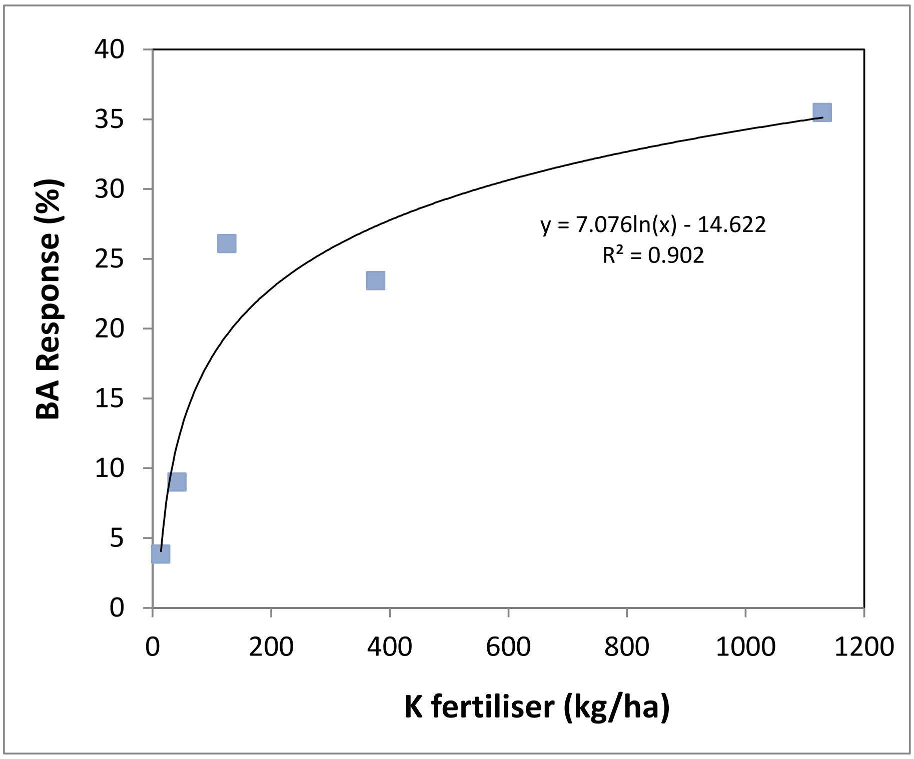


Figure 4: Relationship between basal area growth response to K fertiliser over 21 months and the rate of K application for 6 year old trees based on data from Hall and Raupach (1963).

To develop a relationship between foliar K concentrations and response to K fertiliser, it was assumed that:

- The main limitation to growth was K deficiency;
- the maximum response measured represented the maximum possible response to K fertiliser at this site;
- the growth rate of trees fertilised with intermediate rates of K represented the growth rate for the corresponding post-application foliar K concentration; and
- the relative difference between growth response of treatments fertilised with intermediate rates of K and the maximum growth response represented the relative response to K fertiliser for trees with foliar K concentrations equal to the post treatment foliar K of those treatments.

Using these assumptions, the theoretical response to fertiliser was calculated as:

$$Theoretical\ response\ (\%) = \left(\frac{Maximum\ response}{Observed\ Response} - 1\right) \times 100.$$

The theoretical response for each treatment was plotted against post-treatment foliar K and the relationship was analysed using linear and non-linear regression techniques.

The second experiment involved reporting growth rates of unfertilised stands aged 8-9 years with varying foliar K concentrations (Raupach and Hall, 1974). Current annual increment for these stands increased from 17.5 m^3/ha/y to 31.5 m^3/ha/y as foliar K concentrations in the 2nd whorl increased from 2.8 g/kg to 9 g/kg (Figure 19).

Similar to the earlier experiment, it was assumed that:

- the main limitation to growth was K deficiency;
- the stand with the highest growth rate (and highest foliar K concentration) represented the potential growth of stands with adequate K;
- the relative difference between growth of each of the other stands and the stand with the maximum foliar K represented the potential response to K fertiliser for stands with that foliar K concentration.

Theoretical responses were calculated in the same manner as for the earlier study by Raupach and Hall (1963) and were plotted against foliar K concentrations. A relationship was modelled using a non-linear regression.

The two relationships from the separate studies were compared to test for significant differences. From these, a third relationship including data from both was developed.

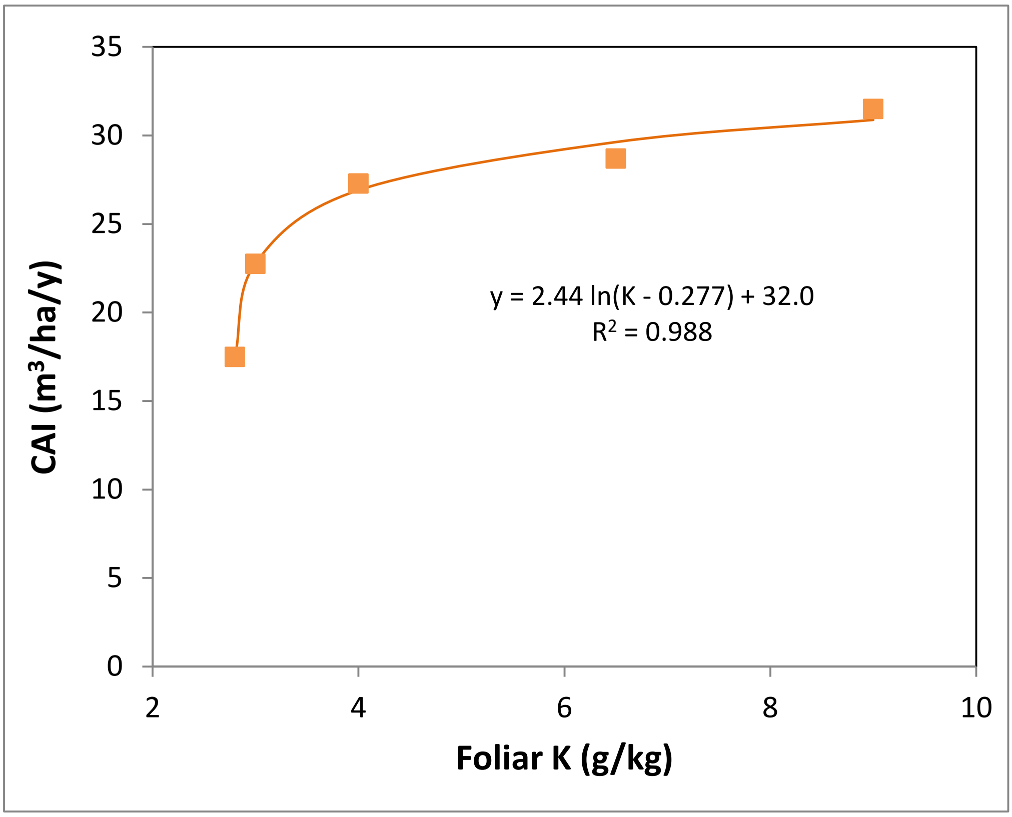


Figure 5: Relationship between foliar K concentrations and current annual increment of trees from on data for 8-9 year old trees from Raupach and Hall (1971).

Relationships developed

Predicting response to N fertiliser using foliar N

Victorian data

The relationship between response to N fertiliser and foliar N based on Victorian data explained 69% of variation in response when all data points were included and 79% of variation in response when stands deficient in P, S or Cu were excluded (Figure 1b).

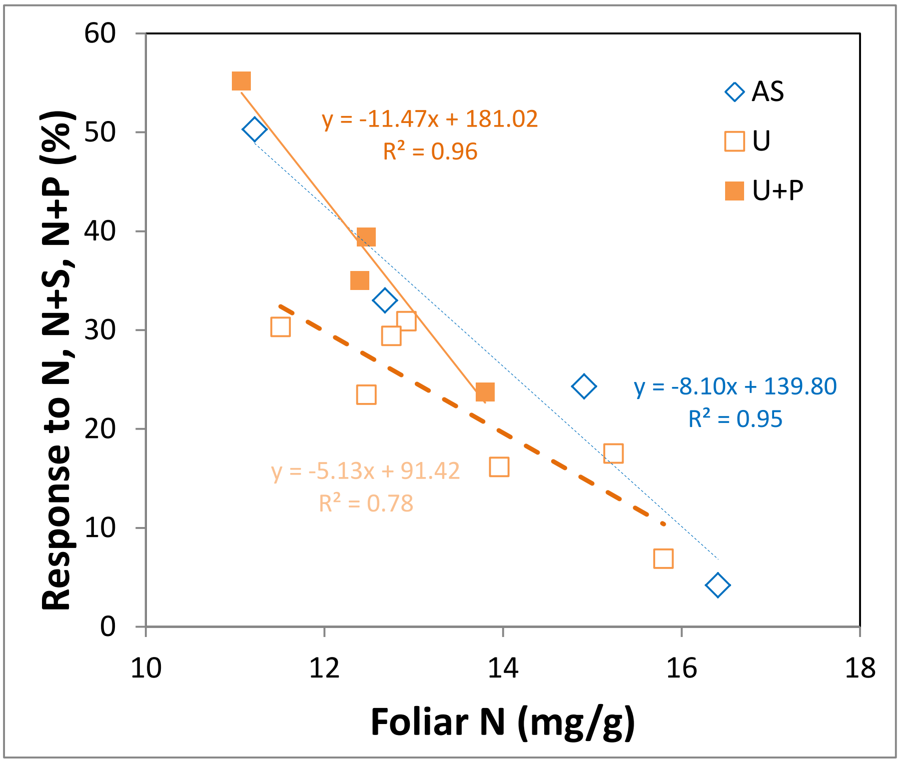
These relationships included treatments fertilised with N as ammonium sulphate, urea alone and urea + P as triple super phosphate. When separate relationships for each N form were tested, the slope of that where N was applied as urea alone was significantly less than those where N was applied as urea in combination with P ($P = 0.037$) and was marginally less than that where N was applied as ammonium sulphate ($P = 0.083$, Figure 6a). In contrast, there was no difference between the slope of the relationships where N was applied as urea + P or as ammonium sulphate. This indicates that the N response was less for urea compared with urea + P or ammonium sulphate for stands with equivalent foliar N concentration. This result is consistent with results from the Green Triangle indicating that substantial N losses can arise from N applied as urea alone but that these are decreased by the addition of P as triple super phosphate (May *et al.*2009a).

For the Victorian data, a new relationship was developed based on plots where N was applied as ammonium sulphate or, urea plus P and where other nutrients were non-limiting (Figure 6b). This relationship was assumed to represent the optimum response to N fertiliser for stands of varying foliar N concentrations. The difference between the predicted responses to N based on this relationship compared with another, based on plots where urea alone was applied, was assumed to represent the reduction in response due to N volatilisation loss from urea. For foliar N values ranging from 11 mg/g to 16.5 mg/g (corresponding to the range in the dataset) the average predicted response to N applied as ammonium sulphate or urea plus triple superphosphate was 28% compared with 21% for urea alone. The effect of N-form on response is examined in more detail in the section *Effect of N form.*

Green Triangle Data

A relationship between foliar N and response to N applied as urea, ammonium nitrate, ammonium sulphate or Agrotain urea (to reduce potential N volatilisation loss) with or without P explained 33% of variation in responses (Figure 7a). When sites deficient in P or K were removed, the R^2 value increased to 60% and the steepness of the slope of the line of best fit increased from -3.71 to -6.64 (Figure 7b). This result was consistent with that for the Victorian sites where removal of treatments deficient in other nutrients improved the fit and increased the predicted response to N fertiliser (Figure 1).

a)



b)

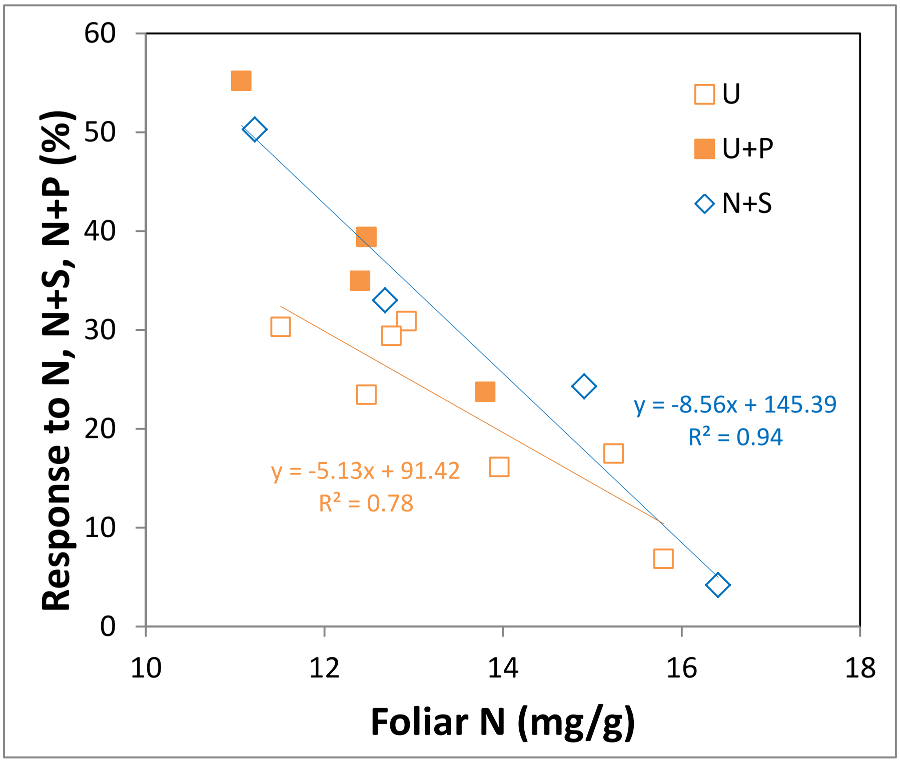
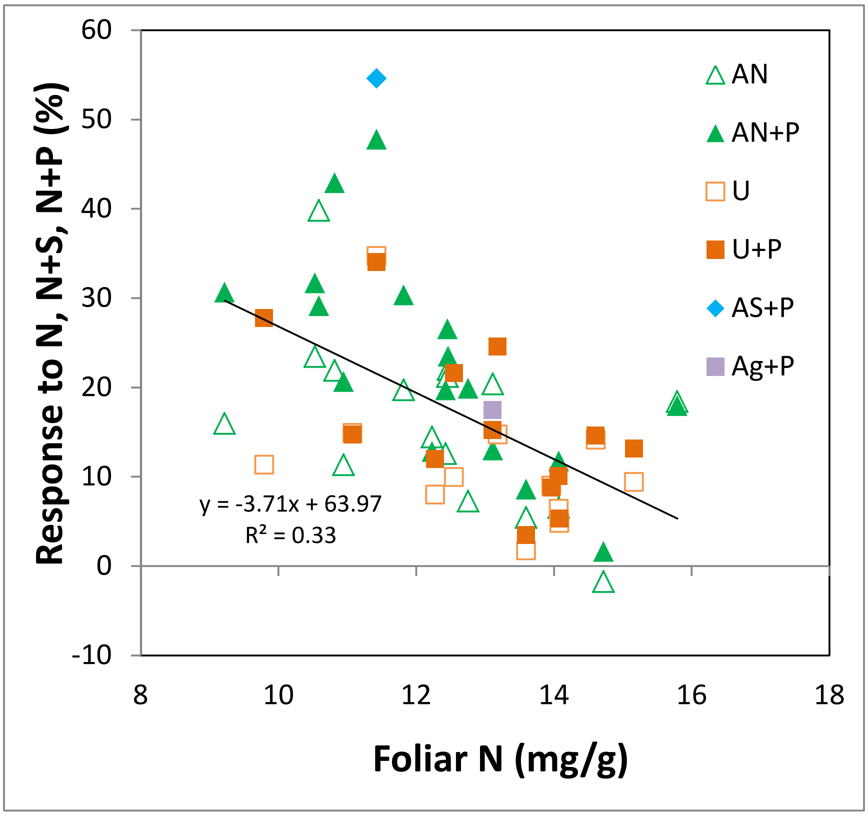


Figure 6: a) Relationships between foliar N and 4-yr volume responses to N showing the effect of N form with N applied as urea alone or as urea plus triple super phosphate (U+P) and ammonium sulphate (N+S) for treatments where foliar concentrations of P, S and Cu nutrients were either marginal or adequate b) same relationships with data for ammonium sulphate and urea plus P pooled.

a)



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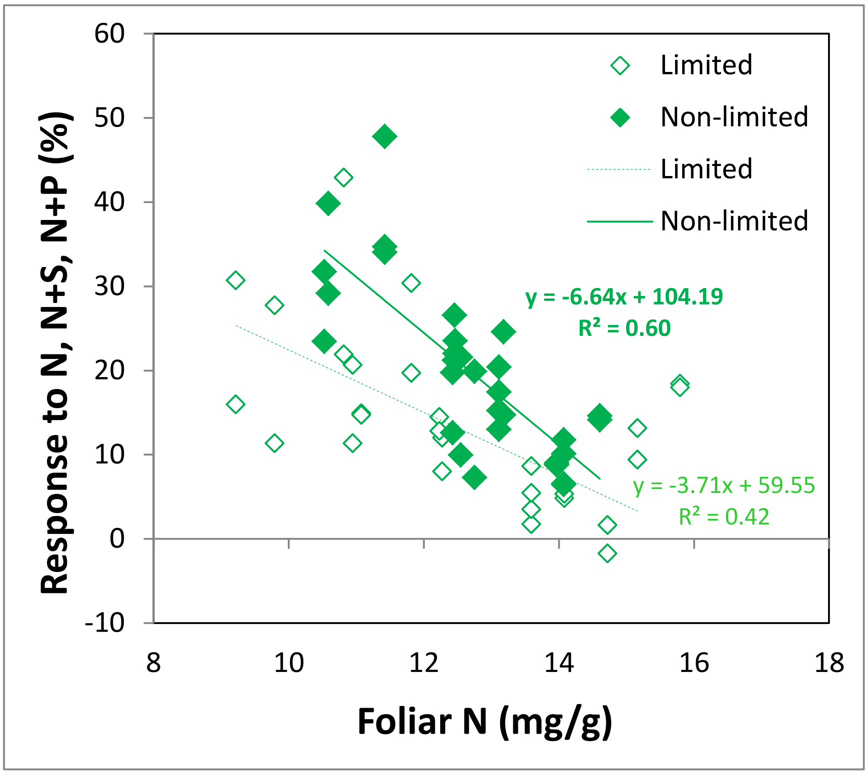

Figure 7: Relationships between foliar N and 4-yr volume responses to N applied as ammonium nitrate (AN), urea (U) ammonium sulphate (AS) or Agrotain urea (Ag), with or without P as triple super phosphate, from experiments located across the Green Triangle, showing (a) a relationship for pooled dataset and (b) those for sites deficient in P or K and sites with marginal to adequate P or K (data courtesy of CSIRO).

There were no significant differences between the slopes or intercepts for the lines of best fit for the different N forms with or without the addition of P (Figure 8). However, results for individual sites where responses to N applied as urea were compared with those to N applied as ammonium nitrate indicated that the average response to urea was 27% less than that to ammonium based fertiliser forms (May *et al.* 2009a) which is similar to the difference in responses for Victorian stands. The difference in responses to different N forms across stands in the Green Triangle and the approach used to model this in ProFert is discussed further in the section *Effect of N form.*

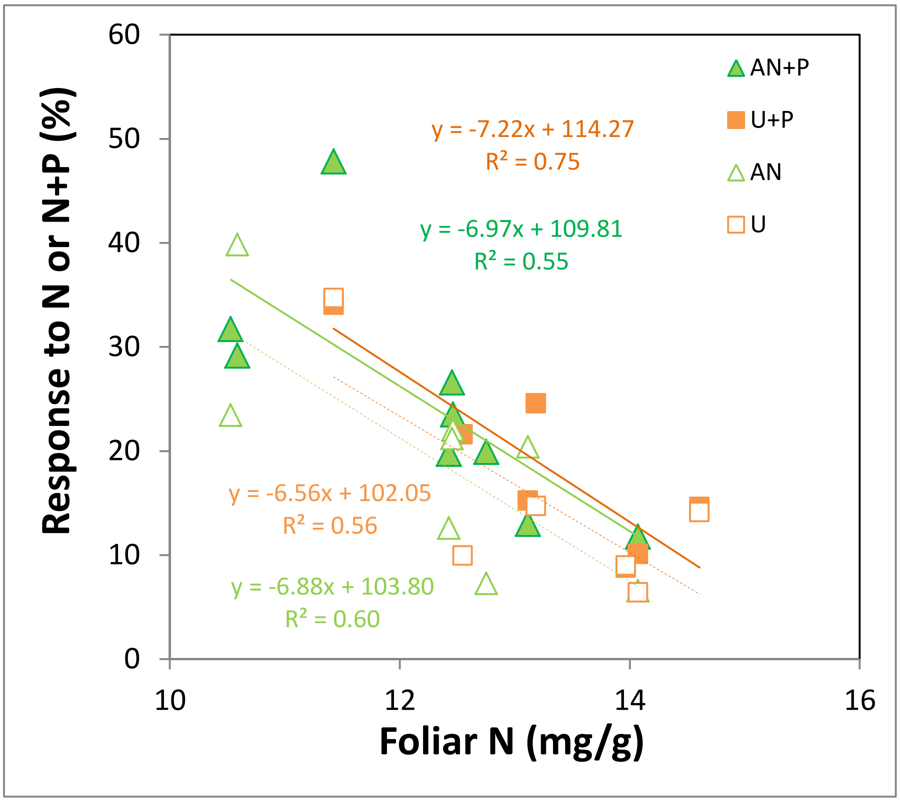

Figure 8: Relationships between foliar N and 4-yr volume responses to N showing the effect of applying N in different forms (ammonium nitrate: AN or urea: U) with or without P, from experiments located across the Green Triangle (data courtesy of CSIRO).

Tasmanian sites

After removing sites that were deficient in P, foliar N explained 87% of variation in response to N or N+P for the Tasmanian experiments (Figure 9, Bruce, 2001). There was no data regarding deficiencies in nutrients other than P. Therefore, less confidence can be placed on this relationship compared with those from stands in the Green Triangle and Victoria.

Urea was the only form of N applied across the Tasmanian experiments so no conclusions could be made regarding the potential reduction in response resulting from using urea compared with other N forms. However, the average response to urea alone was 70% of that to urea plus P for sites where P was marginal to adequate indicating that the volatilisation losses may have reduced the response to urea by a proportion similar to that in other regions.

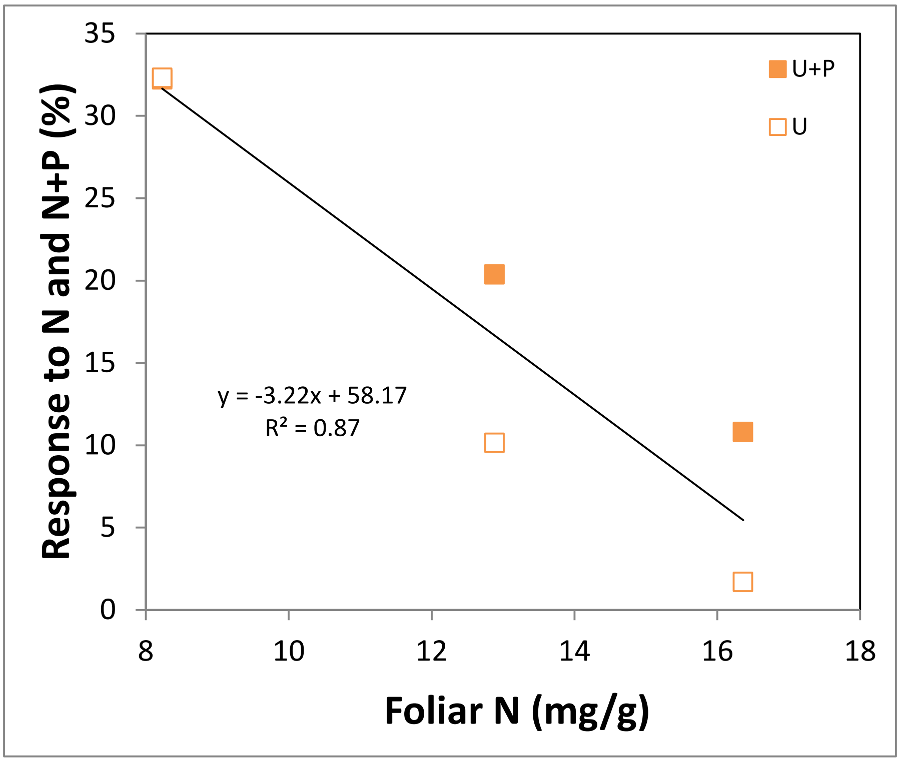

Figure 9: Relationship between foliar N and 4-yr volume responses to N or N+P for Tasmanian sites after removal of stands where foliar P was deficient.

Combined dataset

To test whether there were significant differences between the relationships between response to N and foliar N for the three regions, the datasets were combined (Figure 10). Treatments where nutrients other than N were deficient were excluded and multiple regression analysis was used to determine whether slopes and intercepts were significantly different.

Although the various relationships followed the same trend of decreasing response to N fertiliser with increasing foliar N concentration, there were significant differences between the regions. The intercepts of the relationships for both the Green Triangle and Tasmania and slope of the relationship for Tasmania were significantly less ($P < 0.05$) than those for the Victorian treatments where N was applied as ammonium sulphate or as urea in combination with P, but not where urea alone was applied. There was no significant difference between the slopes or intercepts of the relationships for Tasmania and those for the Green Triangle. As a result, for the range in foliar N concentrations present across the experiments (11-14.5 mg/kg), the predicted responses to N fertiliser for Tasmanian and Green Triangle sites were 30-70% less than that for Victoria where N was applied as ammonium sulphate or urea plus P (average 44%, Figure 11).

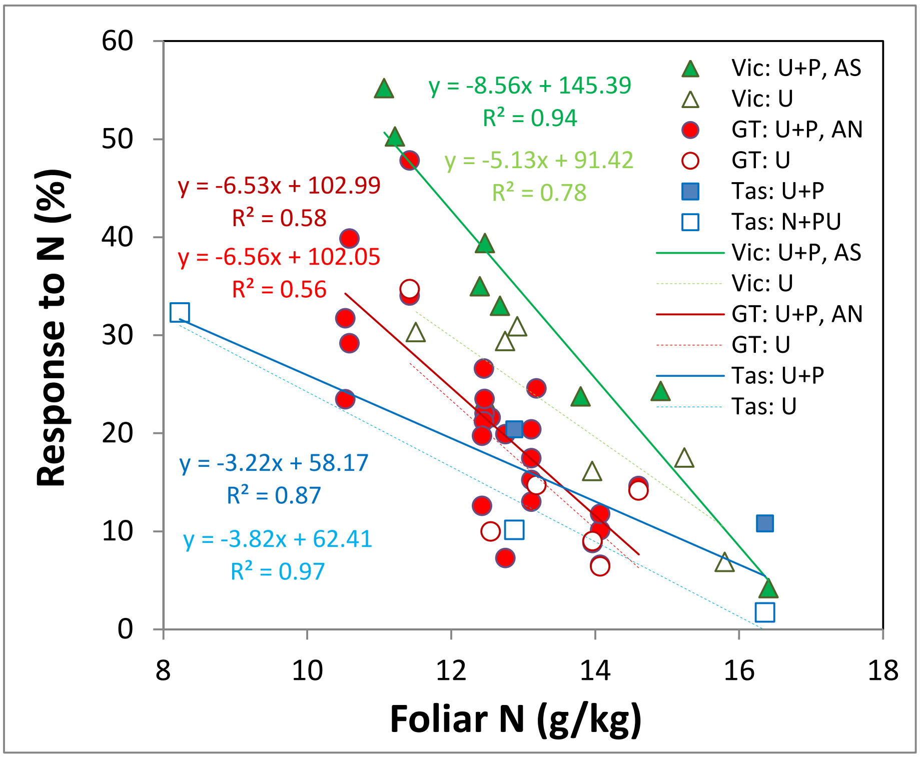

Figure 10: Relationships between foliar N and 4-yr volume responses to N as urea alone (U) and urea plus P (U+P) or other forms of N (AN, AS) for sites in Victoria (Vic), Green Triangle (GT) and Tasmania (Tas). Lines show lines of best fit for points of the corresponding colour.

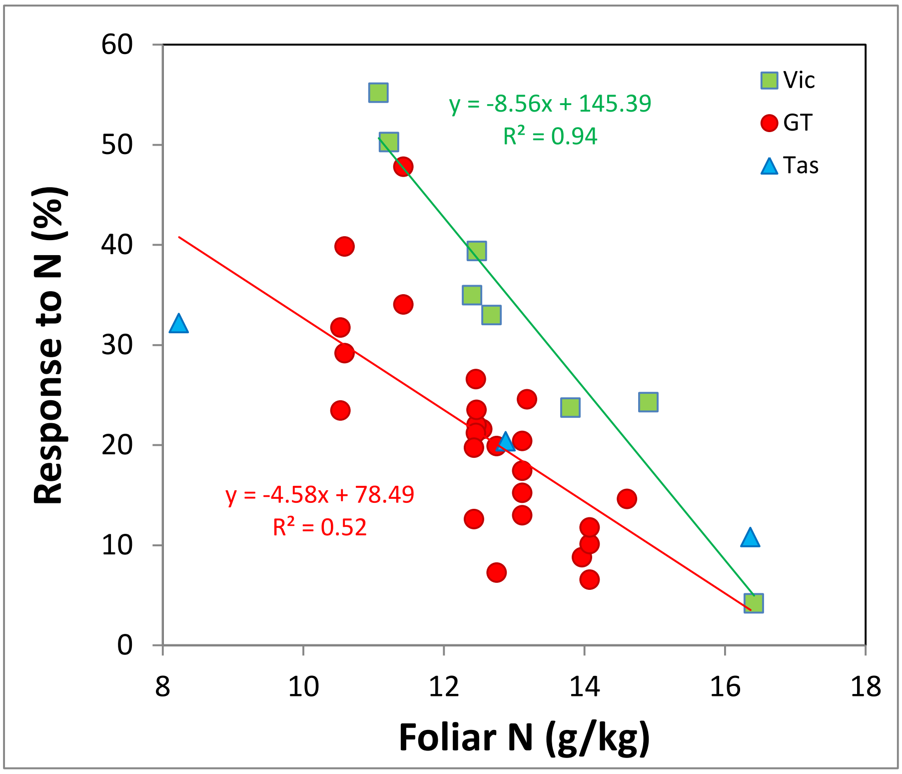

Figure 11: Relationships between foliar N and 4-yr volume responses to N as ammonium nitrate, ammonium nitrate or urea plus P for sites in Victoria (Vic) and Green Triangle/Tasmania (GT). Note: treatments where urea alone was applied are excluded.

One possible reason for the smaller responses to N in the Green Triangle and Tasmania compared with Victoria is the lower rate of N application (200 kg N/ha for sites in the Green Triangle and Tasmania compared with 300 kg N/ha for the Victorian sites). However, the magnitude of the difference for urea+P and ammonium based forms (40%) was larger than the relative difference in the rate of application (33%). Furthermore, where N was applied at a rate of 400 kg N/ha on three sites in the Green Triangle, there was no evidence of a larger response compared with 200 kg N/ha. Therefore, it is likely that other factors (e.g. soil type, climate or other nutrients that were not accounted for) contributed to the difference. These factors are discuessed in the section *Accounting for differences between regions*.

Because of the differences between the relationship based on the Victorian sites fertilised with ammonium sulphate and urea plus P compared with those based on sites fertilised with ammonium nitrate and urea plus P from the Green Triangle, it was decided to use two separate relationships for predicted response to N fertiliser in the ProFert model (Figure 11). The default setting for the model was to use the relationship based on the Victorian sites for Victorian plantations managed by HVP, while the relationship based on the Green Triangle sites was used for other plantations.

The resulting relationships for Victoria ($R_{N\text{-}Vic}$, %) and other regions ($R_{N\text{-}GT}$, %) from foliar N (mg/g) were:

$$R_{N\text{-}Vic} = -8.56 * F_N {}^{+} 145.4 \quad r^2 = 0.939, SE\ (\ln Response)^b = 4.30$$

$$R_{N\text{-}GT} = -4.58 * F_N {}^{+} 78.5 \quad r^2 = 0.521, SE\ (\ln Response)^c = 7.04$$

Predicting response to N using other stand parameters

The Green Triangle study investigated a range of approaches for predicting response to N fertiliser (May *et al.* 2009a). These approaches included leaf area index (LAI) either alone or in combination with foliar sampling, total soil nitrogen and various indices of soil N availability, and forest floor (needles and other fine debris on the soil surface) nitrogen. This work indicated that indices other than foliar N could be used to predict response to N and N+P fertiliser with varying degrees of accuracy.

LAI explained 42% of variation in response to N+P fertiliser (Figure 12). However, there was a significant difference between the slope of the relationship for sites fertilised in 1996 (after 2nd thinning) and those fertilised in 2002 (after 3rd thinning). This difference indicated that the number of stems per hectare may have influenced the relationship with younger, more highly stocked stands giving a larger response to N fertiliser for a given LAI compared with older, stands with lower stocking.

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[b] The standard error presented is that for the transformed linear form of the relationship (i.e. ln(Rp) = a ln(Fp) + b) on which the regression is based.

[c] The standard error presented is that for the transformed linear form of the relationship (i.e. ln(Rp) = a ln(Fp) + b) on which the regression is based.

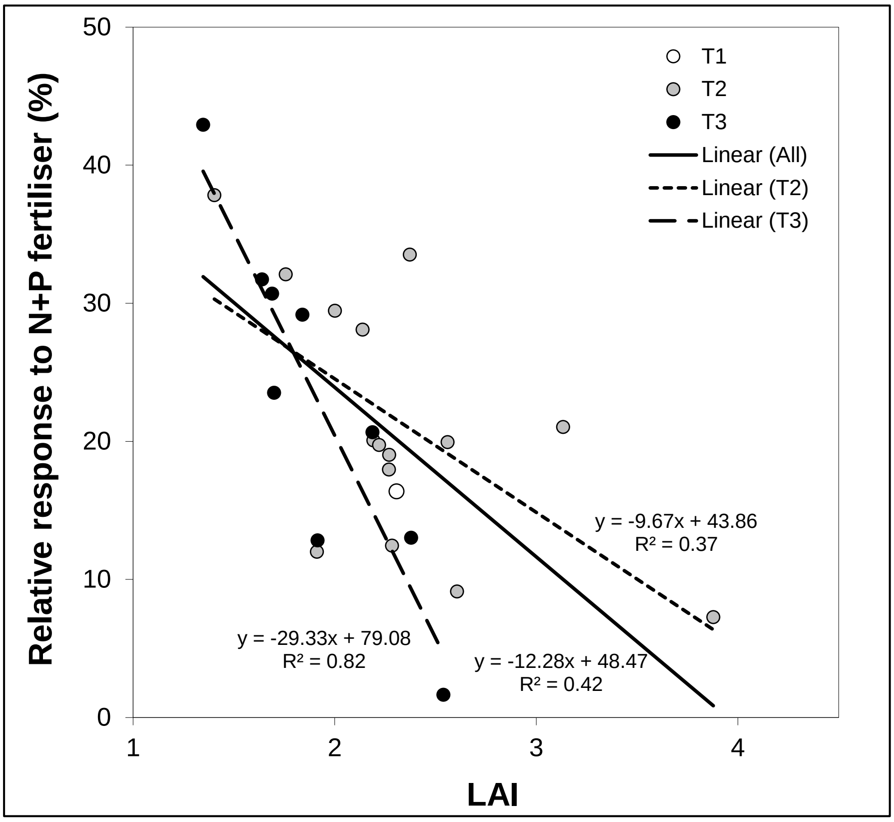

Figure 12: Relationships between response to N+P fertiliser and LAI for Green Triangle stands fertilised after 1st (T1), 2nd (T2) and 3rd thinning (T3) showing separate relationships for 2nd and 3rd thinning as well as the pooled relationship (SE = 7.9, P < 0.001).

Multiplying LAI by foliar N concentration to provide an index of canopy N content explained more of the variation in response to N+P fertiliser than foliar N or LAI alone (Figure 13). This relationship explained 62% of variation in response. However, as with LAI, there appeared to be a difference in the relationship for stands fertilised after 2nd thinning compared with those fertilised after 3rd thinning.

Total soil N explained 35% of variation in response to N+P fertiliser across sites in the Green Triangle (Figure 14). Total soil N also explained 42% of response to N alone. However, this relationship was strongly influenced by three sites at the upper and lower limits of the range in soil N concentration. Other indices of soil availability tested include anaerobic N and aerobic mineralisable N. However, these indices proved to be highly variable over time and did not provide robust relationships that could be used to predict N response with any reliability.

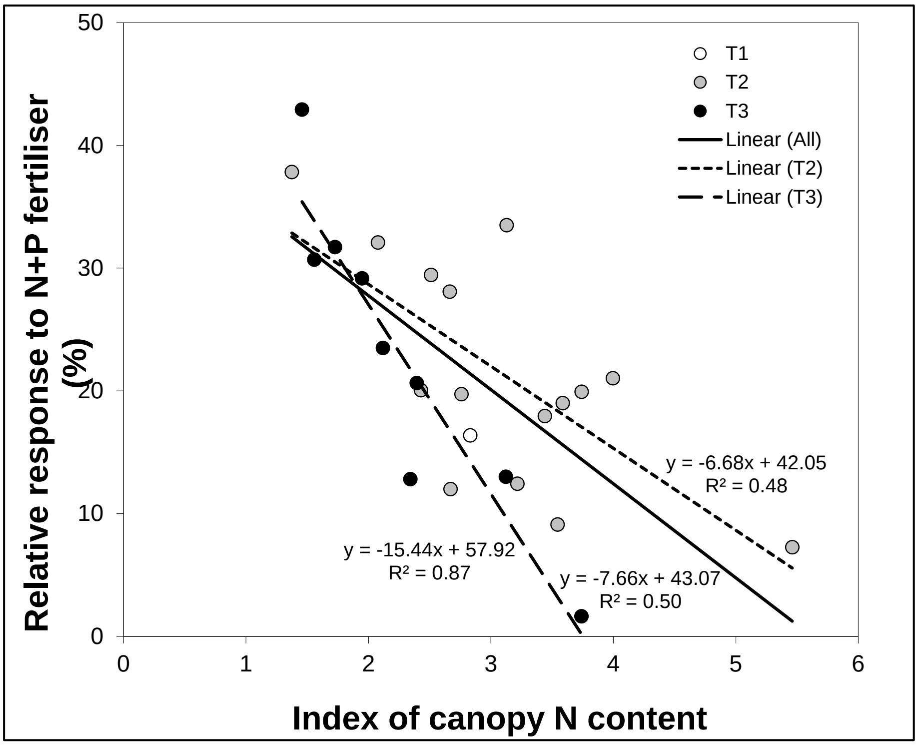

Figure 13: Relationships between response to N+P fertiliser and index of canopy N content (LAI x Foliar N) for Green Triangle stands fertilised after 1st (T1), 2nd (T2) and 3rd thinning (T3) showing separate relationships for 2nd and 3rd thinning as well as the pooled relationship (SE = 7.3, P < 0.001).

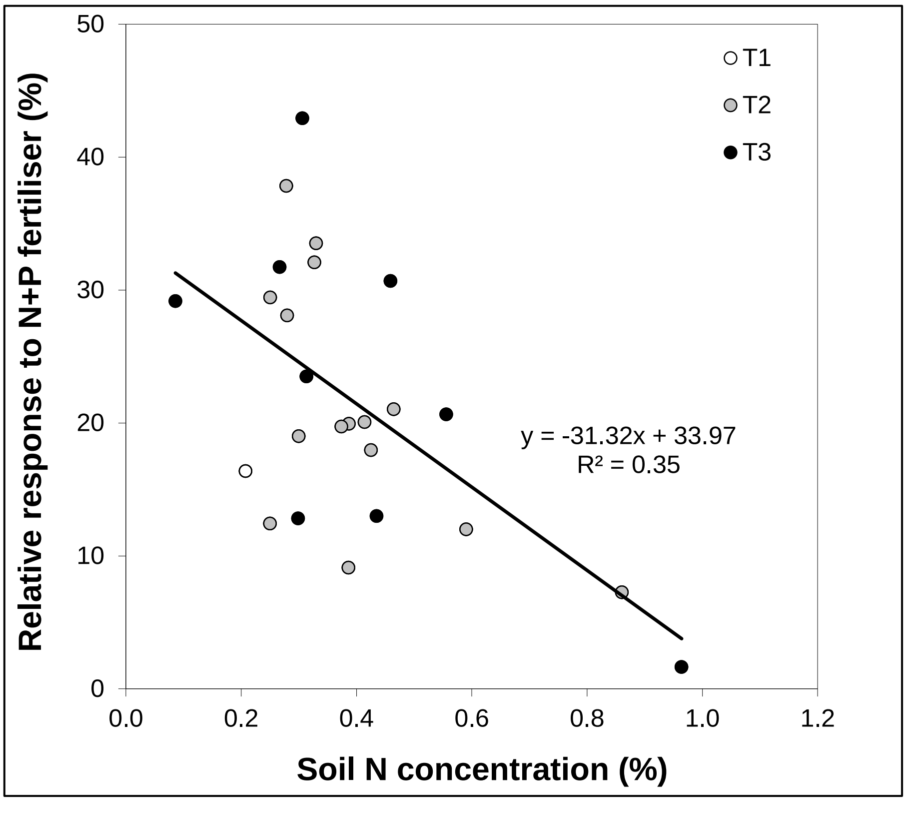

Figure 14: Relationship between response to N+P fertiliser and total soil N concentration for Green Triangle stands fertilised after 1st (T1), 2nd (T2) and 3rd thinning (T3). P < 0.001, S.E. = 7.1.

Predicting response to P fertiliser

Victorian data

There was a very strong relationship between foliar P and response to P fertiliser across experiments established in 1st rotation plantations within HVP's plantations in Victoria (Hopmans Pers. Comm., Figure 15). This relationship explained 85% of variation in response to P fertiliser applied 5-12 years earlier as superphosphate (80-120 kg P/ha). Responses across second rotation stands fertilised with super phosphate and 1st rotation stands fertilised with di-ammonium phosphate (DAP) appeared to also fit this relationship. No information was available regarding concentrations of nutrients other than N, but given the strength of the relationship, it appears that these did not significantly limit the response.

The original relationship between relative response to P (R_P, %and foliar P concentration (F_P, mg/g) was a simple power function:

$$R_P = 20.5 * F_P^{-6.84} \quad r^2 = 0.85, SE\ (\ln Response)^d = 0.55$$

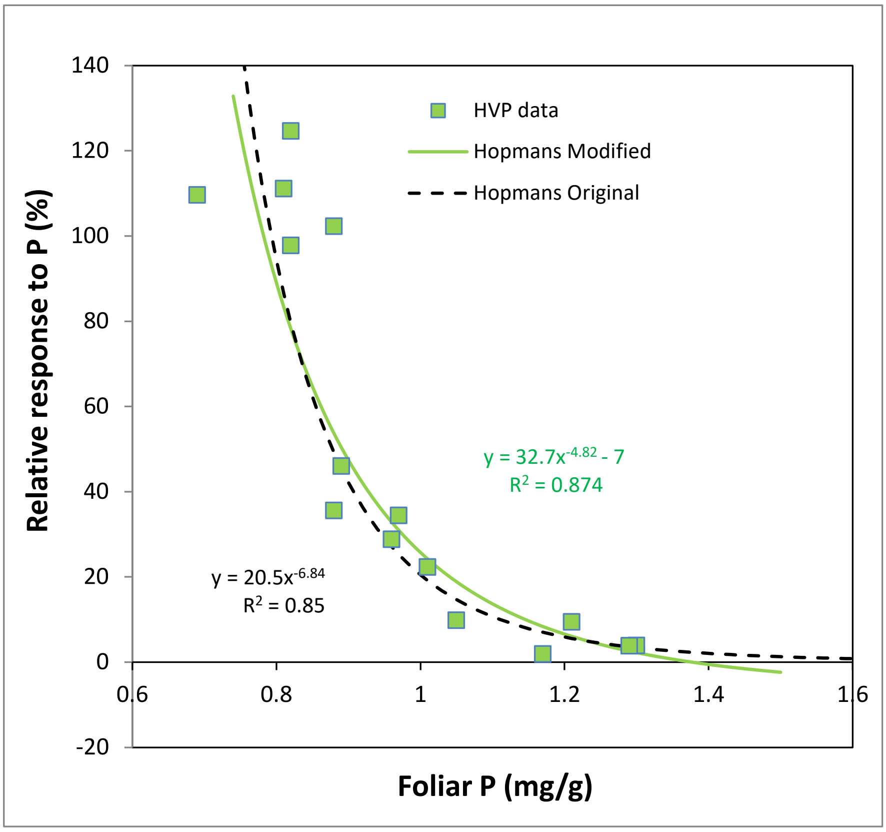

Figure 15: Relationships between response to P fertiliser and foliar P concentration for Victorian sites. Dotted black line shows the original relationship developed by Hopmans Pers. Comm. Solid green line shows modified relationship used in ProFert.

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[d] The standard error is that for the transformed linear form of the relationship (i.e. ln(Rp) = a ln(Fp) + b) on which the regression is based.

However, the above relationship results in a problem when predicting responses to P fertiliser where foliar P concentrations are non-limiting (i.e. > 1.4 mg/g, Reuters and Robinson 1997). In these situations, it predicts a positive response to P fertiliser which, even though small (<= 2%) may still result in the response to P being overestimated.

In order to rectify this situation, a new relationship was developed based on the HVP data which incorporated a constant which allowed the curve to intersect the x-axis (Figure 15). The modified relationship for predicting response to P fertiliser across Victorian sites ($R_{P\text{-}Vic}$, %) was:

$$R_{P\text{-}Vic} = 32.7 * F_P^{-4.82} - 7.00 \quad r^2 = 0.874, SE\ (\ln Response)^e = 0.356$$

The amount of variation explained by the modified relationship (87%) was greater than that for the original (84%). More importantly, the standard error for the modified relationship (0.36) was 35% less than that for the original (0.55).

Green Triangle data

There was a significant relationship between foliar P and response to P fertiliser for the Green Triangle experiments ($r^2 = 0.68$, May *et al.* 2009a, Figure 16). However, the slope of this relationship was significantly less than that for the HVP relationship ($P = 0.006$). As a result, the increase in growth for the most P responsive site (13%) was less than a quarter of that predicted by the HVP relationship (55%). The relationship for predicting response to P for the Green Triangle sites ($R_{P\text{-}GT}$, %) was:

$$R_{P\text{-}GT} = 17.8 * F_P^{-1.82} - 10.00 \qquad r^2 = 0.666, SE\ (\ln Response)^f = 0.302$$

Tasmanian data

There was no relationship between foliar P concentrations and response to P fertiliser across the Tasmanian sites (Bruce, 2001, Figure 17). The lack of any relationship may have been due to nutrients other than P limiting the response. No information was available for the concentrations of nutrients other than N or P for the sites even though at least one site was considered to be critically deficient in K. However, the magnitude of the average response to P (8%) was similar to that for the more responsive stands in the Green Triangle (Figure 18).

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[e] As above

[f] As above

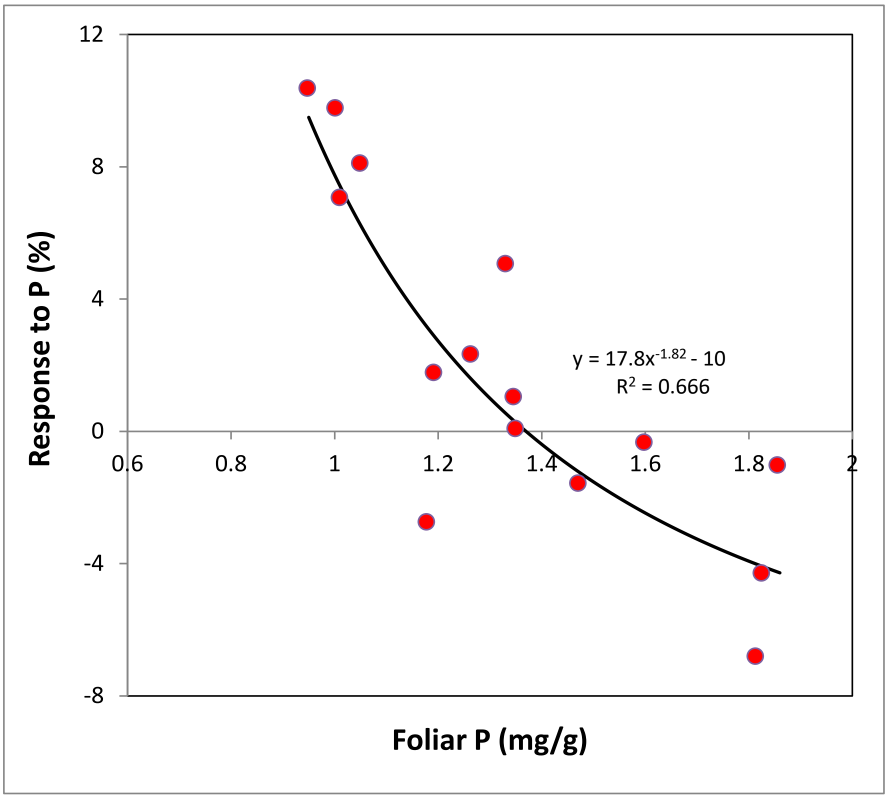

Figure 16: Relationship between 4 year response to P fertiliser and foliar P concentration for Green Triangle stands fertilised after 1st and 2nd. $P < 0.001$, S.E. = 0.30.

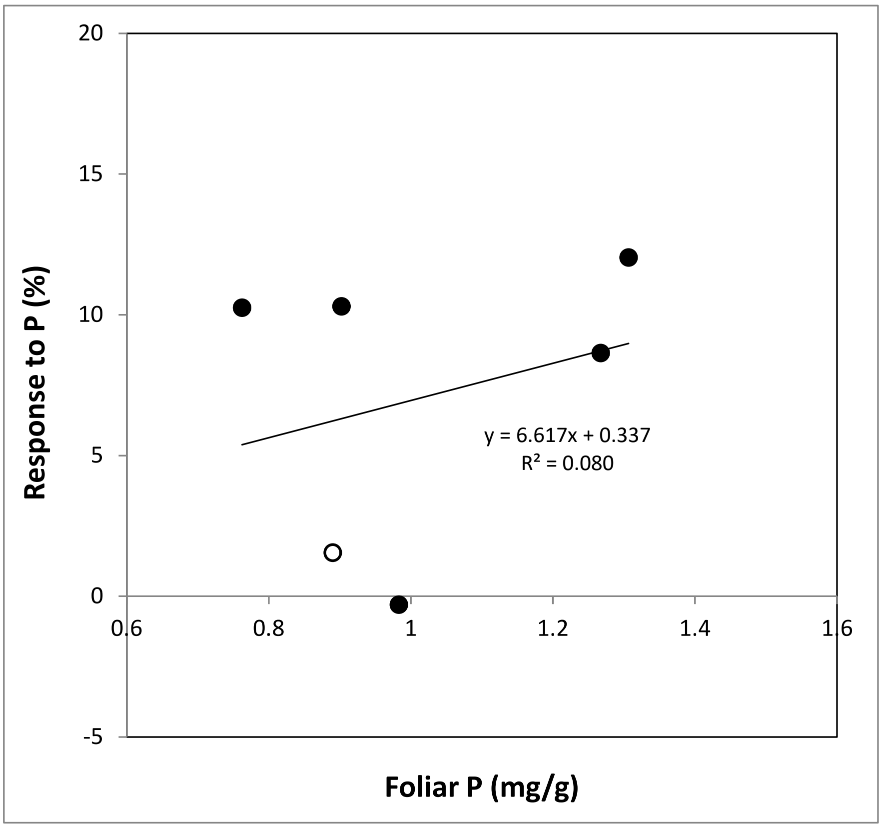

Figure 17: Relationship between 4 year response to P fertiliser and foliar P concentration for Tasmanian stands. P = 0.585, S.E. = 5.5. White point indicates site with K deficiency.

Combined data

As with predicting response to N, it was decided to use two separate relationships to predict P response. These relationships included one, based on the Victorian dataset, for predicting response across HVP plantations in Victoria and the other, based on the Green Triangle dataset, used to predict response across other plantations (Figure 18). Possible reasons for the differences in response for the different regions are discussed in the section *Accounting for differences between regions.*

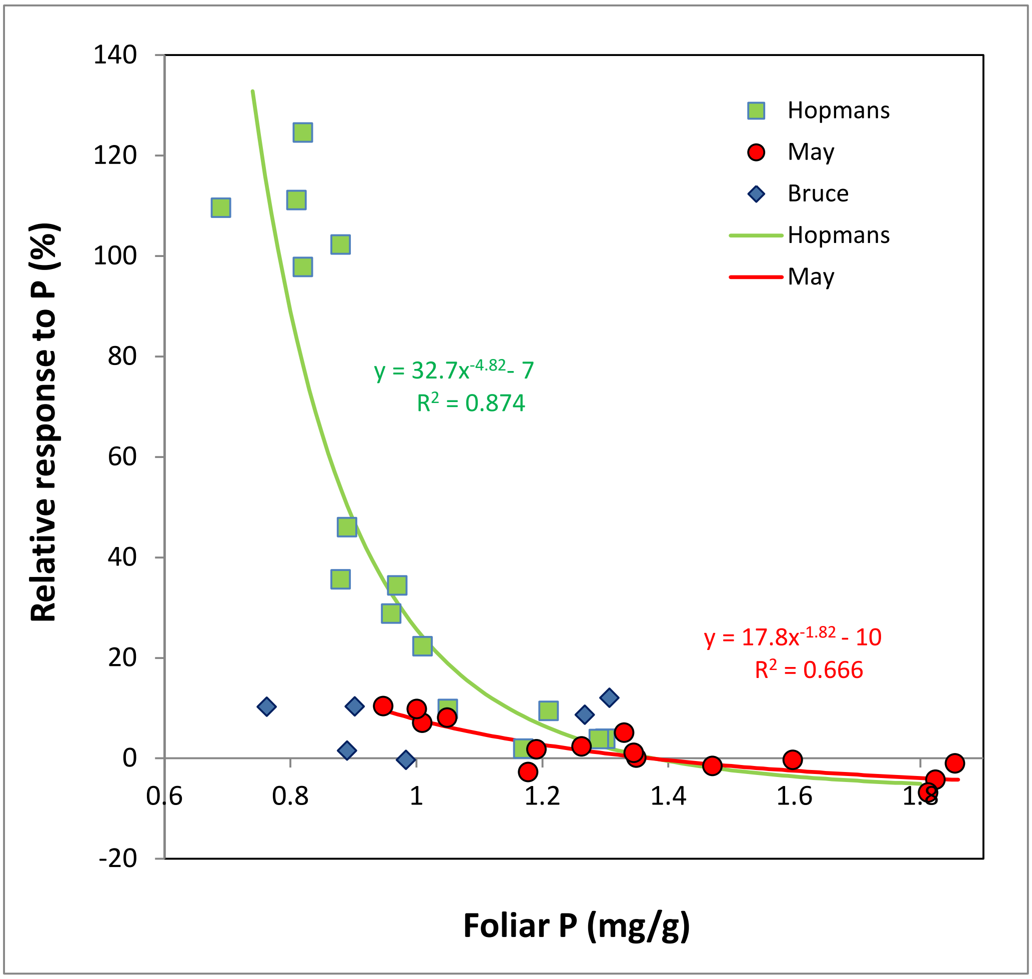

Figure 18: Relationships between response to P fertiliser and foliar P concentration for Victoria, Green Triangle and Tasmania.

Predicting response to K fertiliser

A theoretical response to K fertiliser based on data from Raupach and Hall (1963) showing increasing foliar K and growth response to different rates of K fertiliser was plotted against post-treatment foliar K (Figure 19). This relationship indicated that response to K fertiliser was related to foliar K in a non-linear function which passed through zero at a foliar K concentration of around 13 g/kg or double the suggested adequate concentration by Reuters and Robinson (1997).

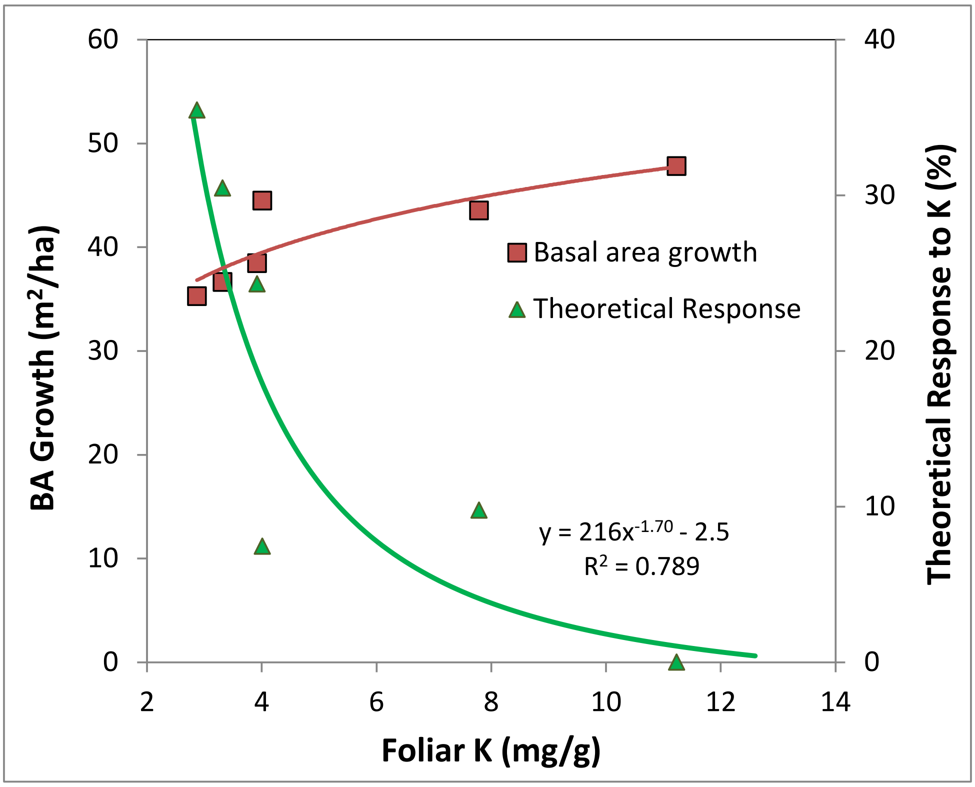

Figure 19: Relationships between foliar K concentrations and current annual increment of trees (brown squares) and theoretical response to K fertiliser (green triangles) based on data for 6 year old trees fertilised with different amounts of K, from Hall and Raupach (1963).

Using data from by Raupach and Hall (1974), a second relationship between theoretical response to K and foliar K (based on different growth rates for stands with differing foliar K concentration) was developed (Figure 20). This relationship was of a similar form to that derived from the earlier study by Hall and Raupach (1963) being non-linear and rising steeply for foliar K concentrations < 4 mg/g and passing through zero at a concentration of 9 mg/g.

The two relationships derived from data from the two separate studies were very similar with no significant difference in their slopes ($P > 0.05$). Therefore, a third relationship for predicting relative response to K (R_K, %) from foliar K (F_K, mg/g) was developed from the combined datasets (Figure 21) :

$$R_K = 390 * F_K^{-2.06} - 2.4 \qquad r^2 = 0.832, SE \ln(Response)^g = 0.483$$

This relationship explained 83% of variation in potential response with foliar K alone. The fact that this relationship is based on independent datasets from separate studies using different approaches to estimate potential response to K, demonstrates that it is likely to be robust. In the absence of separate fertiliser experiments which measure response to K across different sites, this new relationship is considered the best available means to predict response to K fertiliser across different sites.

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[g] The standard error presented is that for the transformed linear form of the relationship (i.e. ln(Rp) = a ln(Fp) + b) on which the regression is based.

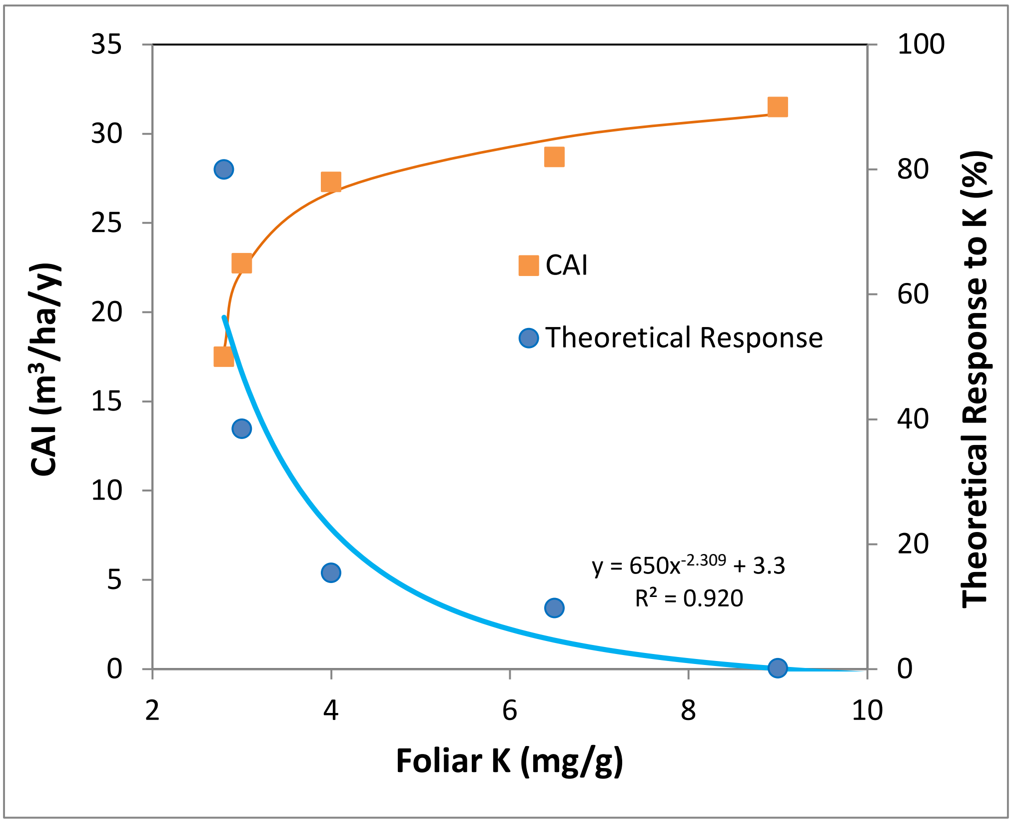


Figure 20: Relationships between foliar K concentrations and current annual increment of trees (brown squares) and theoretical response to K fertiliser (blue circles) based on data for 8-9 year old trees from Raupach and Hall (1971).

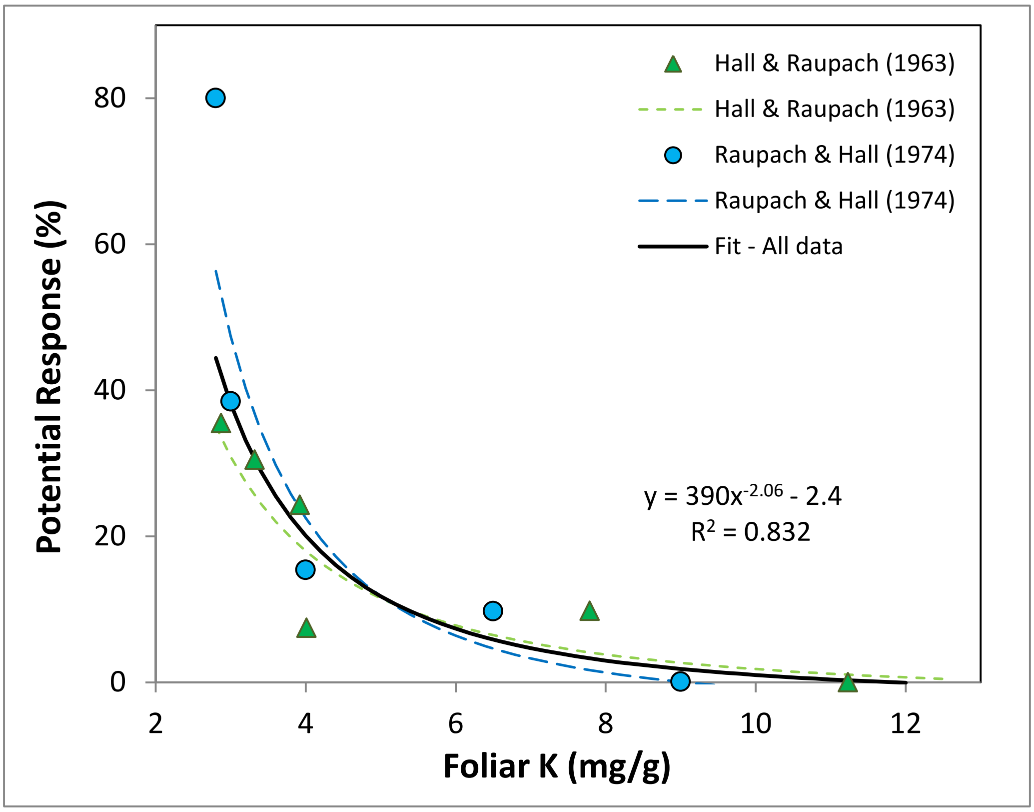


Figure 21: Relationship between foliar K concentrations and theoretical response to K fertiliser (blue circles) derived from data from Hall and Raupach (1963) and Raupach and Hall (1974).

Accounting for differences between regions

Predicted responses to N and P fertiliser for the Green Triangle and Tasmania were less than those for Victorian stands. Across the range of foliar N concentrations included in the studies (10.5-16.5 mg/kg), the average predicted response to N was 40% less for the relationship based on the Green Triangle and Tasmanian stands compared with that from Victoria (Figure 11). Similarly, across the range of foliar P concentrations included (0.95-1.33 mg/kg) the average predicted response to P was 67% less for the Green Triangle compared with Victoria. These difference may have been a result of a number of factors including differences in rate of fertiliser application, soil type, nutrients other than N and P, rainfall or the time period over which stands were measured.

As mentioned already, a key difference between the experiments in the Green Triangle compared with those in Victoria was the difference in rates of N fertiliser applied (200 kg N/ha for the former and 300 kg N/ha for the latter). Data from three experiments in the Green Triangle indicates that, there was little increase in response for N rates above 200 kg N/ha (May *et al.*, 2009a). However, this may because of the limited capacity of the sandy soils in the region to retain N or P fertiliser. Mineral P was found to be leached to a depth of 1 m within 6 months of application at a site in the Green Triangle with sandy soil, indicating that a large proportion of P could be rapidly leached below the region of maximum rooting density (0-30 cm, May unpublished data). In contrast, on the finer textured soils on some Victorian sites, response to N has been shown increase with N rates up to at least 300 kg N/ha (Hopmans Pers. Comm.). Therefore, it is suggested that at least part of the reason for the larger predicted response to N for Victorian plantations was due to the combined effect the higher rate of N applied and the difference in soil texture.

It is also possible that secondary nutrient deficiencies may have limited the response to fertiliser across some stands. In the Green Triangle, most stands were limited by N and responded to N fertiliser, indicating that response to P alone may have been limited by N availability (see section *Accounting for effects of secondary nutrient limitations*). This especially appeared to be the case for a number of stands with low foliar P concentrations which also had critically low foliar N. Since the P response curve was based on treatments fertiliser with triple super phosphate only, the potential response to P in the absence of other nutrient limitations was likely underestimated for these sites.

Nutrients other than N or P may have also limited response. In the Green Triangle, concentrations of a wide range of additional nutrients including K, Mg, Mn, Fe, S and B were measured across most sites. Of these nutrients, K was found to be less than adequate (< 6.5 mg/kg, Reuter and Robinson, 1998) at over half of the sites and Fe, Mg and Mn were marginal at a number of sites. As mentioned, no data was available for nutrients other than N or P across the Tasmanian stands, but observations indicated that at least one suffered from acute K deficiency during the experiment. These stands were located in an area of low rainfall that is subject to a wide range of nutrient deficiencies including K, B and N which may have limited the capacity of the trees to respond to P fertiliser (Hopmans Pers. Comm.).

Differences in rainfall may have affected the responses to some treatments. The period from 1996-2002 when 10 of the experiments in the Green Triangle and all those in Tasmania were measured included several years with below average rainfall which may have reduced the response to N. In particular, during 1999-2000, rainfall across the Tasmanian stands was 30% below average and coincided with reductions in both growth rates and fertiliser responses. Therefore, it is likely that responses may have been greater if rainfall had been closer to average throughout the experiments.

Responses across all but one of the Tasmanian sites were reported for 5 years compared with 4 years for the other regions. This longer time period for these Tasmanian sites is likely to have reduced the response slightly. Results from individual stands in both the Green Triangle and Tasmania indicated that annual response to N fertiliser peaks in the third year after application and decline sharply from then on (see section on *Variation in response over time*). Therefore, it is likely that the average response over 4 years would have been greater than that reported for 5 years for the Tasmanian stands.

Because of the apparent regional differences in the N response relationships, the predictions from the relationship should be treated with caution and require further validation. To account for the regional differences in N and P response in the ProFert model, two different relationships were included for each nutrient. The relationships based on the Victorian data were assumed to be applicable to Victorian stands managed by HVP only while the relationships based on data from the Green Triangle and Tasmania were assumed to be generally applicable to stands across these regions. However, the user could freely select which relationship to apply to their stands. This was considered to be the most conservative approach while allowing the user the flexibility to test the effect of using different response relationships for their stands.

Accounting for effects of secondary nutrient limitations

Responses to single nutrients

Interactions between different nutrients occur when one nutrient limits a plantation's capacity to respond to another. The most frequent interactions reported are between N and P fertiliser applied in experiments with factorial designs (e.g. May 2009a). However, other interactions are common. For example, results from fertiliser trials established in HVP's plantations indicated that responses to N applied either alone or together with P or S were reduced by 37-59% on sites deficient in P, Cu or Zn (Figure 22).

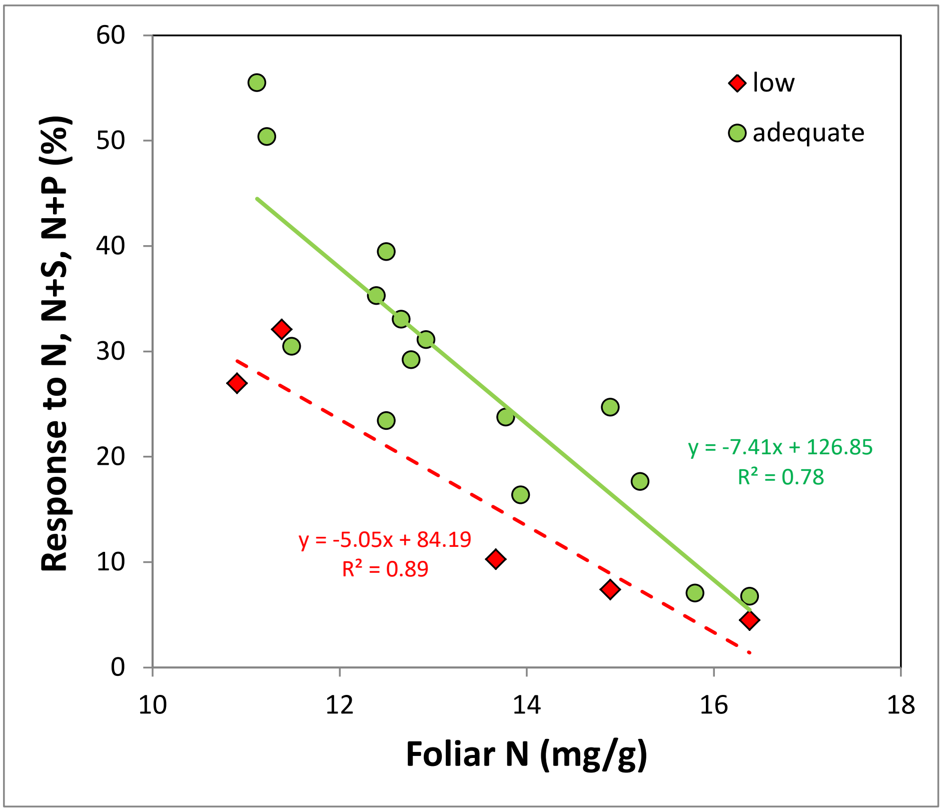


Figure 22: Relationship between 4 year response to N and foliar N concentrations across Victorian sites fertilised with N, N+P or N+S after 2nd thinning where concentrations of P, Zn and Cu were marginal to adequate (green squares) or deficient (red squares).

To account for the effects of multi-nutrient limitations on growth, surfaces were developed based on the relationships for predicting responses to N, P and K fertiliser. The model used to develop these surfaces was based on three assumptions:

a) where the concentration of the secondary nutrient (Y) is adequate, the response to the primary nutrient (X) is equal to that predicted by the original relationship provided that the rate of application is equal to that used in the original experiments (e.g. Figure 11 and Figure 18);

b) where the concentration of the secondary nutrient (Y) is less than the adequate level, the response to the primary nutrient is reduced linearly with the concentration of Y until it reaches 0%; and

c) the slope of the relationship for b) is such that, where the concentration of the secondary nutrient (Y) is equal to that classed as *Deficient*, the response to the primary nutrient (X) is reduced by 50%.

The resultant model is illustrated in Figure 23. Where more than one secondary nutrient is less than adequate, the response to the primary nutrient (X) was assumed to be limited by the most limiting nutrient. This model is obviously a simplification of the actual nutrient response mechanism. In particular, the effects of concentrations of some nutrients on responses are likely to be non-linear (as demonstrated with the response to P fertiliser). Furthermore, application of fertiliser can induce deficiencies in otherwise non-limiting nutrients as a result of increases in foliage mass (May *et al.*2009a). However, the model represents a major improvement compared with most existing models which are generally based on simple relationships between response to and availability of individual nutrients.

Four nutrients were selected for calculating fertiliser responses and nutrient limitations in ProFert:

- N
- P
- K
- S as indicated by foliar N/S ratio

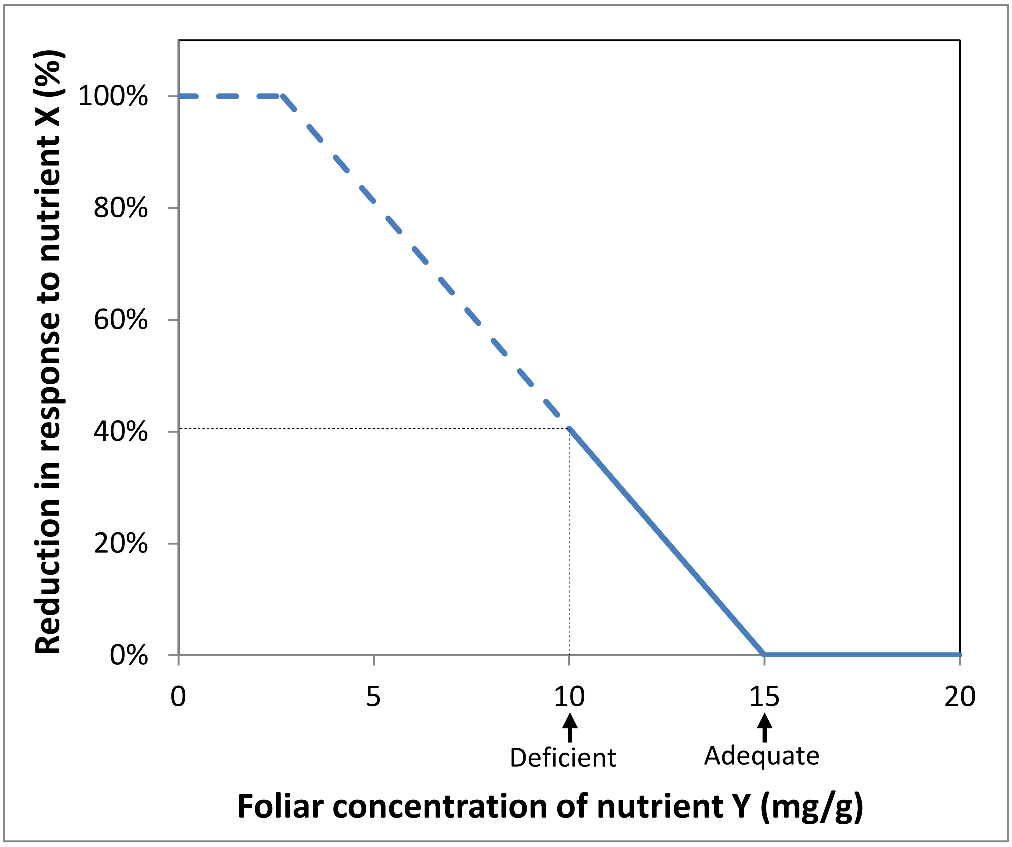


Figure 23: Illustration of the model used to account for limitations in response to N resulting from deficiency in a second nutrient (e.g. P).

This selection was based on results of foliar sampling across the Green Triangle (data provided by TPPL) and anecdotal accounts of the most common observed nutrient deficiencies across HVP and Norske Skog's plantations. It was noted by the companies that Cu and Zn are often deficient in young stands, but that this deficiency is readily detected and if corrected is rarely a problem in older stands being considered for fertiliser application.

Adequate and *Deficient* concentrations N, P and K in foliage were based on values from Reuters and Robinson (1997) for mature *Pinus radiata* (see Table 1). Deficiency of S was considered to be best indicated by the ratio of N/S in foliage. Ratios indicating *Adequate* and *Deficient* levels of S, derived from earlier work by Kelly and Lambert (1972), were provided by Peter Hopmans (Pers. Comm.).

Examples of response surfaces generated by the nutrient interaction models are illustrated in Figure 24. These surfaces all exhibit the same characteristics:

- as the concentration of the primary nutrient (i.e. the nutrient being applied as fertiliser) increases the response decreases;
- as the concentration of the secondary nutrient increases, the response to the primary nutrient increases;
- where the concentration of the primary nutrient is below the reported range from fertiliser experiments, the response is assumed to reach a maximum (the maximum measured response used in the relationship);
- where the concentration of the primary nutrient exceeds the reported range, the response is assumed to reach a minimum (the minimum measured response or zero, whichever is lower);

Responses to multiple nutrients

To estimate responses to combinations of nutrients being applied (e.g. N+P), it was assumed that:

a) provided the amount of a nutrient applied is at least equal to that used in the original fertiliser experiments, any potential limitation due to that nutrient, on responses to other nutrients, is removed.
b) the upper limit of the response to a combined nutrient application is equal to the maximum of the predicted responses to each nutrients applied; and
c) limitations resulting from nutrients other than those applied have the same effect on response to combined nutrient applications as for single nutrient applications.

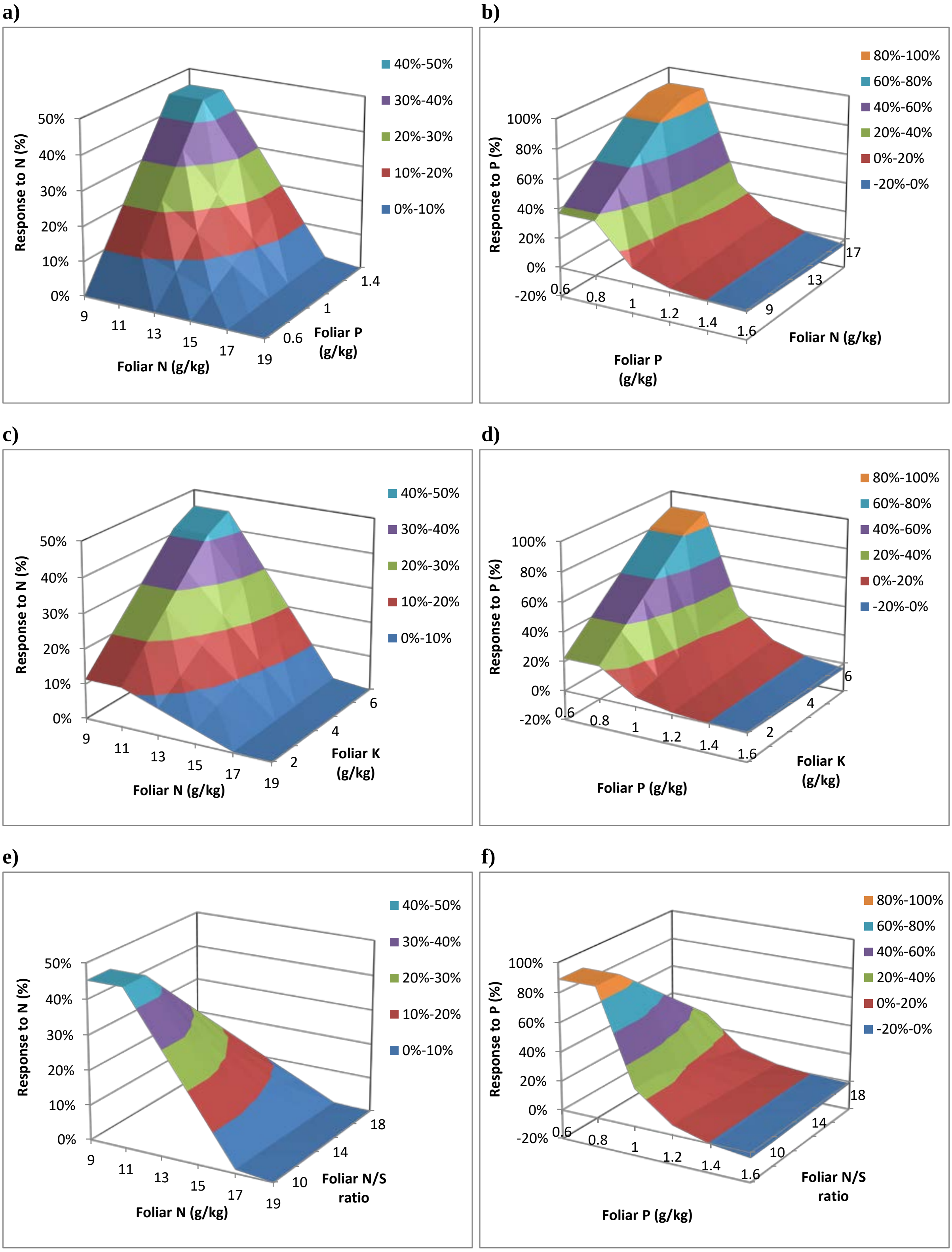


Figure 24: Modelled variation in response to N fertiliser and P fertiliser with foliar N and P concentration and N/S ratios: a) N response vs. foliar N and P; b) P response vs. foliar N and P; c) N response vs. foliar N and K; d) P response vs. foliar N and K; e) N response vs. foliar N and N/S ratio; f) P response vs. foliar N and N/S ratio.

These assumptions were consistent with the earlier assumption that tree growth is limited by the most limiting nutrient. They are also consistent with experimental results demonstrating that, where concentrations of two or more nutrients are less than adequate, growth response tend to be greater when both nutrients are applied compared where either nutrient is applied on its own. Some of the resultant surfaces are shown in Figure 25.

An example of the predicted responses from the model to various fertiliser treatments and foliar nutrient concentrations is provided in Figure 26. This chart shows the responses to N and P fertiliser applied separately or together to stands with varying foliar N and foliar P concentrations. The rates of fertiliser application are assumed to be 200 kg N/ha and 100 kg P/ha, which typically sufficient to remove any N or P deficiency.

Where P is non-limiting (1.6 g/kg) and foliar N is deficient (9 g/kg), the response to N is maximized where N is applied alone. In this situation, there is no response to P either by itself or in combination with N. Similarly, where N is non-limiting (17 g/kg), and foliar P is deficient (0.8 g/kg), the response to P is maximized and there is no response to N. Where both nutrients are deficient (foliar N = 9 g/kg and foliar P = 0.8 g/kg), responses to either N or P applied separately are well below their maximum and there is a strong NxP interaction. Where both nutrients are between adequate and deficient concentrations, responses to N or P applied separately are less than their maximum and there is a smaller NxP interaction.

These responses are consistent with those from fertiliser experiments where elevation of P through prior application of P fertiliser increased subsequent response to N fertiliser (May *et al.* 2009a). Therefore, this simple model should be effective in explaining differences in responses to different foliar nutrient concentrations and fertiliser combinations.

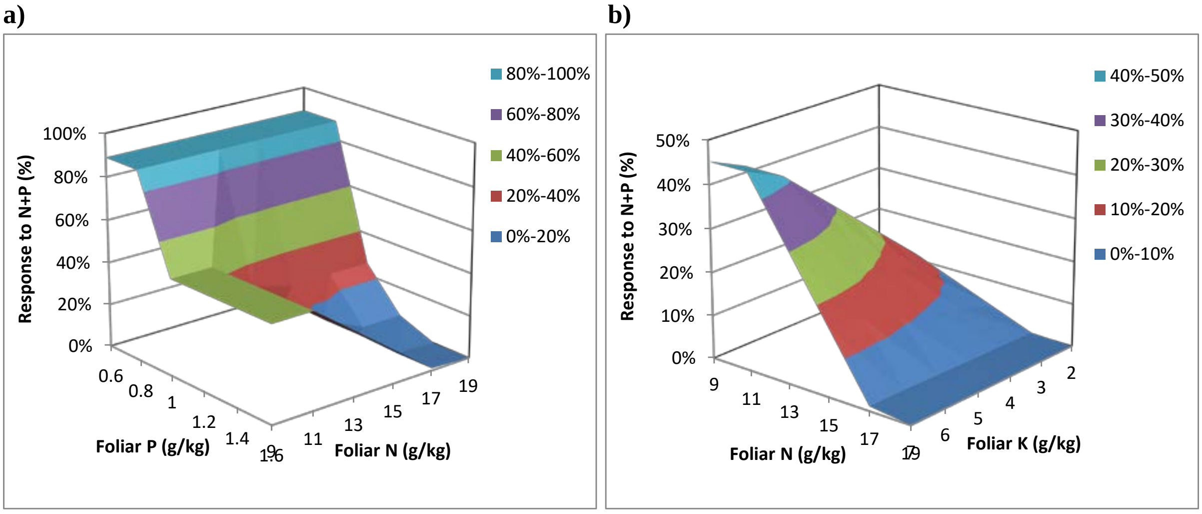


Figure 25: Modelled variation in response to N+P fertiliser with a) foliar N and P concentration and b) foliar N and K concentration.

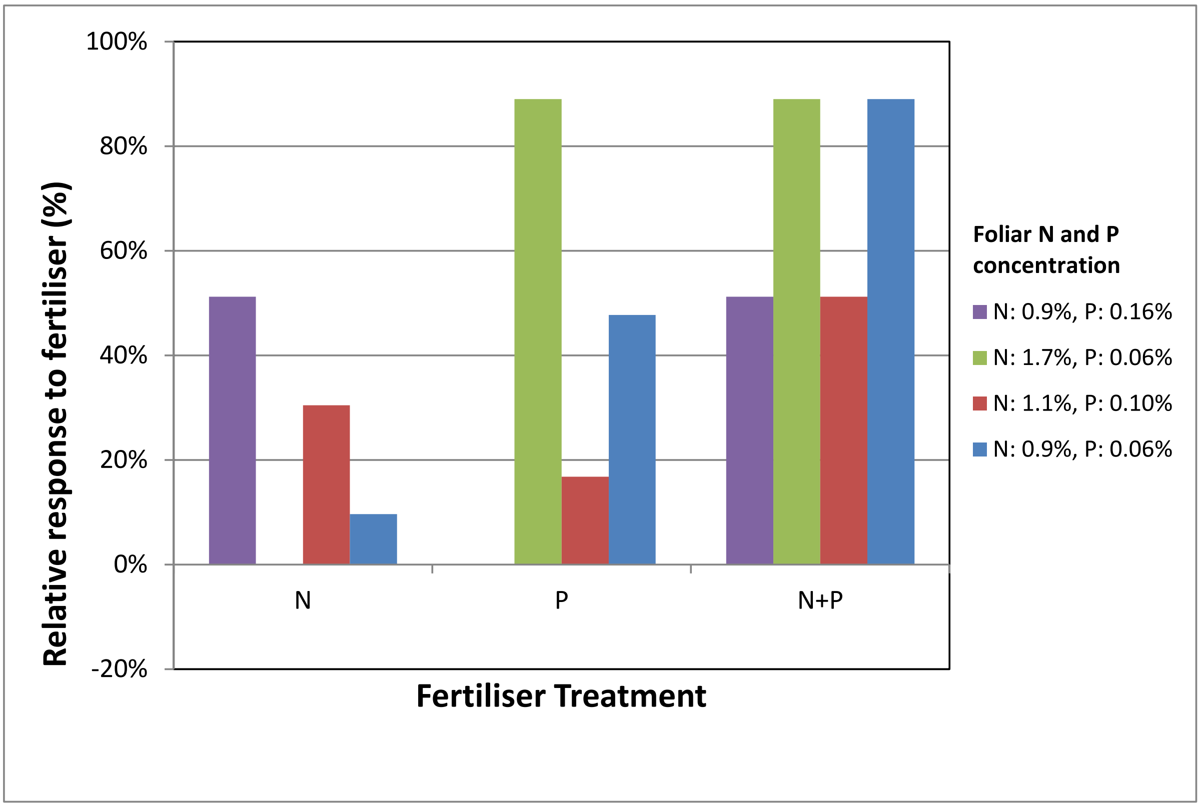


Figure 26: Modelled responses to N and P fertiliser applied separately or together to stands with differing foliar N and P concentrations. Note: other nutrients are assumed to be non-limiting.

Accounting for effects of fertiliser rate and form

Effect of N form

Green Triangle Experiments

A series of experiments in the Green Triangle demonstrated that the form of N applied has a major impact on the growth response to N fertiliser. When N was applied as urea across a range of sites, the response was 10-50% less compared with that to ammonium nitrate (Figure 27). The average reduction in growth for urea compared with ammonium nitrate was 27%.

The smaller response to urea was shown to be largely due to loss of N as a result of N-volatilization. This loss was measured using isotopically labelled fertiliser applied to lysimeters installed at four sites. Three months after application only 53-73% of N applied as urea could be recovered from soil and water from the lysimeters compared with 86-96% applied as ammonium sulphate or ammonium nitrate. These results indicated that 27-47% of N applied as urea was volatilised compared with 4-14% of that applied as ammonium sulphate and ammonium nitrate (Figure 28).

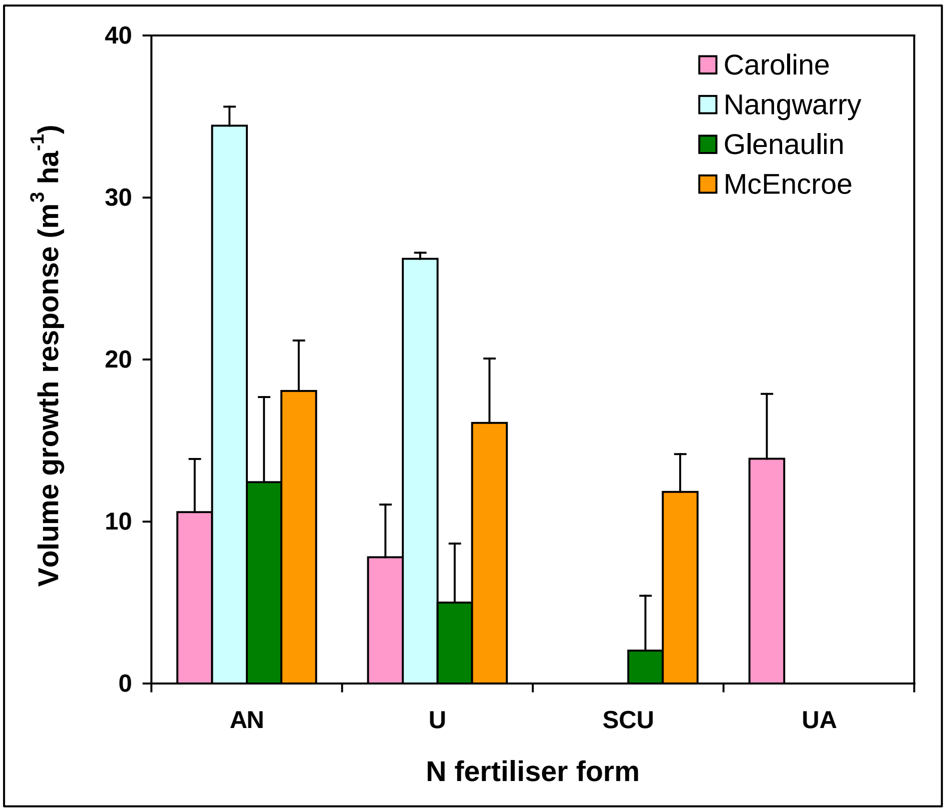


Figure 27: Growth response relative to controls to different forms of N fertiliser in the Green Triangle (AN, U: urea, SCU: sulphur coated urea, and UA: Agrotain-urea) three years after application across four sites.

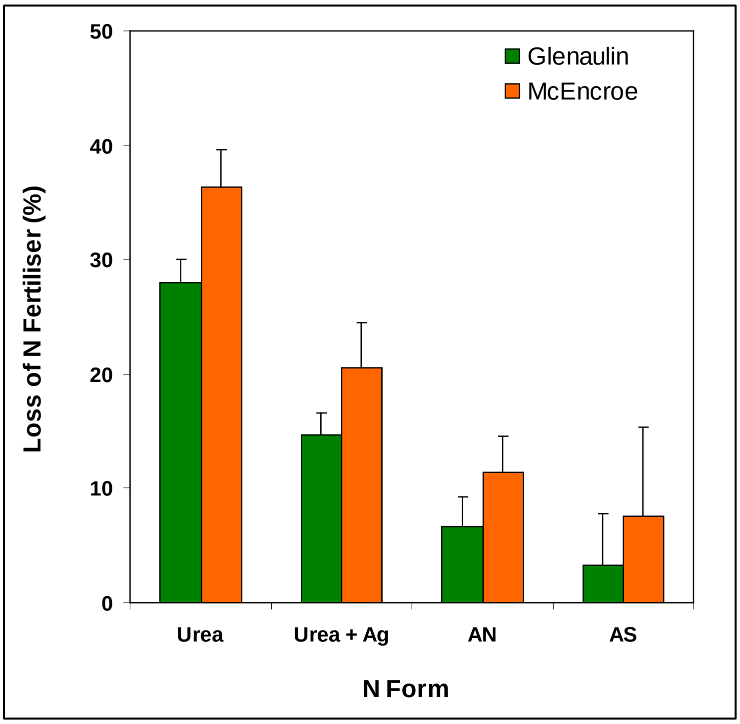


Figure 28: Differences between N volatilisation losses from urea, Agrotain urea (Urea + Ag), ammonium nitrate (AN) and ammonium sulphate (AS) applied to lysimeters at two sites in the Green Triangle.

Application of P as triple super phosphate together with urea also reduced N volatilization (Figure 29). This was most likely a result of the acidic triple super phosphate reducing the pH of the soil which in turn reduces the potential for N volatilization. The response to urea alone was 68% of that to ammonium nitrate alone while that to urea plus triple super phosphate was 78% of that to ammonium nitrate plus triple super phosphate although this difference was not significant (P > 0.05).

The work also demonstrated that growth responses were greater (Figure 27) and volatilization losses were lower if the urea was first mixed with a volatilisation inhibitor marketed as Agrotain (Figure 28). However, for this to be effective it was important that rainfall was sufficient to wash the urea into the soil within the first 28 days after application. Where plots were covered to exclude rainfall, there was little or no benefit in using Agrotain-urea compared with urea.

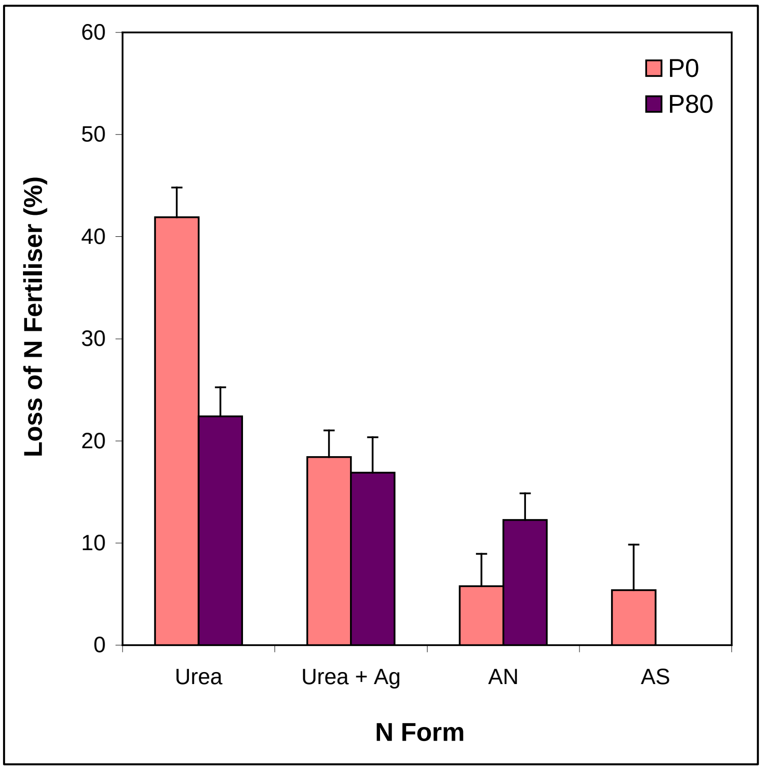


Figure 29: Nitrogen volatilisation losses from urea, Agrotain urea (Urea+Ag), AN and AS, applied with or without P as triple super phosphate in the Green Triangle.

HVP Experiments

Responses to different N forms were also examined using the data from HVP as described in the section *Predicting response to N fertiliser using foliar N*. Based on the different slopes of the relationship between N response and foliar N based on treatments with N applied as ammonium sulphate or urea plus P and another based on treatments with N applied as urea only, it was estimated that the latter resulted in a 25% reduction in response (see Figure 6).

The fact that there was no difference between the response to ammonium sulphate and the response to urea applied together with P is consistent with the measured reduction in N volatilisation from urea and increase in response to N applied as urea in combination with triple super phosphate in the Green Triangle (32%). There was no P only treatment in the HVP experiments with which to account for any response to P. However, the fact that P was marginal to adequate at all the sites included in the relationship indicates that any response to P was likely to have been small.

Based on the results from the experiments in the Green Triangle, Victoria and Tasmania, it was assumed that applying N as urea alone would reduce the response to fertiliser by 25% for a rate of 200 kg N/ha. Where P was applied together with urea at a rate of 80 kg P/ha, it was assumed there was no reduction in response. For other rates of N the reduction in response was varied as explained below.

Effect of N rate

Relationships between rate of N or P fertiliser application and response were developed by May *et al.* (2009a) based on results from a series of experiments in thinned *Pinus radiata* stands in the Green Triangle. This work demonstrated that the form of N applied had a major impact on the form of the relationship.

N fertiliser was applied as urea and ammonium nitrate at three rates (100, 200 and 400 kg N/ha) at two sites. The response to urea was lower than ammonium nitrate for all rates applied, consistent with the results of other N volatilisation studies. However, the shape of the rate/response curve differed between the two fertiliser types with the average response to urea much less than that to ammonium nitrate when applied at 100 kg N/ha (78% less) compared with 200 kg N/ha (23% less, Figure 30). This difference may have been a result of more rapid uptake by soil micro-organisms of urea compared with ammonium nitrate. It was concluded that the combined effects of greater volatilisation and immobilisation of urea compared with ammonium nitrate limited the amount of N from urea available for tree uptake and growth especially at low rates of application (<150 kg N/ha). The N rate verses response curves were normalised by expressing the responses as a proportion relative to the response to 200 kg N/ha for each fertiliser form at each site (Figure 31).

In addition to urea and ammonium nitrate, normalised responses for N applied as DAP (di-ammonium phosphate) at rates of 70 kg N/ha and 200 kg/ha across three additional sites were included. This curve based on these results fell roughly midway between those for urea and ammonium nitrate for rates < 200 kg N/ha. This was consistent with other results from the Green Triangle which indicated that ammonium sulphate (which has similar properties to ammonium phosphate) tends to be the more mobile than urea in soil, but less mobile than ammonium nitrate (May, unpublished data). Therefore, it was assumed that the N rate response curves for ammonium sulphate and MAP (mono-ammonium phosphate) were of the same form as the normalised curve for DAP.

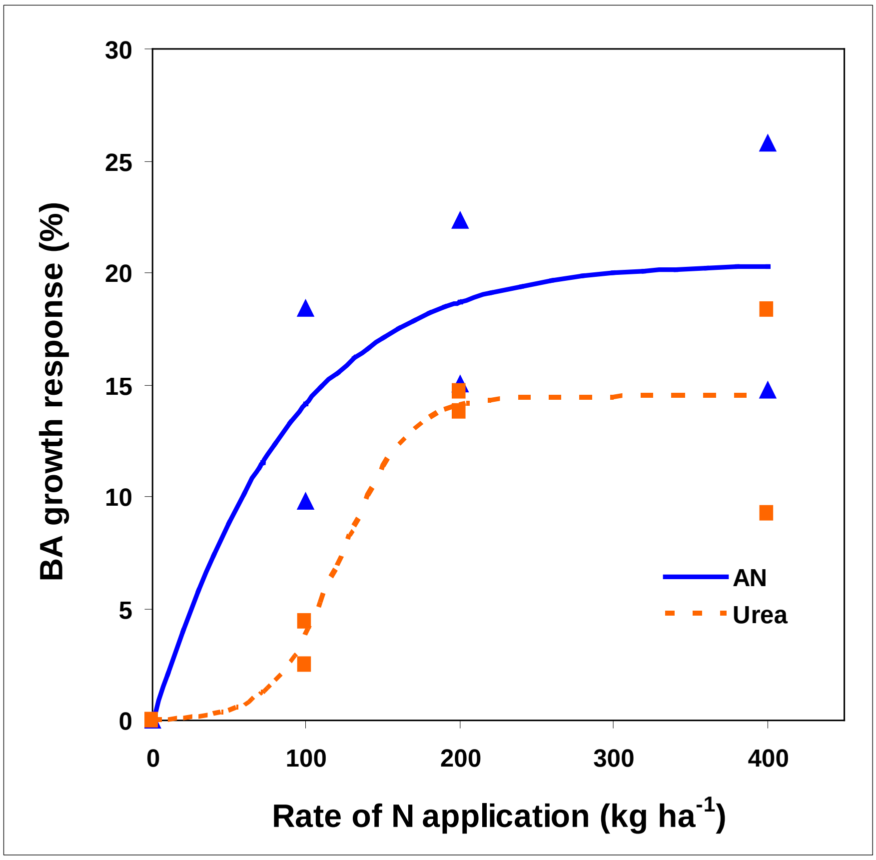


Figure 30: Relationship between rate of application and three year basal area (BA) growth response to urea and AN fertiliser relative to controls across two sites.

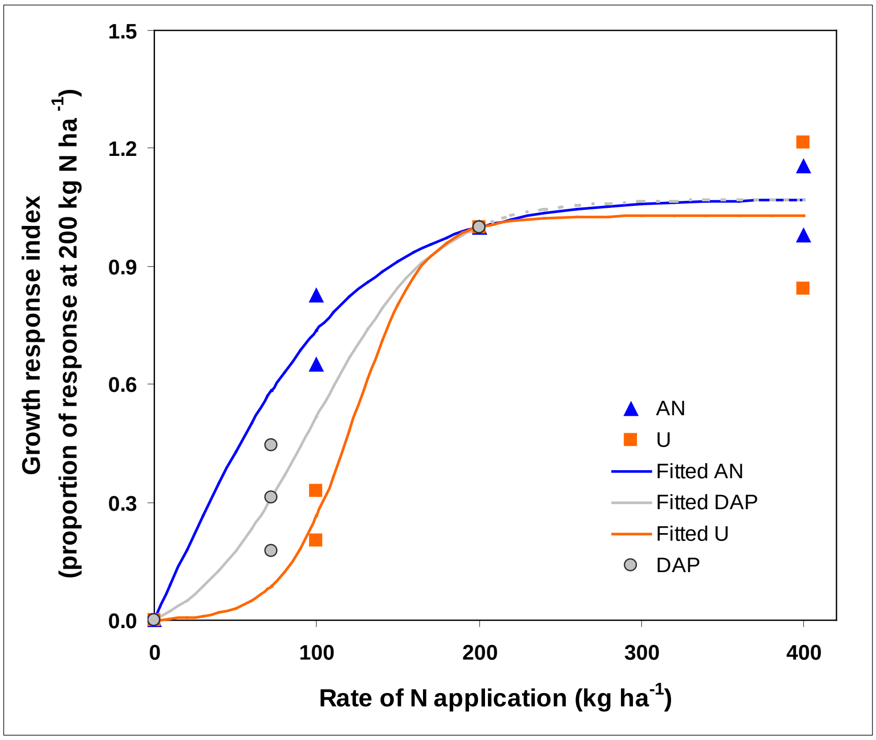


Figure 31: Normalised rate response curves for N applied as AN, Urea, and DAP. Basal area responses are expressed relative to those to 200 kg N ha^{-1} for each N form for each site.

There was no evidence that there was a significant increase in response for N application rates higher than 200 kg N/ha across stands in the Green Triangle on sandy soils. Therefore, it was assumed that the response to 400 kg N/ha was 7% greater than that to 200 kg N/ha for all N forms applied to sandy soils. The resultant rate response relationships for stands on sandy soils are illustrated in Figure 32.

For plantations in Victoria and Tasmania, it was assumed that the difference in response to different rates of N applied as urea relative to ammonium nitrate in plantations followed the same pattern as that measured in the Green Triangle.   However, based on evidence that responses to N applied to fine textured soils, continued to increase for rates greater than 200 kg N/ha, it was assumed that the response to N applied at a rate of 300 kg N was 25% greater than that to 200 kg N/ha. Since the response prediction curve for HVP stands was based on a rate of 300 kg N/ha, the response to 200 kg N/ha would therefore be 20% less than that predicted by this relationship. The rate-response curves for fine textured soils were normalised by expressing the predicted responses relative to that for N applied as ammonium sulphate applied at a rate of 300 kg N/ha (on which N prediction relationship for Victorian plantations was based). These relationships are illustrated in Figure 32.

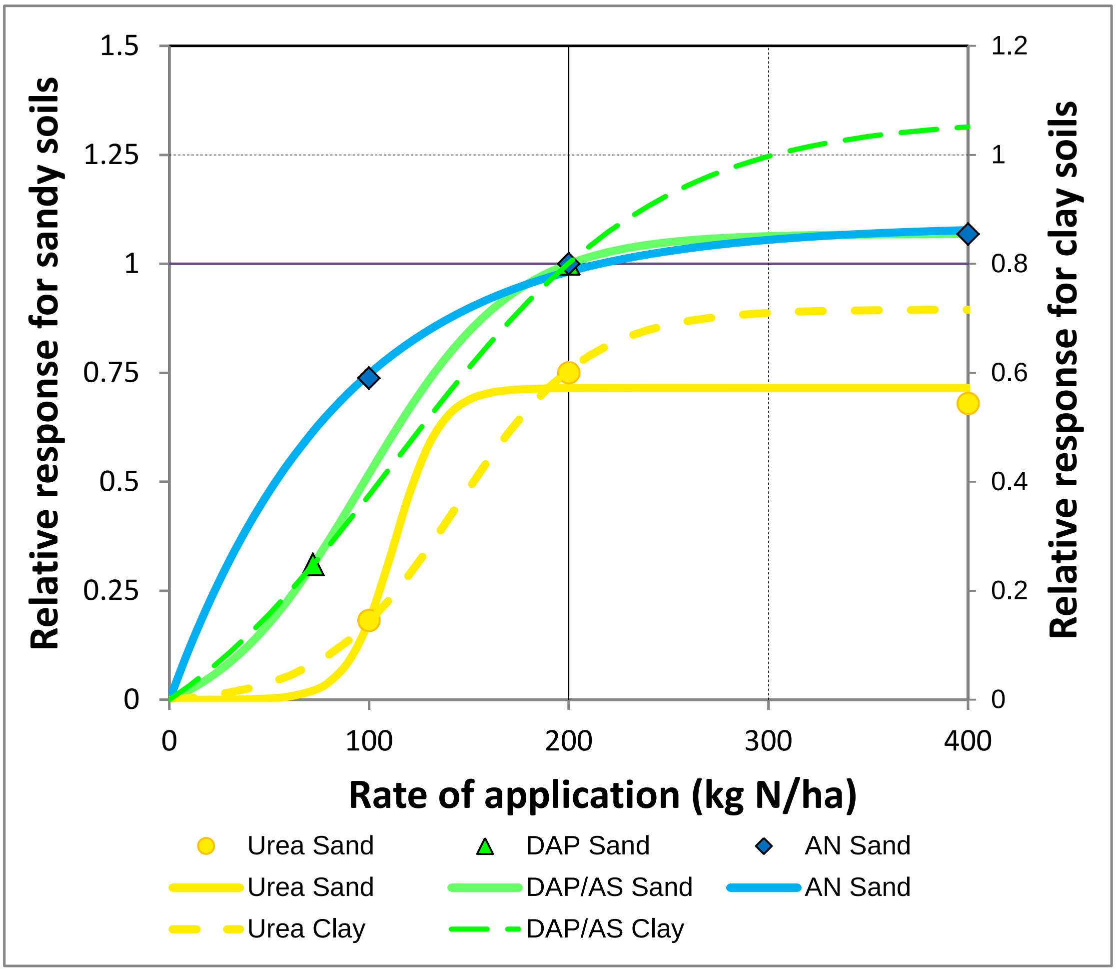


Figure 32: Relationships between rate of application for different N forms and soil textures and normalised growth response expressed relative to the expected response to 300 kg N/ha applied as urea to clay soil.

The equations for predicting the relative change in response (*C*) to different rates and forms of N fertiliser were:

- sandy soils:
    - C_{AN}: $1714/(40.9 - 1.09\ e^{-1.18\ R}) – 40.9$
    - C_{DAP}: $0.0940/(0.0816 - 1.07\ e^{-.2.66\ R}) – 0.0816$
    - C_{Urea}: $0.00164/(0.00170 – 0.961\ e^{-5.26\ R}) – 0.00170$
- Clay or loam soils:
    - C_{DAP}: $0.245/(0.194 - 1.07\ e^{-2.66\ R}) – 0.194$
    - C_{Urea}: $0.0121/(0.0125 – 0.956\ e^{-3.01\ R)}) – 0.0125$

where R is the rate of N application in kg/ha divided by 100

These equations were used in ProFert to estimate the effect of different rates of N fertiliser application on response for different N forms and soil types.

Effect of rate and form of P fertiliser

Unlike N, there was no evidence of variation in either the maximum response or the shape of the rate/response curve for different forms of P fertiliser applied to sandy soils in the Green Triangle (Figure 33, May *et al.* 2009a). As a result, a single equation was developed to account for the effects of different rates of P. As with N rate-response relationships the responses were normalised by expressing them relative to P applied at a rate of 80 kg/ha (the rate on which the relationships for predicting P response were based). Information from HVP indicated that the effect of rate of application on P response for fine textured soil was likely to be similar to that measured on sandy soils in the Green Triangle. Therefore the same curve was used for both soil types.

The normalised rate response curve for P fertiliser is shown in Figure 34. The equation for predicting the relative change in P response (C_P) with rate of P application (P, in kg P/ha) was:

CP: $45.1/ (6.16 - 1.16\ e^{-2.68\ R}) – 6.16$

where R is the rate of P application in kg P/ha divided by 100.

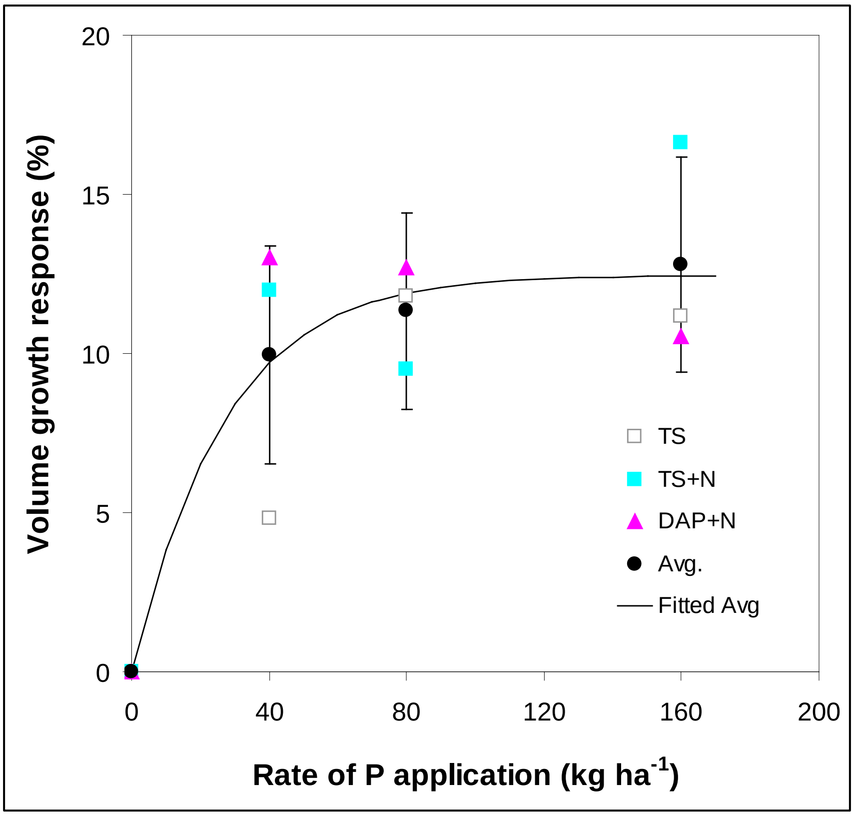


Figure 33: Rate response curve for average relative volume response to P applied as TS, with or without N, and DAP at one site. Error bars are standard errors of means.

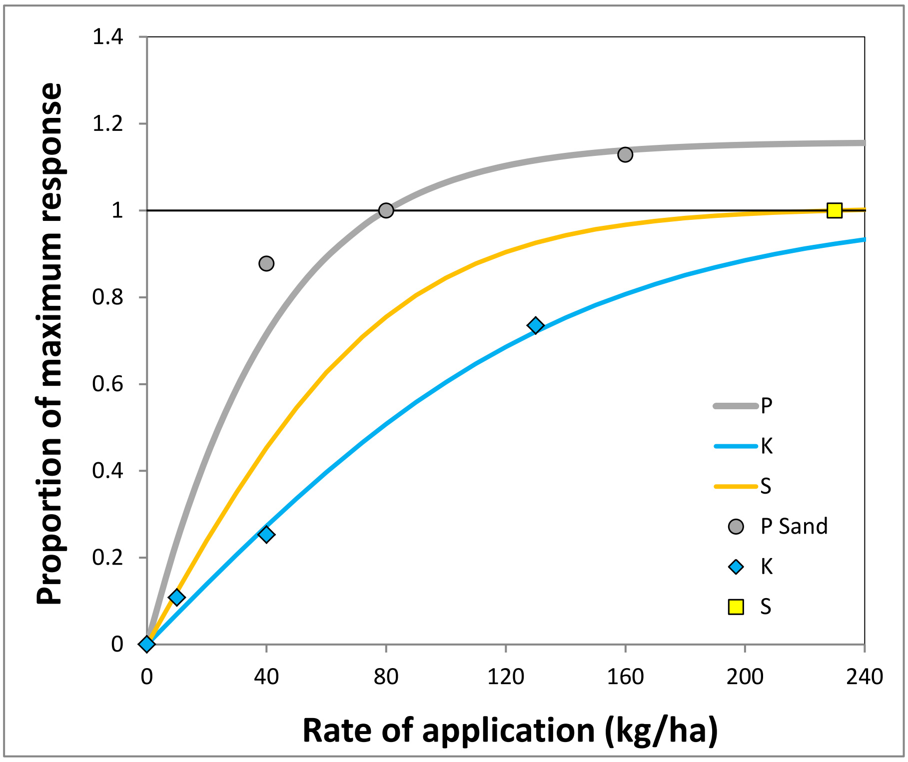


Figure 34: Rate response curves for P (applied to sandy and clayey soils), K, and S. Points for relationship between K rate and response are from Hall and Raupach (1961). The point for S was from Hopmans Pers. Comm.

Effect of K rate on response

Data from Hall and Raupach (1963) used to develop the K response relationship was also used to develop a rate response curve for K. Five rates of K were applied to 6 year-old trees and DBH responses measured over 21 months (Figure 4). The relationship between growth response and rate of P application indicated that response to K fertiliser may continue to increase for rates up to 1130 kg K/ha. However, the slope of the curve tended to plateau at rates above 125 kg K/ha, equivalent to 74% of the maximum response. The normalised rate-response curve (with responses expressed relative to K applied at 1130 kg) is shown in (Figure 34) and had the equation:

$$C_K: 2/(1 - e^{-1.4 \times K}) - 1$$

where:

C_K is the normalised response to K fertiliser and

R is the rate of K application in kg K/ha divided by 100.

Effect of S rate on response

ProFert does not attempt to predict responses to S fertiliser applied alone because there is no data from experiments on which to base such predictions. However, it does predict the effect of S fertiliser on S limitations which may reduce responses to other nutrients applied. To estimate the effect of S application on S limitation, the model takes into account the amount of S applied and so requires a rate response relationship for S. It was assumed that the form of the rate-response curve for S had the same form as that for ammonium nitrate applied to sandy soils. It was assumed that the response plateaued for rates above 230 kg S/ha (Hopmans, Pers. Comm.).

The resultant curve is illustrated in Figure 34 and had the equation:

$$C_S: 1.96/(0.983 - 1.01\, e^{-2.44 \times R}) - 0.983$$

where

C_S is the normalised response to S fertiliser and

R is the rate of S application in kg S/ha divided by 100.

Accounting for time since application and multiple fertiliser applications

Variation in response over time

In the Green Triangle, responses to fertiliser were tracked over 10 years, providing data on the variation in response over time. The sites were thinned and refertilised 6-7 years after the initial fertiliser application. However, treatments were applied in a manner that allowed the responses to the original application to continue to be measured for up to 10 years.

The average annual responses to N, P and N+P fertiliser were normalised by expressing them relative to the average cumulative response over 4 years (the period over which predictive relationships were based for N and P responses in the Green Triangle and Tasmania and N responses in Victoria). The normalised average annual responses to N, P and N+P fertiliser for the sites are shown in (Figure 35). The responses to N and N+P peaked in the 2nd – 3rd year while the response to P did not peak until the 6th year after application. Responses to both N and N+P decreased rapidly after peaking with the former falling to less than zero 7 years after application. However, the responses to P fertiliser and N+P fertiliser remained positive to at least 10 years after application.

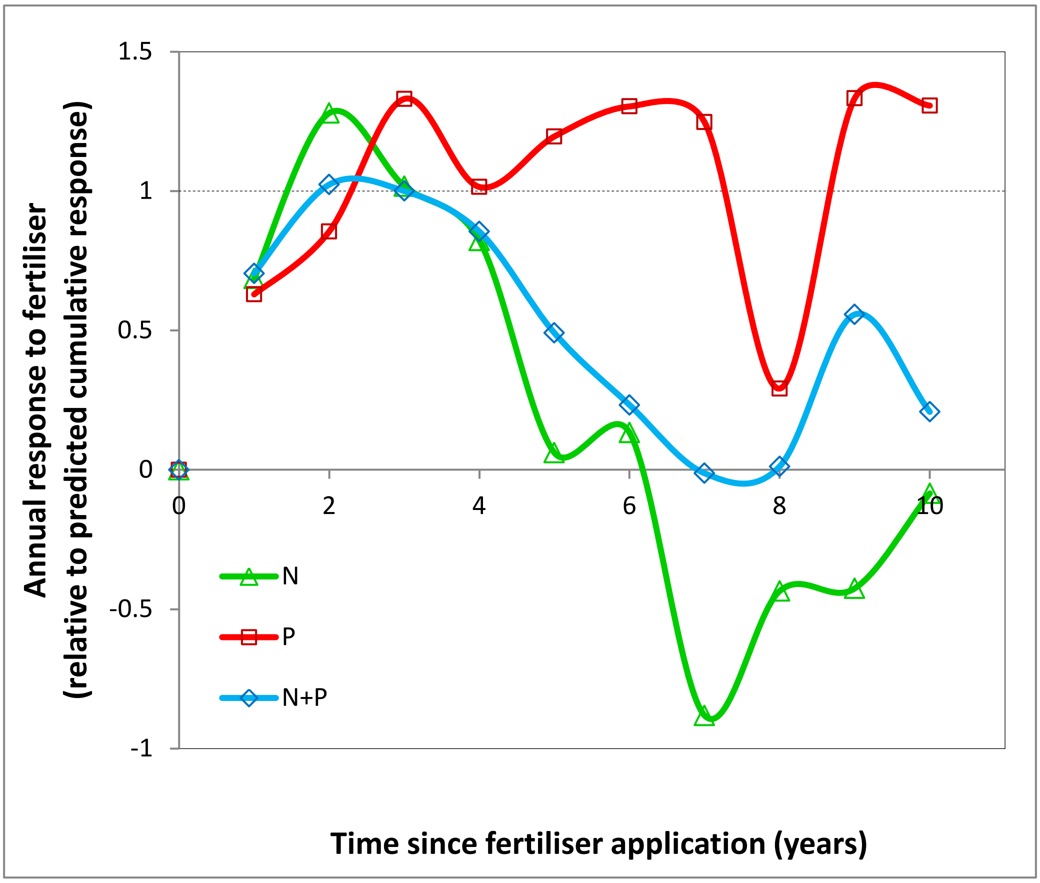


Figure 35: Average annual growth responses to N, P and N+P fertiliser applied in 1995-96 across Green Triangle sites expressed relative to 4 year cumulative responses to N, N+P and P and relative to cumulative 6 year response to P.

The difference in longevity of the response to N compared with the response to P is consistent with results from other studies. Results from a long-term fertiliser experiment in Tasmania in the Fingal Valley showed that the response to P (72 kg/ha) did not peak until 7 years after application and was still significant 8 years after application (Ringrose and Neilsen, 2002; 2005). Other studies from Tasmania report responses to P continuing for at least 16 years at one site (Nielsen and Adams 2005b) and over 20 years at another site (Nielsen and Adams 2005a). Similarly, results from HVP report growth continuing to increase in response to P for periods of 5-12 years. The negative response to N after 6 years was consistent with that reported by Snowdon (2002) as being commonly observed with Type 1 responses to fertiliser.

The annual responses to N, P and N+P fertiliser were modelled by fitting 3rd order exponential functions to the normalised cumulative responses over 10 years after fertiliser application (Figure 36). Cumulative responses over time were normalised by expressing them relative to the average 4 year cumulative response for N, P and N+P. In addition, the cumulative responses to P were expressed relative to the average response over 6 years (the period over which the predictive relationship for P response from Victorian sites was based).

Curves were fitted to the cumulative response data using an iterative process. Based on data from experiments in the Green Triangle, Tasmania and Victoria, it was assumed that annual responses were zero after 11 years for N and N+P and 20 years for P. The general form of the equations for the curves for cumulative responses to N, P and N+P fertiliser was:

$$C_t = a\,e^{it} + b\,e^{jt} + c\,e^{kt} + d$$

where :

- t is the number of years after application;
- C_t is the relative cumulative response t years after application;
- e is Euler's number (2.7182) and
- a, b, c, d, i, j and k are constants.

Smoothed annual responses (Figure 37) were calculated from the fitted cumulative response relationships using the following formula:

$$A_t = C_t - C_{(t-1)}$$

where :

- A_t is the relative annual response from $t-1$ to t years after fertiliser application and
- C_t is the relative cumulative response t years after application.

The data for annual response to P fertiliser indicated that the actual response to P may remain elevated for a longer time period than predicted by the fitted function. However, in the absence of better long-term data, a more conservative estimate was considered preferable.

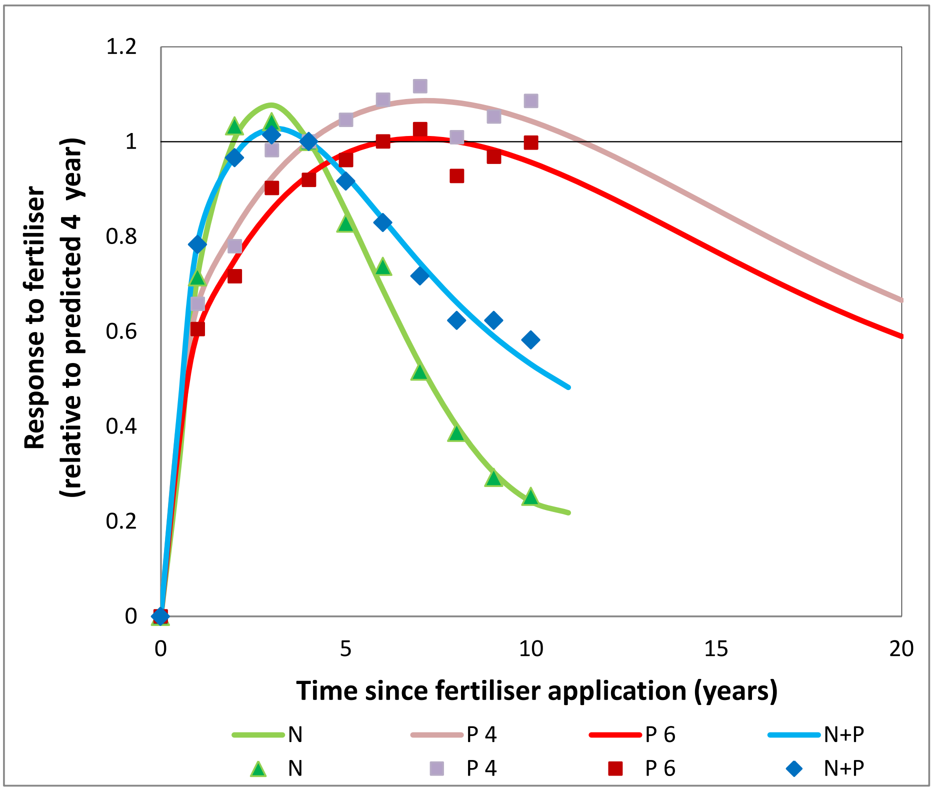


Figure 36: Curves (solid lines) fitted to measured cumulative responses to N, P and N+P fertiliser (points) expressed relative to the cumulative 4 year response to N and N+P and 4 and cumulative 6 year response to P from average responses from 10 sites in the Green Triangle.

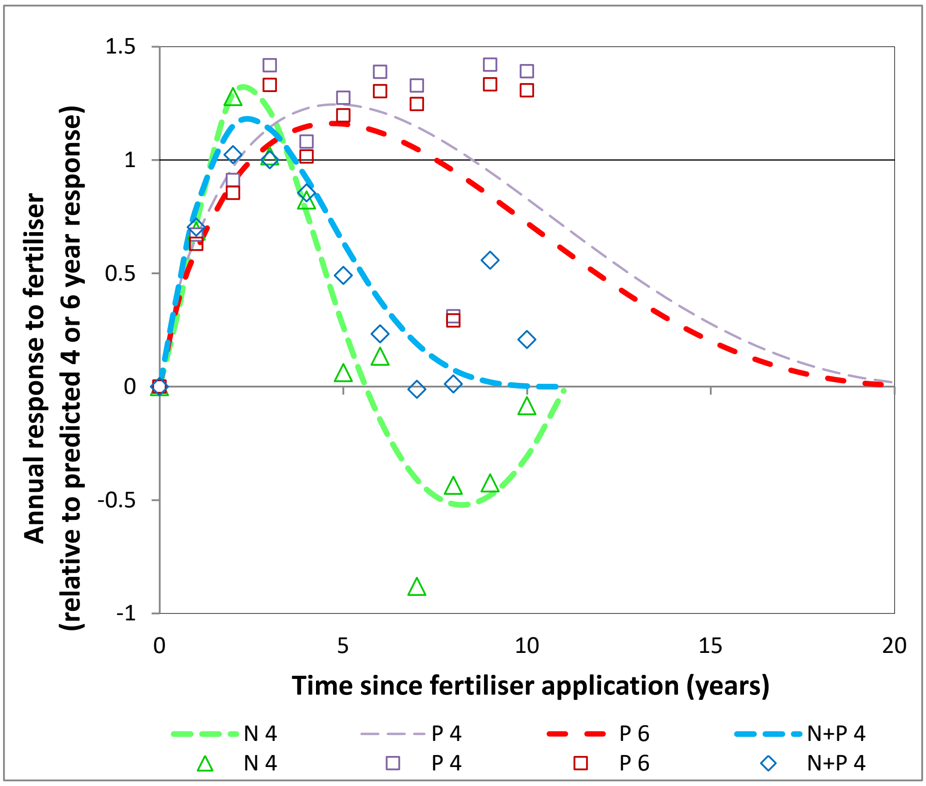


Figure 37: Annual response curves calculated from fitted normalised cumulative response curves for N, P and N+P plotted against average annual responses to N, P and N+P fertiliser from 10 sites in the Green Triangle.

Effect of past fertiliser applications to response to future applications

A key finding from the study in the Green Triangle was that current fertiliser applications can have a major impact on the response to future applications for at least 6 years. This is because the application of fertiliser changes stand nutrient status in several ways:

- by increasing the uptake of the nutrient applied;
- by reducing the concentration of other nutrients in foliage as a result of accelerated growth and expansion of tree crowns; and
- by increasing the mineralisation and uptake of other nutrients from the soil.

The first and second mechanisms were observed in changes in foliar N and P in the Green Triangle (May *et al.* 2009a). Application of N or N+P fertiliser resulted in a rapid increase in foliar N concentrations. These increased to 15-20% above those of the control within the first year, but then fell rapidly to be the same as the control 5 years after application (Figure 38). In contrast, application of P fertiliser did not significantly affect foliar N concentrations

Application of P or N+P fertiliser increased foliar P concentrations to 40% above those of the control 2-3 years after treatment. However, in contrast to the short term effect of N fertiliser, foliar P concentrations decreased more slowly over time and remained significantly above those of the control 10 years after treatment (Figure 39). In contrast, application of N alone decreased foliar P concentrations to 5-10% below those of the control. This decrease was associated with a 10% increase in leaf area on N fertilised treatments. The decrease in foliar P was still apparent 9 years after N application, possibly explaining the observed negative annual growth response to N 7-10 years after treatment (Figure 39).

In order to model the effect of fertiliser on stand nutrient status over time, curves were fitted to the foliar response data (Figure 40). The equation used to fit the curves had the general form:

$$R_t = R_{max}/(1+ e^{r(t-m)})$$

where :

- R_t is the relative increase/decrease in foliar nutrient concentration;
- R_{max} is the observed maximum/minimum response;
- t is the time since fertiliser application; and
- r and m are constants.

It was assumed that the effects of K fertiliser on foliar K concentrations and S fertiliser on foliar S concentrations followed the same relationship as N fertiliser (Figure 40). The equations were incorporated into ProFert to estimate the effects of fertiliser applications on foliar N and P status over time. These changes in foliar nutrients changed the response to future fertiliser applications, both by changing the foliar concentrations on which the primary response was based as well as by changing secondary nutrient limitations.

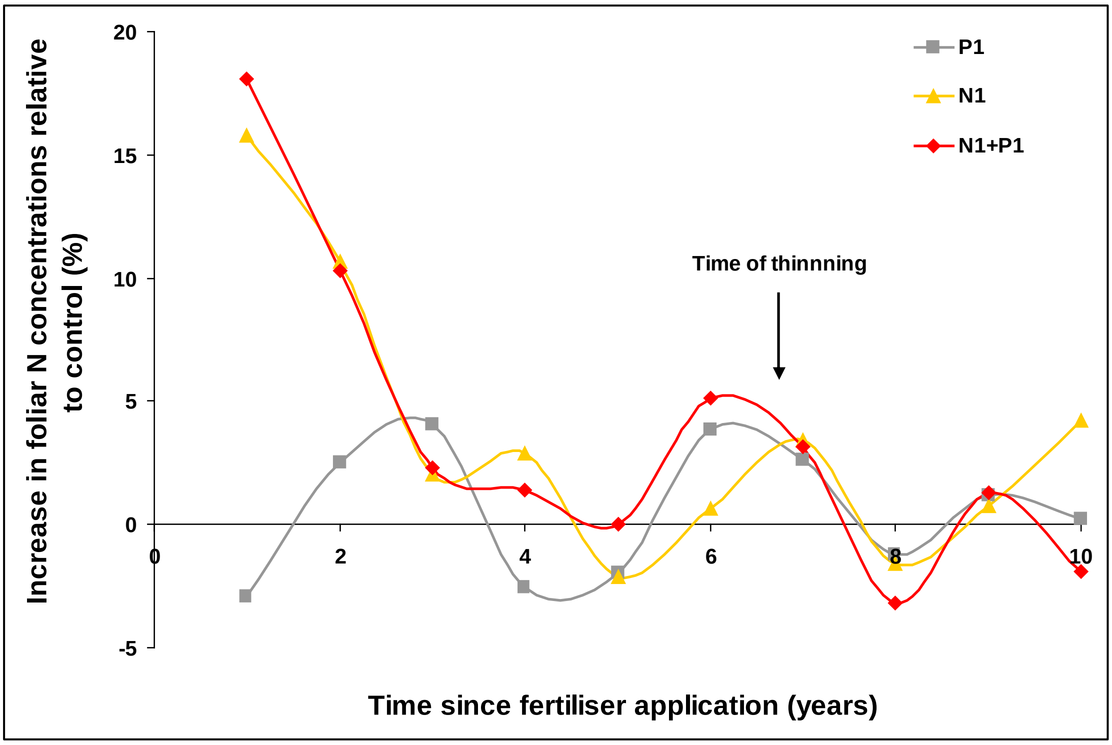


Figure 38: Average foliar N response to N and P fertiliser treatments up to 10 years after application.

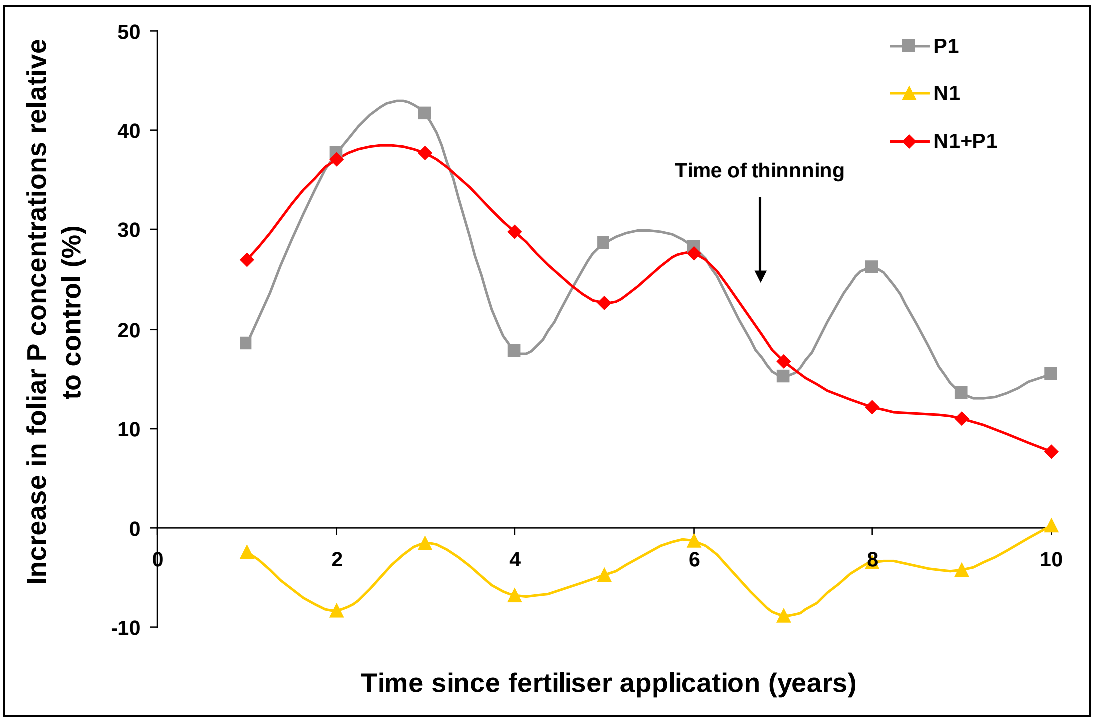


Figure 39: Average foliar P response to N and P fertiliser treatments up to 10 years after application.

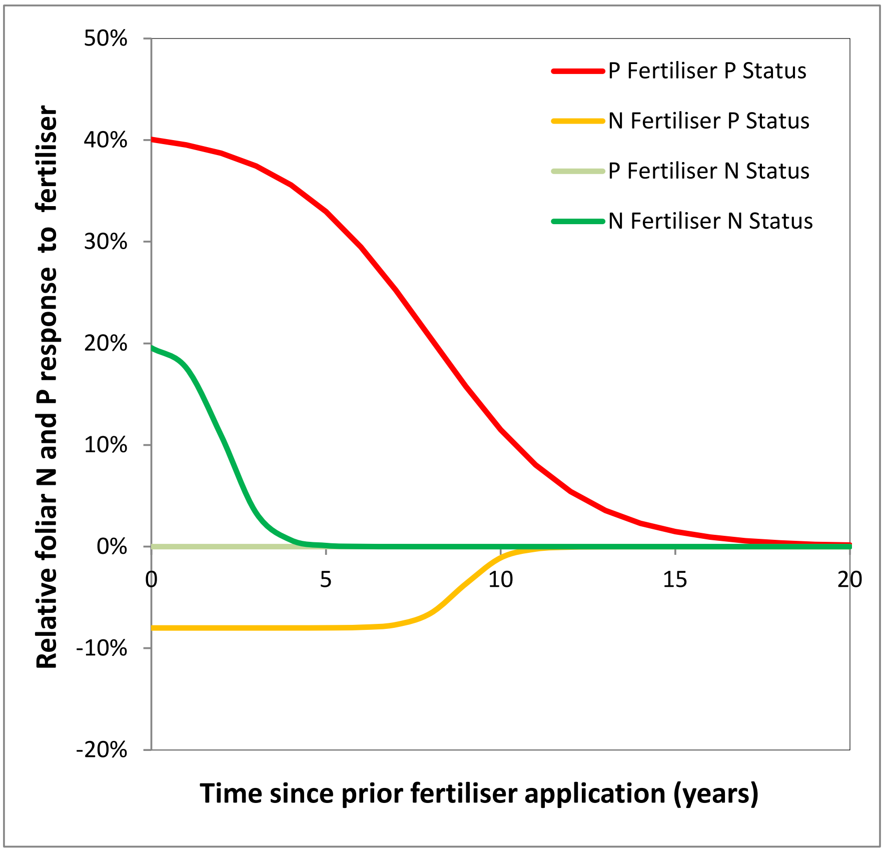


Figure 40: Idealised relationships based on measured changes in foliar nutrients for predicting the relative effects of N and P fertiliser on foliar N and P concentrations over time since fertiliser application.

Predicting growth of unfertilised stands

General Approach

To estimate the increase in the volume of wood produced in response to fertiliser, it is necessary to be able to predict the future growth of the unfertilised stand. Growth following fertiliser application is normally calculated as

$$G_F = G_C * R$$

where :

- G_F is the predicted growth of the fertilised stand;
- G_c is the predicted growth of the original stand without fertiliser; and
- R is the cumulative growth response to fertiliser.

However, since both the annual growth and annual response to fertiliser vary with time, harvesting and future fertiliser applications, in ProFert the growth of the fertilised stand is calculated by summing the products of the predicted annual growth of the unfertilised stand and the predicted annual fertiliser response as follows:

$$G_F = \sum_{t=1}^{n} G_{Ct}\, A_t$$

where :

- G_F is the predicted cumulative growth of the fertilised stand;
- G_{ct} is the predicted growth of the original stand without fertiliser in year t; and
- A_t is the annual growth response to fertiliser in year t.

To estimate growth of the unfertilised stand, outputs from operational models or estimates from regional growth curves can be used. Because of different growth and yield systems used by different companies, the front end of ProFert was modified to be able to read several different types of data.

Simulating growth using default growth curves

The original version of ProFert used regional growth equations to estimate future growth. Site Index or Site Quality determined at around 10 years was used to model future growth of unfertilised stands in the Green Triangle and northern Tasmania (e.g. Figure 41). Volume verses age data for the seven Site Qualities used in the Green Triangle is available in Lewis *et al.* (1976). Curves were fitted to this data with the general form:

$$V_{it} = M_i \times e^{-tmax_i \times t^{-D_i}}$$

where :

- V_{it} is the predicted total volume a stand of site quality i aged t years;
- M_i is the estimated maximum volume for the stand;
- $tmax_i$ is the age at which growth is maximum for the stand; and
- D_i is the rate of decline in growth over time for the stand.

The original site quality tables provide volumes only for stands aged from 10 years to 50 years. These curves were extrapolated back to Age 0 to allow growth responses of younger stands to be predicted. In addition, two more curves estimating growth of stands with productivities greater than that for Site Quality 1 were developed by extrapolating relationships between volume and site quality based on the other seven site qualities. This allowed ProFert to model growth of a wider range of stand productivities.

Annual growth is calculated by ProFert from the cumulative volume for the fitted growth equations for each site quality (Figure 42). For stands of intermediate site quality (e.g. 3.4) growth is interpolated within ProFert from the two closest growth curves (e.g. the curves for site qualities 3 and 4).

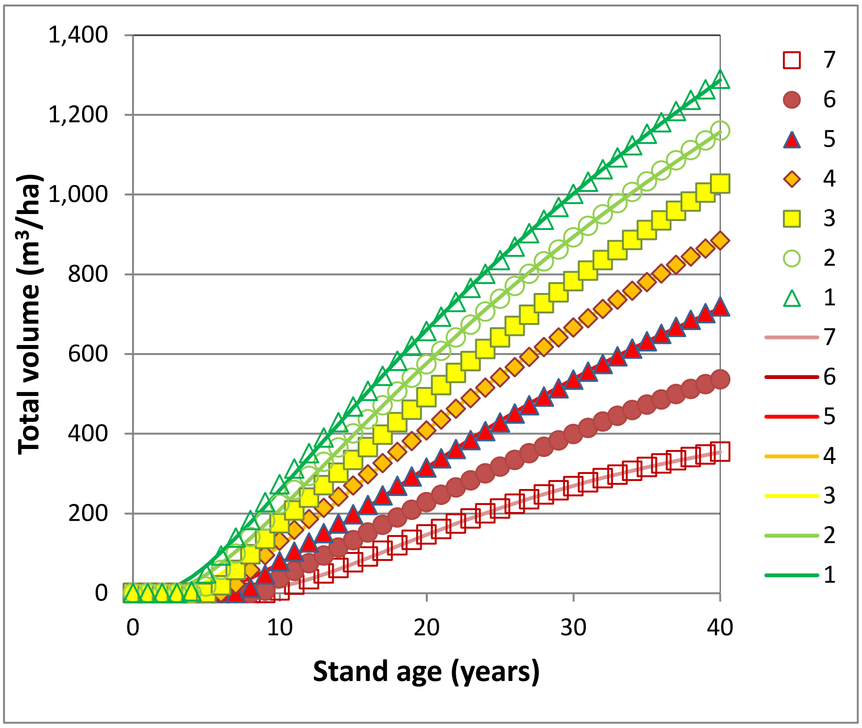


Figure 41 'Actual' verses modelled cumulative volume growth for the seven different site qualities across the Green Triangle.

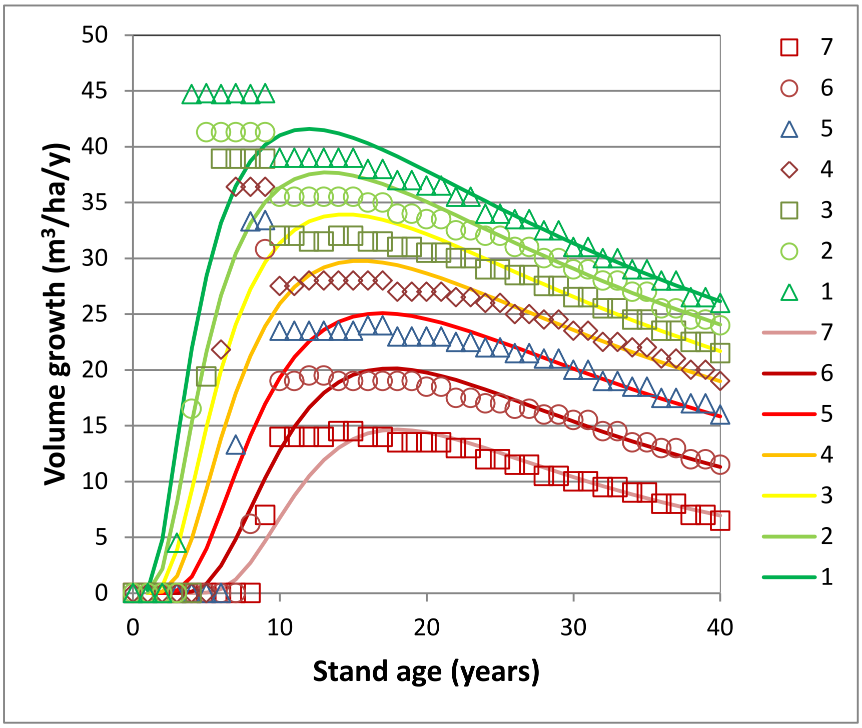


Figure 42 'Actual' verses modelled total current annual increment for the seven different site qualities across the Green Triangle.

ProFert was modified allow it to predict future growth of stands that had not had their site quality assessed, or where subsequent inventories indicated they were growing faster or slower than the original site quality estimates. Where the standing and cumulative harvested volumes are known, ProFert can estimate the site quality by interpolating between the two closest site quality curves. This estimated site quality is then used to predict future growth of the unfertilised stand. However, it is important to note that, if total volume removed in prior harvests is not known and only standing volume is used, ProFert will underestimate the site quality using this approach.

If default growth curves are used, then the user must input the age, residual stocking and residual volume for all future thinning events as well as the age of clear felling. This allows the model to predict the wood yields for the unfertilised and fertilised stand for each future harvest event as well as the growth and average volume of the retained trees.

Predicting future growth using site specific forecasts

With the advent of site specific growth and yield modelling, volume growth and harvest information is now available for individual stands. Therefore, ProFert was modified to enable it to accept site specific growth and yield information for the purpose of estimating growth of the unfertilised stand. However, the type and format of available data used by each organisation can differ substantially so the model was designed to be able to accept different types of data.

Procedures were incorporated in ProFert to accept data from two different growth and yield systems: YTGen (used by TPPL and HVP) and Norske Skog's growth model. Both systems provide site specific estimates of future stocking, standing and harvested volumes, and product yields at thinning and clearfell. Clearfell volumes and product yields are provided from the current stand age to clearfell age by YTGen and over a 40 year rotation by the Norske Skog system. Pre- and post-thinning assessment data is used by each system to forecast growth of each stand. In the case of YTGen, future growth and product yields are modelled directly from the assessment data. In the case of the Norske Skog system, the user allocates a crop type to a stand based on the inventory measurements and the growth model forecasts future growth and product yields for that crop type.

This data is used by ProFert in three ways to:

1. forecast future volume growth of the unfertilised stand;
2. estimate the % breakdown of total merchantable volume into different products (e.g. sawlogs, pulplogs, posts etc.) at each future harvest for both the fertilised and unfertilised stand; and
3. estimate the change in product mix at clearfelling resulting from an increase in average tree size after fertiliser use.

When using YTGen data, the user generates data files for each stand and allocates these to the appropriate site being modelled within ProFert. The user specifies the name and location of the spreadsheet holding the data for each site and this information is stored in the model so the data can be retrieved when the response to fertiliser is calculated. Because product mix is determined by tree size and since fertilised trees will often grow larger than unfertilised trees, it is important that the user ensures that output from YTGen continues for several years beyond the expected age of clearfelling. In this way, ProFert can account for the expected change in product mix resulting from an increase in tree size at clearfelling beyond that of the unfertilised stand.

For Norske Skog data, the growth and yield data for all crop types is first copied by the user into ProFert from the growth model. This data is then stored permanently in the model's database until it needs to be updated. When running ProFert, the user inputs the crop type for each site and the model selects the relevant growth data, harvest regime and product mixes for that crop type.

To simplify the process of loading and storing data in ProFert, a procedure was developed which prompts the user to select the directory, file name and sheet name where the data is stored. This procedure copies the path and sheet name (for YTGen data) or the growth and yield data for each crop type (for Norske Skog data) into ProFert.

Predicting harvested volumes and revenue

Predicting product volumes

ProFert calculates the increase in stand value in response to fertiliser by estimating the total value of harvested products from the fertilised and unfertilised stand. The volume of each product removed at each harvesting operation is calculated as follows:

$$V_{pt} = V_t \times Y_{pt}$$

where :

- V_{pt} is the predicted volume of product p harvested at age t;
- V_t is the total merchantable volume harvested at age t and
- Y_{pt} is the percentage recovery of product p at age t.

ProFert was modified to calculate the percentage recovery of each product in one of two ways, depending on the harvest operation and the type of growth and yield data available:

1. from the outputs of the growth and yield model (e.g. YTGen or Norske Skog's growth model) for thinning operations for both the fertilised and unfertilised stand and clearfell for the unfertilised stand; or

2. from relationships between percent product recovery and average tree volume developed from product data from the Green Triangle where generic growth curves are used and for the fertilised stand at clearfell.

To estimate product breakdowns for stands modelled using generic growth curves, data provided by TPPL from its YTGen growth and yield system was used. Plots of the outputs indicated that the percentage recovery of each log class could be predicted from average tree size alone (Figure 43). A procedure was developed in ProFert to estimate the product mix for any tree volume within the range covered (0.03 m^3 to 1.97 m^3) by interpolating between the nearest larger and smaller tree volumes in the dataset.

The growth and yield systems used by HVP, TPPL and Norske Skog output the estimated percent recovery of each product at each thinning operation. These systems also output estimated recovery of products from retained trees from current age to the clearfell age specified by the user for YTGen, or 40 years for the Norske Skog system. To estimate product recoveries for the fertilised stand at clearfell, ProFert was modified to calculate average tree volume and interpolate recoveries from the closest upper and lower tree volumes for retained trees in the dataset. This approach allowed changes in product mix at clearfell arising from an increase in average tree volume due to fertiliser to be accounted for. This information is used together with tree volumes and product values to calculate the total value of the trees harvested.

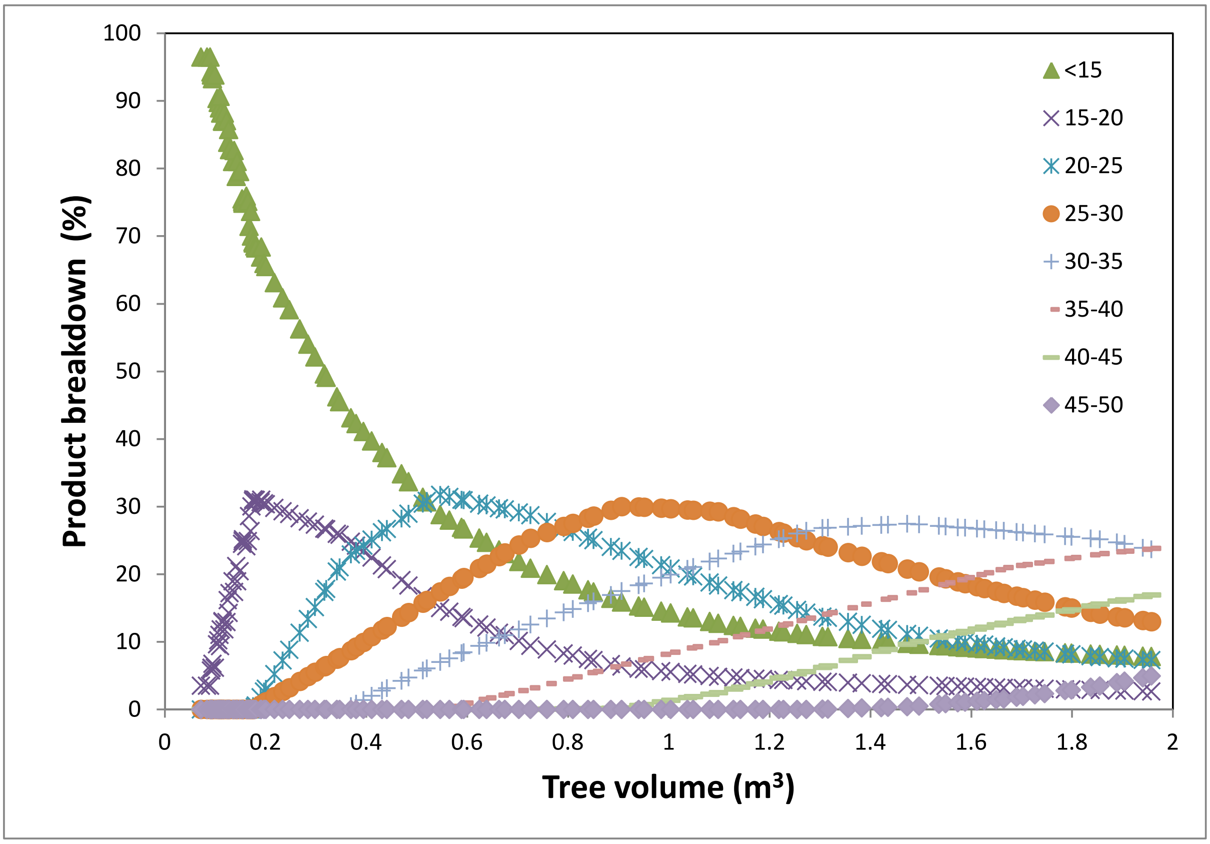


Figure 43: Outputs from TPPL growth and yield model showing % recoveries of different products from harvested trees of increasing volume across a range of crop types.

In addition to estimating product mix and value of harvested trees, ProFert also estimates the potential product mix and value of standing trees. Where data is available for the estimated product mix of standing trees (e.g. outputs from YTGen and Norske Skog growth models) this is used to estimate the percentage recovery of each product each year up until clearfell, for the unfertilised stand, or final thinning, for the fertilised stand. After final thinning of fertilised stands, product recovery for standing trees is estimated from average tree volume in the same way as for clearfelled trees.

Where generic growth curves are used, the product mix of standing trees is estimated from the default product recovery data, in the same way as for harvested trees, by interpolating between the closest upper and lower tree sizes.

Calculating gross product values

Net values (known as the stumpage value) of harvested wood products from mill door values (the effective price paid for the products at the sawmill or port) were calculated for products by subtracting harvesting and haulage costs. This allowed the model to account for differences in stumpage values resulting from differences in harvesting costs or haulage costs for different sites or different harvesting operations.

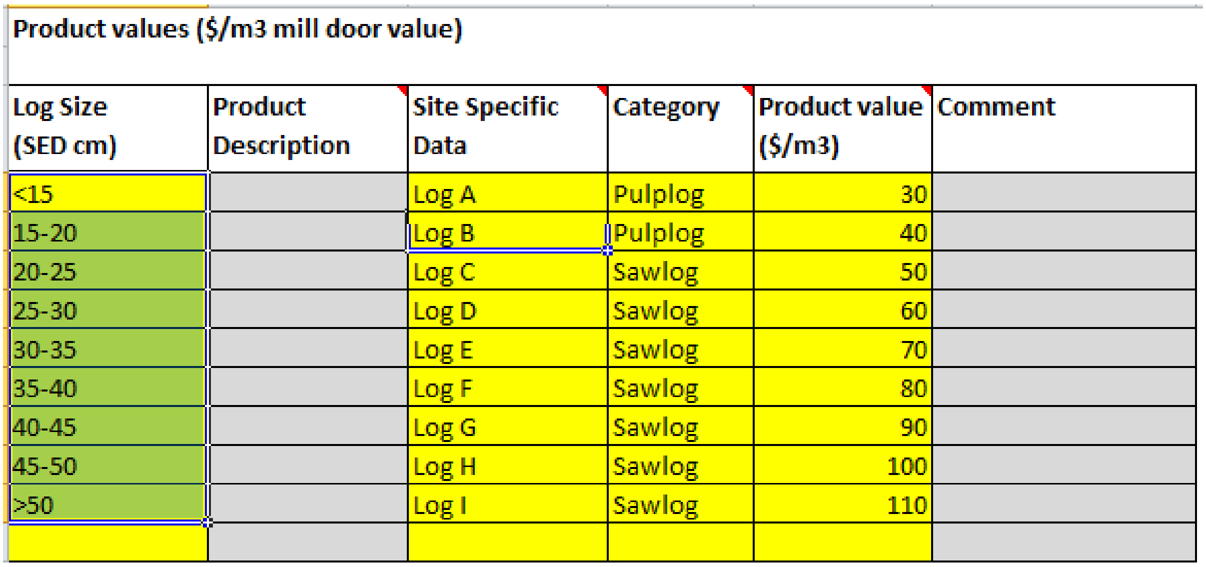
A procedure was developed to handle data for product values in two ways:

- where data for values of products is available for individual stands, this can be automatically loaded with the growth and yield data during the data loading procedure (see section *Predicting product volumes*);
- otherwise product values are assumed to be uniform across a company's plantation estate and the user enters the name, category (sawlog, pulplog or other) and value of each product into a table in the sheet called 'Product values'.

For the latter case, the names of products entered in the Product Value sheet are automatically linked to those on the product recovery and haulage costs sheets except where site specific growth and yield data is used. In this case, the user must ensure that the product names entered match those output by the growth and yield system (Table 2). The user must also input the product category (Pulplog, Sawlog or Other) and value for each log type.

Product categories are used by ProFert to summarise information for outputs. For Multi-Site analysis, these outputs include the total volume and value for each product category harvested at thinning and clearfell for both the unfertilised and fertilised stand. For Single Site analysis, outputs include annual volumes and values of both standing and harvested trees for each product category from the current age until clearfell.

Table 2: Product value data table showing the names, categories and mill door values of the various log sizes harvested.



Product values ($/m3 mill door value)

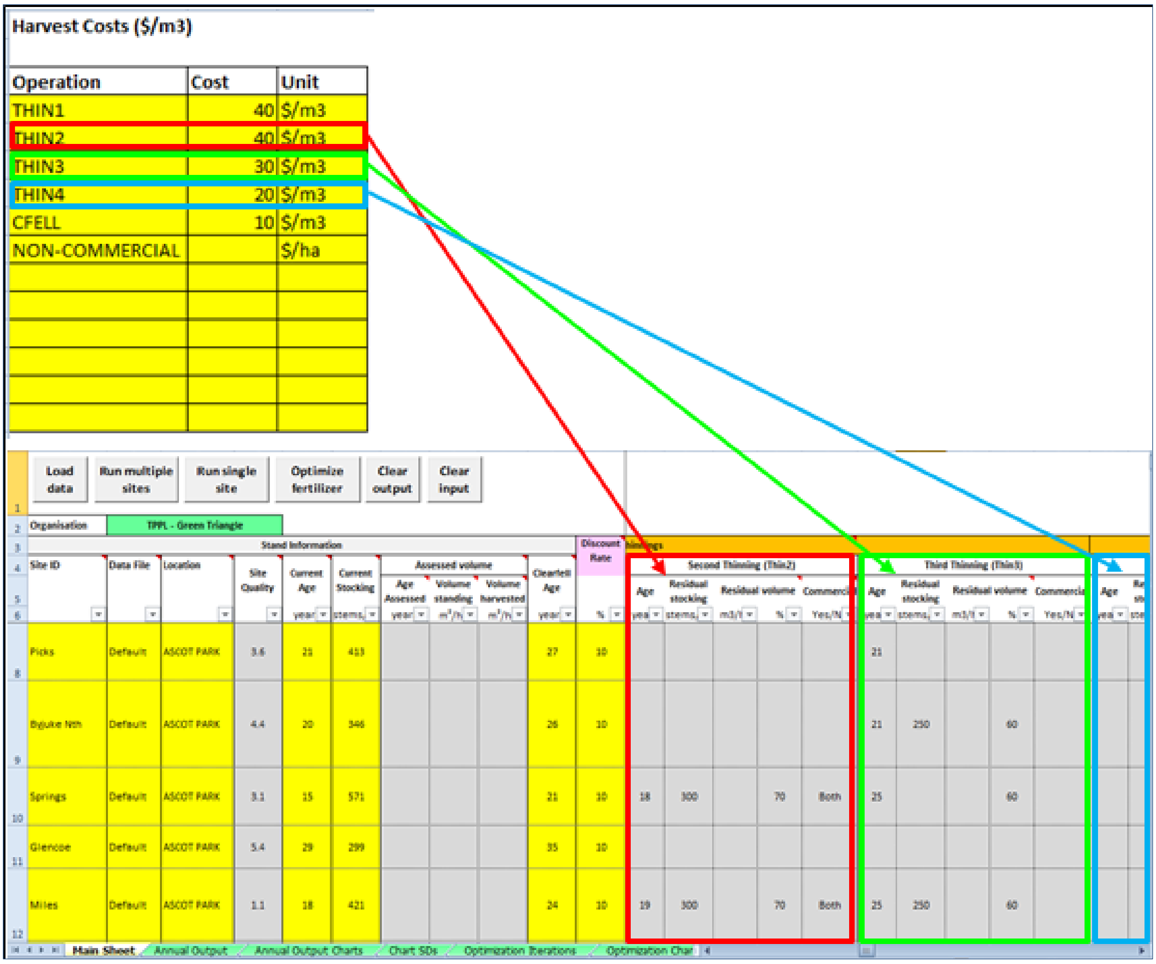
Log Size (SED cm)	Product Description	Site Specific Data	Category	Product value ($/m3)	Comment
<15		Log A	Pulplog	30	
15-20		Log B	Pulplog	40	
20-25		Log C	Sawlog	50	
25-30		Log D	Sawlog	60	
30-35		Log E	Sawlog	70	
35-40		Log F	Sawlog	80	
40-45		Log G	Sawlog	90	
45-50		Log H	Sawlog	100	
>50		Log I	Sawlog	110	

Calculating harvesting and haulage costs

Harvesting and haulage costs are handled by the new version of ProFert in the same way as product values. Where site specific harvesting and haulage costs available, these can be stored in external data workbook together with growth data and product values and referenced during the Load Data procedure. Otherwise, the user must enter costs manually into the sheets titled '*Harv. Costs*' and '*Haul. Costs*'. These generic costs are then applied to all stands being modelled by ProFert.

ProFert can accept up to four thinning operations during a rotation. Since harvesting costs often vary with thinning operation, ProFert was modified to select the appropriate cost for each operation. Where site specific harvest costs are used, these are automatically allocated to the appropriate thinning or clearfell operation. Where generic costs are used, costs are allocated to specific harvest operations using data input by the user with the names of thinning operations on the *Harv. Cost* sheet matching those on the *Main Sheet* (e.g. Thin1, Thin2, Thin3 etc., Figure 44). In this case, if a stand has already had one or more thinnings, or a thinning operation is skipped for some reason, these thinnings must be left blank on the Main Sheet and information for future thinnings entered under the next thinning operation.

As with harvest costs, haulage costs can either be entered automatically into ProFert, where these are provided by the growth and yield system and stored in external workbooks together with stand growth, product recoveries and harvest cost data. Otherwise, haulage costs must be entered manually into the *Haul. Costs* sheet (Figure 45).



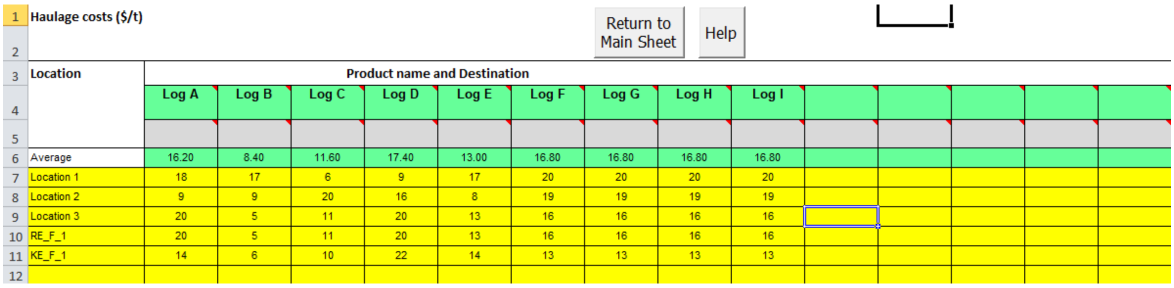
Harvest Costs ($/m3)

Operation	Cost	Unit
THIN1	40	$/m3
THIN2	40	$/m3
THIN3	30	$/m3
THIN4	20	$/m3
CFELL	10	$/m3
NON-COMMERCIAL		$/ha

Organisation: TPPL - Green Triangle

Stand Information										Discount Rate	Second Thinning (Thin2)					Third Thinning (Thin3)				
Site ID	Data File	Location	Site Quality	Current Age	Current Stocking	Assessed volume: Age Assessed	Assessed volume: Volume standing	Assessed volume: Volume harvested	Clearfell Age		Age	Residual stocking	Residual volume		Commercial	Age	Residual stocking	Residual volume		Commercial
				year	stems	year	m³/h	m³/h	year	%	yea	stems	m3/t	%	Yes/N	yea	stems	m3/t	%	Yes/N
Picks	Default	ASCOT PARK	3.6	21	413				27	10						21				
Byjuke Nth	Default	ASCOT PARK	4.4	20	346				26	10						21	250		60	
Springs	Default	ASCOT PARK	3.1	15	571				21	10	18	300		70	Both	25			60	
Glencoe	Default	ASCOT PARK	5.4	29	299				35	10										
Miles	Default	ASCOT PARK	1.1	18	421				24	10	19	300		70	Both	25	250		60	

Figure 44: Table for harvesting costs for thinnings, clearfell and non-commercial operations (top) and relationships between these and harvest operations on the *Main Sheet* (bottom).



Haulage costs ($/t)

Location	Product name and Destination													
	Log A	Log B	Log C	Log D	Log E	Log F	Log G	Log H	Log I					
Average	16.20	8.40	11.60	17.40	13.00	16.80	16.80	16.80	16.80					
Location 1	18	17	6	9	17	20	20	20	20					
Location 2	9	9	20	16	8	19	19	19	19					
Location 3	20	5	11	20	13	16	16	16	16					
RE_F_1	20	5	11	20	13	16	16	16	16					
KE_F_1	14	6	10	22	14	13	13	13	13					

Figure 45: Haulage cost table showing product names, locations and costs in $/t for each product and destination combination.

In the latter case, haulage costs are assumed to be uniform for different harvest operations and to vary only with site location and product destination. Haulage costs must be entered for each product included in the product recovery data (Figure 45). The number of site locations that can be entered is unlimited, but, for a given location, only one cost may be entered per product. Names for products are automatically linked to the names in the sheet *Prod. Values* and transport costs are in the 4th row down (the units ($/t) are assumed to be equivalent to $/m^3). The first row of the list of locations, titled *Average*, is used by ProFert where the user wishes to use an average Haulage cost for particular site(s). Locations entered in the *Haul. Cost* sheet appear in a drop-down selection for each site on the Main Sheet.

Calculating the net value of harvested and standing trees

The net value of each product harvested (termed its stumpage value) is equal to its gross value (termed its mill door value) minus the cost of harvesting and transporting it to its destination. In ProFert, it is calculated as:

$$N_{pol} = G_p - H_o - T_{pl}$$

where:

- N_{pol} is the net value of product p, harvested during operation o from location l;
- G_p is the gross value of product p;
- H_o is the harvesting cost for harvesting operation o; and
- T_{lp} is the transport cost for product p from location l.

The total value of trees harvested from a particular stand during a particular operation is calculated from the volumes and net values of all logs harvested:

$$Nh_{os} = \sum_{p=1}^{n} Vh_{po} \times N_{pol}$$

where:

- Nh_{ol} is the net value of all products harvested during operation o from stand s;
- Vh_{pos} is the volume of each product p harvested during operation o from stand s; and
- N_{pol} is the net value of each product p harvested during operation o at location l.

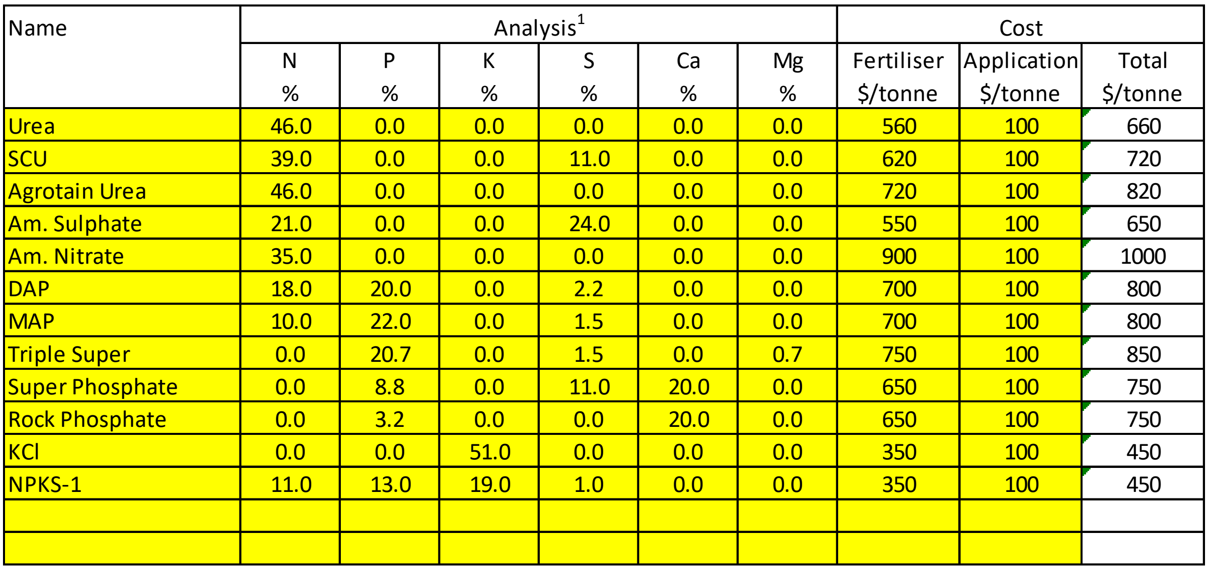
The value of standing trees is calculated in the same way as for harvested trees. However, the theoretical harvesting cost (which is subtracted from the gross value to give the stumpage value) is interpolated between the costs of the previous and next future harvest, based on the stand age. For example, if the stand's current age is 24 years and the last harvest was at age 22 years costing \$20 per m^3 and the next harvest will be at 30 years costing \$10 per m^3, the assumed current harvesting cost for the standing trees is \$17.50.

Calculating Overall Profitability

Fertiliser cost

The costs of purchasing and applying fertiliser are entered by the user into the table in the sheet *Fert. costs* (Table 3). This table includes the % concentration of each nutrient, the purchase price and the estimated application cost of each fertiliser type being considered. The fertiliser types entered in the *Fert. Cost* sheet appear in a drop-down list in the *Main Sheet* where the user selects the fertiliser rates and types that are applied to each site.

Table 3: Fertiliser nutrient analyses and costs on sheet 'Fert. costs'.



Name	Analysis[1]						Cost		
	N %	P %	K %	S %	Ca %	Mg %	Fertiliser $/tonne	Application $/tonne	Total $/tonne
Urea	46.0	0.0	0.0	0.0	0.0	0.0	560	100	660
SCU	39.0	0.0	0.0	11.0	0.0	0.0	620	100	720
Agrotain Urea	46.0	0.0	0.0	0.0	0.0	0.0	720	100	820
Am. Sulphate	21.0	0.0	0.0	24.0	0.0	0.0	550	100	650
Am. Nitrate	35.0	0.0	0.0	0.0	0.0	0.0	900	100	1000
DAP	18.0	20.0	0.0	2.2	0.0	0.0	700	100	800
MAP	10.0	22.0	0.0	1.5	0.0	0.0	700	100	800
Triple Super	0.0	20.7	0.0	1.5	0.0	0.7	750	100	850
Super Phosphate	0.0	8.8	0.0	11.0	20.0	0.0	650	100	750
Rock Phosphate	0.0	3.2	0.0	0.0	20.0	0.0	650	100	750
KCl	0.0	0.0	51.0	0.0	0.0	0.0	350	100	450
NPKS-1	11.0	13.0	19.0	1.0	0.0	0.0	350	100	450

Calculating profitability and cost/benefit of fertiliser use

The financial benefits arising from the increased production of wood associated with fertiliser use can be assessed in a number of ways. ProFert provide three measures that can be used by managers to compare the profitability of fertilising different stands or using different fertiliser regimes. These are:

- Net Present Value (NPV);
- Internal Rate of Return (IRR); and
- Amount of additional wood produced per $100 spent on fertiliser.

Usually, NPV is used to estimate the profitability of investment decisions. This measure calculates the total revenues from the additional wood harvested minus the total costs of fertiliser in terms of their current dollar value. The current value is determined by applying an appropriate discount rate which represents the minimum acceptable return on an investment.

An alternative measure of profitability is IRR. This is the rate of return achieved, in terms of the value of additional wood harvested, from the money invested, in terms of the cost of fertilising a stand one or more times in the future. It is calculated as the discount rate at which the effective NPV is zero. One advantage of using IRR is that it does not require the sometimes arbitrary setting of a discount rate. However, it measures the relative increase rather than the absolute increase in value and so a small increase in productivity is achieved from a small investment may have a higher IRR than a larger growth response which requires a larger investment.

In some situations, overall profitability may be less important than the increase in wood production, especially where land is expensive or there is a need to boost wood production to meet future supply contracts. Fertilising stands can represent a useful means to increase future harvest volumes relatively quickly (i.e. 5-10 years rather than 20-30 years if new land was planted). In these situations, the amount of additional wood produced per dollar spent on fertiliser (here termed unit wood production and measured as m^3/\$100) may be a more useful measure than NPV or IRR. For this calculation, ProFert divides the total increase in wood production by the total discounted cost of fertiliser (using the same discount rate as for NPV).

Optimizing fertiliser regime

Rationale

In many cases, the optimum fertiliser types and rates may be known by the forest manager. However, in other situations, complex interactions between stand nutrient status, fertiliser type and year of application mean that the most profitable fertiliser regime may be difficult to determine. Therefore, ProFert includes a built-in optimizer which evaluates a range of different fertiliser types and rates specified by the user and selects the optimum fertiliser regime for selected sites (Figure 46).

To run the optimizer, the user must first input all stand variables, predictors, the harvesting regime and proposed years for fertiliser application and types of fertiliser to consider. The optimizer then calculates the NPVs and unit wood production (m^3/\$100) for all possible combinations of types and rates of fertiliser for each year of application. The user can prompt the optimizer to select the fertiliser regime that maximizes NPV or which maximizes unit wood production for the stand.

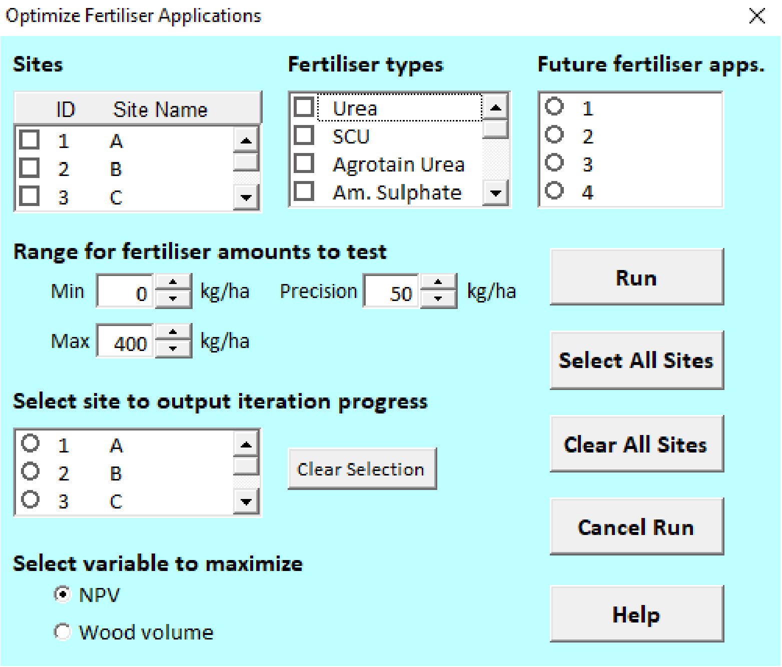
Input screen

The input for the optimizer includes:

- the sites to optimize;
- fertiliser types to select from;
- maximum number of potential future applications;
- maximum and minimum rates to test;
- degree of precision in rate in kg/ha to use; and
- the variable to optimize (NPV or unit wood production).

The choices of fertiliser types, maximum rates and maximum number of future applications are very important because they have a large impact on the time taken to complete the optimization as well as the accuracy of the result. This is because ProFert tests all combinations of the variables by increasing the rate of each fertiliser type until there is a decrease in the value of the selected indicator. As a result, each additional factor has an exponential effect on the number of iterations required.

In addition to simply outputting the optimal fertiliser regime, the user can choose to output the results of all iterations for a single site. The output includes both charts and a table of results including increases in wood production, NPV, unit wood production and IRR. This output can be useful in confirming that the optimiser is providing sensible results and for allowing the user to identify alternative fertiliser combinations which might provide similar benefits to the one selected.


Optimize Fertiliser Applications

Sites

	ID	Site Name
☐	1	A
☐	2	B
☐	3	C

Fertiliser types

☐ Urea
☐ SCU
☐ Agrotain Urea
☐ Am. Sulphate

Future fertiliser apps.

○ 1
○ 2
○ 3
○ 4

Range for fertiliser amounts to test

Min 0 kg/ha
Precision 50 kg/ha
Max 400 kg/ha

Select site to output iteration progress

○ 1 A
○ 2 B
○ 3 C

Select variable to maximize

● NPV
○ Wood volume

Figure 46: Optimizer panel

Optimization process

The optimization process is divided into two steps. The first step involves testing every combination of fertiliser types and rates at a coarse scale. In this process, the rate of each fertiliser type is increased by an amount four times the final precision selected by the user. Up to two different fertiliser types are tested for each future application with the rate of one increased until there is a decrease in in the variable being optimized. The fertiliser regime with the maximum NPV or m^3/\$100 is then selected for finer scale testing in the second step.

In the second step, fertiliser amounts are increased at a rate less than or equal to the degree of selected precision. As with the first step, this process continues until an increase in fertiliser rate results in a decrease in the variable being optimized. The rates and types of fertiliser with the optimum NPV are then selected and printed on the *Main Sheet* together with the predicted outcome of the fertiliser regime.

Detailed outputs from the optimization of the fertiliser regime for a single stand are illustrated in the chart in Figure 47 and tables in Figure 48. The chart shows the results for 1100 different fertiliser combinations and rates tested for a single site. The first 900 iterations show the results for the first (coarse precision) step, while the final 200 iterations show the results for the second (fine tuning) step. The tables include a summary at the top with the optimum fertiliser regime and predicted additional volume and profitability for the selected site. Below this is another table with the results of all individual iterations which can be filtered to display those with the highest profitability or m^3/\$100. These results can readily be filtered to display those of interest using Excel's filter icon at the top of each column.

Some sites may have limitations of three or more nutrients, which can make the optimization process used by ProFert very slow. Therefore, the optimization process was modified to include the option for the user to input one fertiliser type and rate for each application which remains fixed during the optimization process. This fertiliser data is put by the user under "Type C' in the proposed fertiliser regimes on the *Main sheet*. The optimizer reads this information and uses it in the response calculations, but cannot change the values. This option allows the user to optimize the fertiliser regime automatically while ensuring that core nutrient deficiencies such as S or K deficiency are addressed.

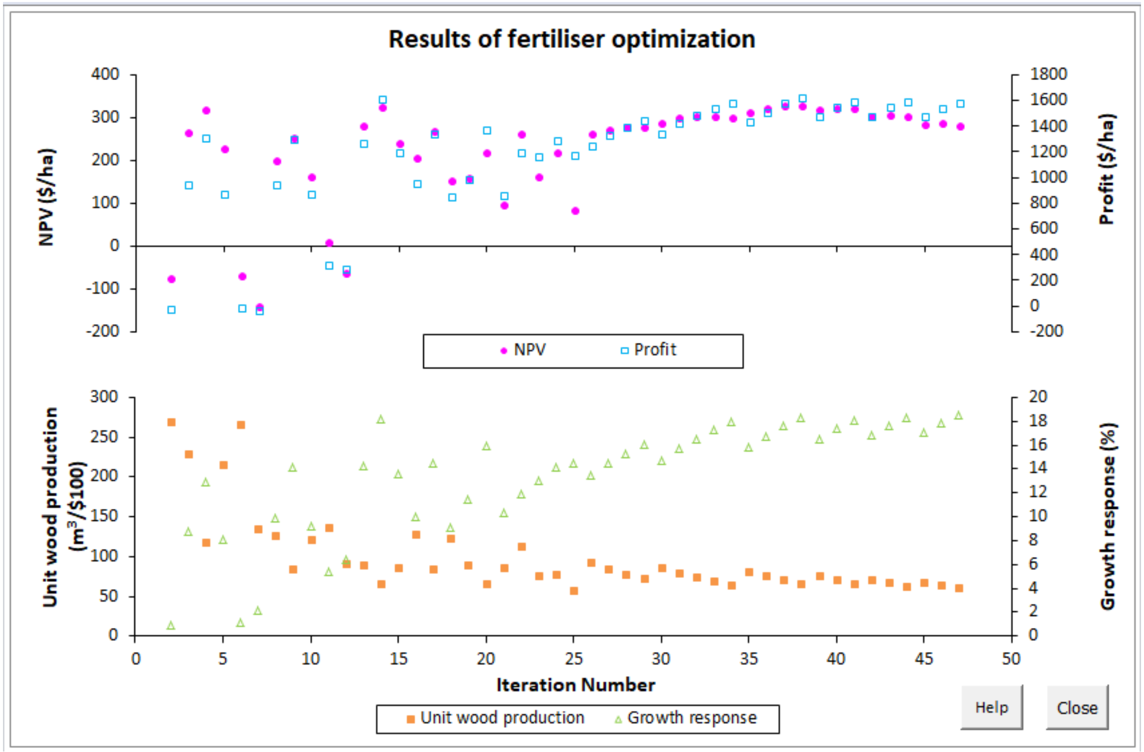
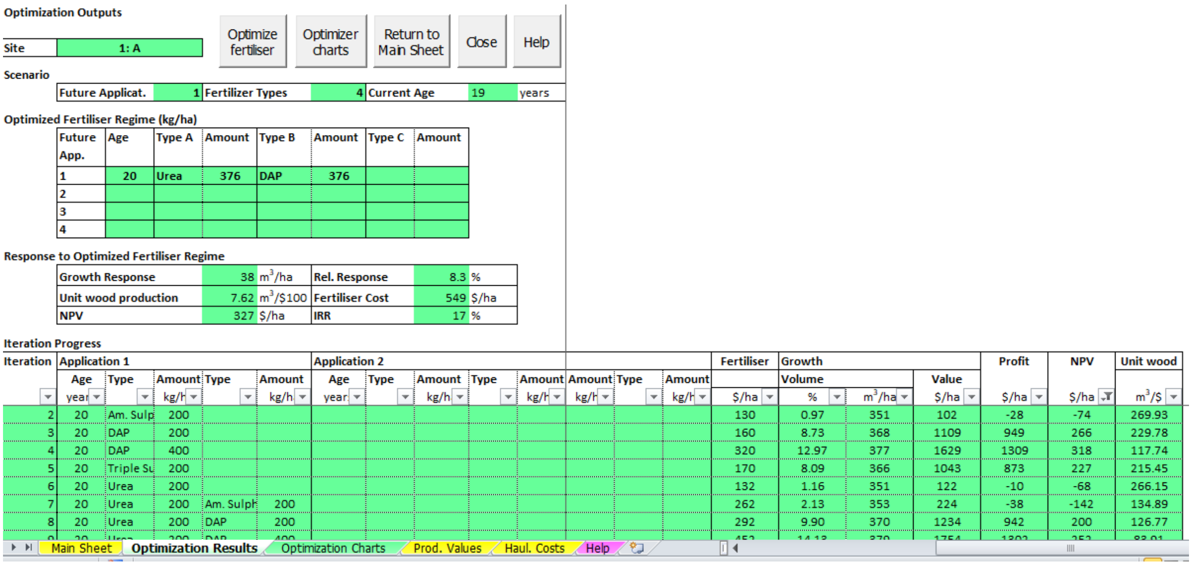


Figure 47: Output chart for the results of all iterations from the optimization of the fertiliser regime for a selected site.



Optimization Outputs

Site	**1: A**

Scenario

Future Applicat.	1	**Fertilizer Types**	4	**Current Age**	19	years

Optimized Fertiliser Regime (kg/ha)

Future App.	Age	Type A	Amount	Type B	Amount	Type C	Amount
1	20	Urea	376	DAP	376		
2							
3							
4							

Response to Optimized Fertiliser Regime

Growth Response	38	m^3/ha	**Rel. Response**	8.3	%
Unit wood production	7.62	m^3/$100	**Fertiliser Cost**	549	$/ha
NPV	327	$/ha	**IRR**	17	%

Iteration Progress

Iteration	Application 1					Application 2								Fertiliser	Growth			Profit	NPV	Unit wood
	Age	Type	Amount	Type	Amount	Age	Type	Amount	Type	Amount	Amount	Type	Amount		Volume		Value			
	year		kg/h		kg/h	year		kg/h		kg/h	kg/h		kg/h	$/ha	%	m^3/ha	$/ha	$/ha	$/ha	m^3/$
2	20	Am. Sulp	200											130	0.97	351	102	-28	-74	269.93
3	20	DAP	200											160	8.73	368	1109	949	266	229.78
4	20	DAP	400											320	12.97	377	1629	1309	318	117.74
5	20	Triple Su	200											170	8.09	366	1043	873	227	215.45
6	20	Urea	200											132	1.16	351	122	-10	-68	266.15
7	20	Urea	200	Am. Sulph	200									262	2.13	353	224	-38	-142	134.89
8	20	Urea	200	DAP	200									292	9.90	370	1234	942	200	126.77

Figure 48: Output of results from optimizer for single site showing the optimum fertiliser regime together with the predicted additional growth and profitability at the top and results for most profitable alternative fertiliser regimes at the bottom.

Results

Validation of model predictions

Process used

Validation of models is normally performed using independent datasets which can be used to compare the model's predictions with actual measurements. In the case of the current project only a subset of the data (i.e. those stands not limited by secondary nutrient deficiencies) was used in the development of the relationships. Furthermore, this subset included only core treatments (i.e. N, P and N+P applied once at rates of 200 kg N/ha and 80 kg P/ha) and excluded the dozens of other treatments applied across the stands in the Green Triangle. Therefore, the predictions from the model were validated using the full range of treatments applied across the Green Triangle. In addition, results from two additional sites from Victoria (one fertilised twice) were tested. These tests included the comparing actual verses predicted increases in volume and profitability as well as relative growth response to both core treatments (which were used to develop the response curves used in the model) as well as additional treatments applied across the sites. The validation datasets included:

- 10 sites in the Green Triangle fertilized with N, P and N+P once in 1995/96 and again in 2002 in a multifactorial treatment x year of application design;
- 6 sites in the Green Triangle fertilised with different rates and forms of N and P fertiliser from 2000 to 2003; and
- 2 operational trials in Victoria Fertilised with N and N+K fertiliser in 2005, with one fertilised again with NPK in 2011.

Green Triangle Comparisons

The model was first calibrated using results from 16 sites in the Green Triangle. The treatments applied across the sites included the following:

1. Core treatments: N, P and N+P fertiliser across 16 stands (10 of which were fertilised once in 1995-96 and again in 2002) with 200 kg N/ha (as urea or ammonium nitrate), 80 kg P/ha as triple super phosphate or both N and P across 16 sites (78 site x treatment combinations after excluding core treatments with 4-6 replicates);
2. Repeat treatments: N, P and N+P fertiliser across 10 sites, 6 years after the first application, with 200 kg N/ha as ammonium nitrate and 80 kg P as triple super phosphate applied in a multifactorial design across unfertilised plots and plots previously fertilised with N, P, N+P (120 site x treatment combinations, excluding core treatments, with 1 replicate);
3. N form x season of application: 200 kg N/ha as urea, ammonium nitrate and ammonium sulphate in summer, autumn and winter at one site and spring only at another site (21 site x treatment combinations with 4 replicates);
4. N Rate x form: 100, 200 and 400 kg N/ha as urea or ammonium nitrate across two sites (28 site x treatment combinations with 4 replicates); and
5. P Rate x form: 40, 80 and 160 kg N/ha as urea or ammonium nitrate across 3 sites (33 site x treatment combinations with 4 replicates).

Some of these data from the core treatments were used to develop the relationships used to predict response to N and P fertilisers. Therefore this cannot be considered a true validation. However, it provides a useful comparison of the accuracy of the model in predicting not only the relative responses to fertiliser, but also the absolute increases in wood volume and profitability. Results from the other four datasets were not used in the response relationships although they were from the same sites as the core treatments. Therefore they can be considered to be partially independent.

Measurement periods for the experiments varied from 3 to 6 years after fertiliser application. Inputs for ProFert included foliar N, P, K and S concentrations, stand age, standing volume and estimated harvested volume for control plots prior to treatment. The predictions of ProFert were initially tested using the core treatments from the sites to check the calibration of the model. Next the model was tested using the additional treatments across the sites. Finally, predictions were compared with measured growth and profitability for the repeat treatment combinations applied post third thinning to test the accuracy of the model accounting for a wide range of initial foliar N and P concentrations arising from previous fertiliser treatments.

Measured relative (%) and absolute (m^3) increases in growth of fertilised plots compared with controls were compared with model predictions. In addition, actual responses to fertiliser were input into ProFert to estimate the increase in the value of harvested products and overall profitability (NPV). These estimates were compared with predicted NPV's for the sites at the end of the experiment (i.e. 3-6 years after fertiliser application). In addition, total growth and profitability at the end of the rotation was estimated by using ProFert to grow the stands on to the scheduled clearfell age using the actual measured responses and growth of controls by the end of the experiment. Future growth of controls was estimated by estimating the site quality of each treatment from the measured growth and assuming that future growth would continue on that site quality trajectory.

Results for Green triangle comparisons

Core treatments

ProFert was able to explain 74% of variation in relative responses to core fertiliser treatments applied across the 16 sites (Figure 49). The overall predictions for relative response were unbiased with the relationship between predicted and actual responses having a slope of (1.04) close to 1 and the intercept (0.9) close to 0. Furthermore, predictions for responses to individual fertiliser treatments (N, P or N+P) were relatively accurate (with R^2 values ranging from 0.34 for P to 0.65 for N+P) with no evidence of bias (slopes ranging from 0.88 for P to 1.04 for N). Predictions were poorest for P alone due to the low responsiveness of most stands to this treatment.

Predictions for the absolute increase in volume due to fertiliser were reasonable. The relationship with between predicted and actual increases in wood volume had an R^2 of 0.60, a slope of 0.78 and intercept of 2.3 (Figure 50). The relationship was weaker than that for the relative response as a result of uncertainty regarding the growth rate of the controls (which was estimated from the current standing volume, records of volume removed and assumptions regarding removals at earlier thinnings). A plot of predicted verses actual volume growth of the controls explained only 73% of variation and indicated that growth over the measurement period was less than predicted for most sites (Figure 51). Nominal site quality estimated at age 10 was an even poorer predictor of growth over the measurement period explaining only 47% of variation and overestimating actual growth by an average 10%.

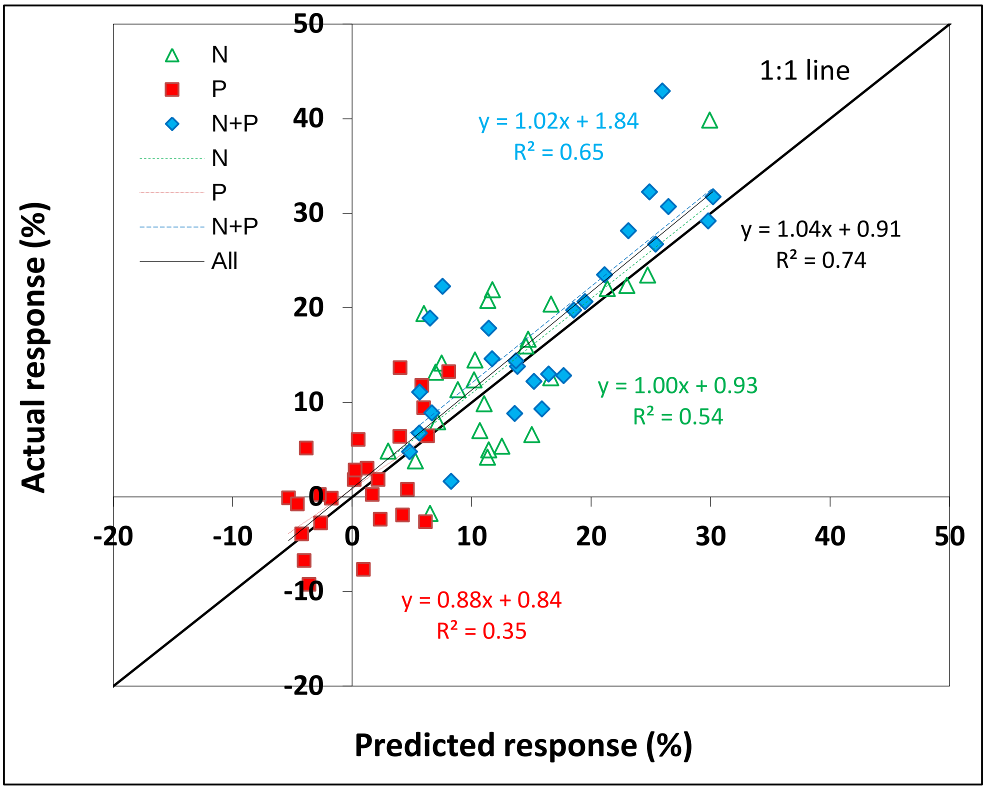


Figure 49: Relationship between actual and predicted relative (%) growth response to core N, P and N+P fertiliser treatments across the 16 Green Triangle sites.

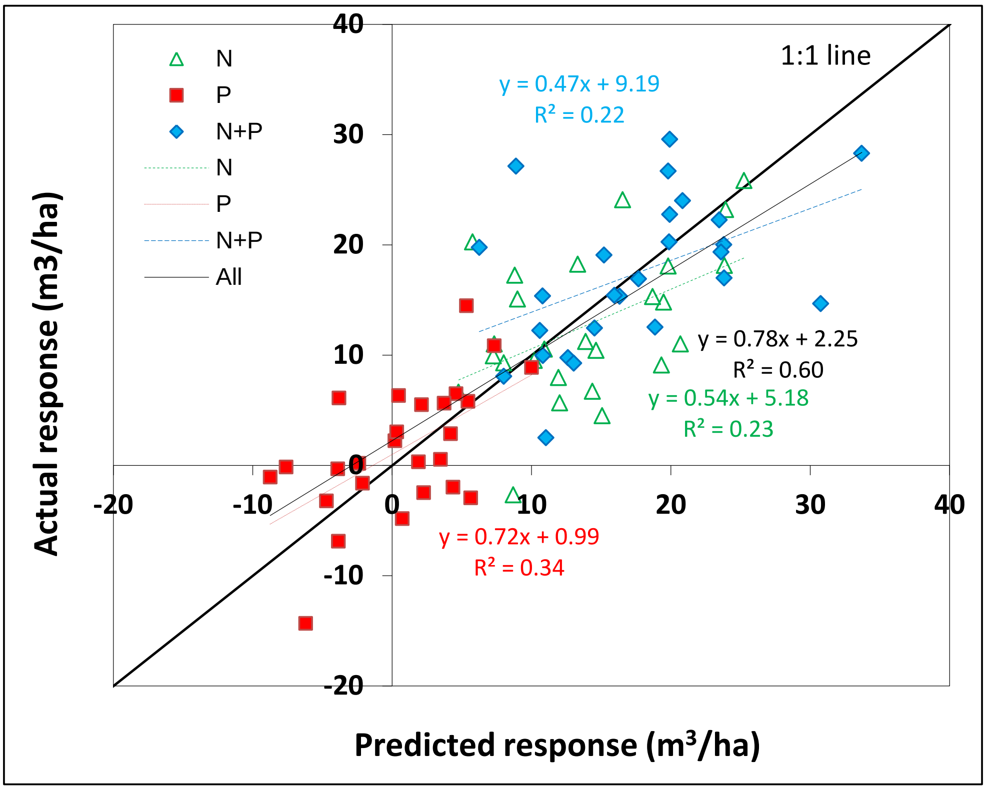


Figure 50: Relationship between actual and predicted absolute (m^3/ha) growth response to core N, P and N+P fertiliser treatments across the 16 Green Triangle sites.

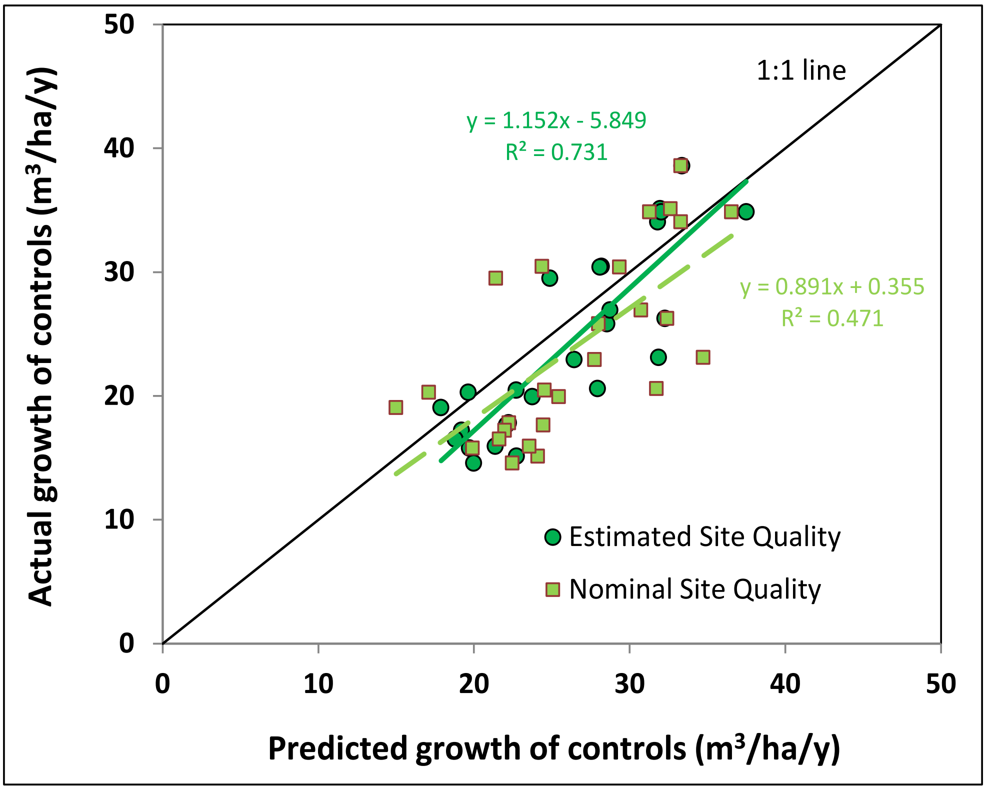


Figure 51: Relationship between actual and predicted growth of controls across the 16 Green Triangle sites over the period of the fertiliser experiments.

ProFert explained 39% of variation in estimated NPV of the fertiliser treatments (Figure 52). Although the slope of the relationship was 0.64, there was no significant difference between this and the 1:1 line, or between the intercept and zero, indicating that the relationship was unbiased. The reason for the lower accuracy in the predicted profitability by the end of the experiment was a combination of the lower than expected volume growth of the stands (resulting in a smaller increase in stand value in response to fertiliser) and the very short time frame (3-6 years) over which the stand was grown, resulting in NPV being highly sensitive to small variations in estimated value. A more robust estimate of the overall profitability is that at the end of the rotation. The predicted NPV from ProFert at the time of final harvest explained 61% of variation in estimated actual NPV with a slope of 0.82 (Figure 53).

The difference between actual and predicted growth was partly due to the relatively short time frame (3-6 years) over which growth was measured combined with variation in rainfall and other environmental factors. Rainfall was well below average for the region during the measurement period and defoliation associated with a newly introduced insect pest (the Monterey pine aphid) reduced growth at most sites between 2001 and 2003 (May *et al.* 2003). Over a longer time period, variation associated with these factors is expected to be less important and actual growth should be closer to that predicted from the site quality curves.

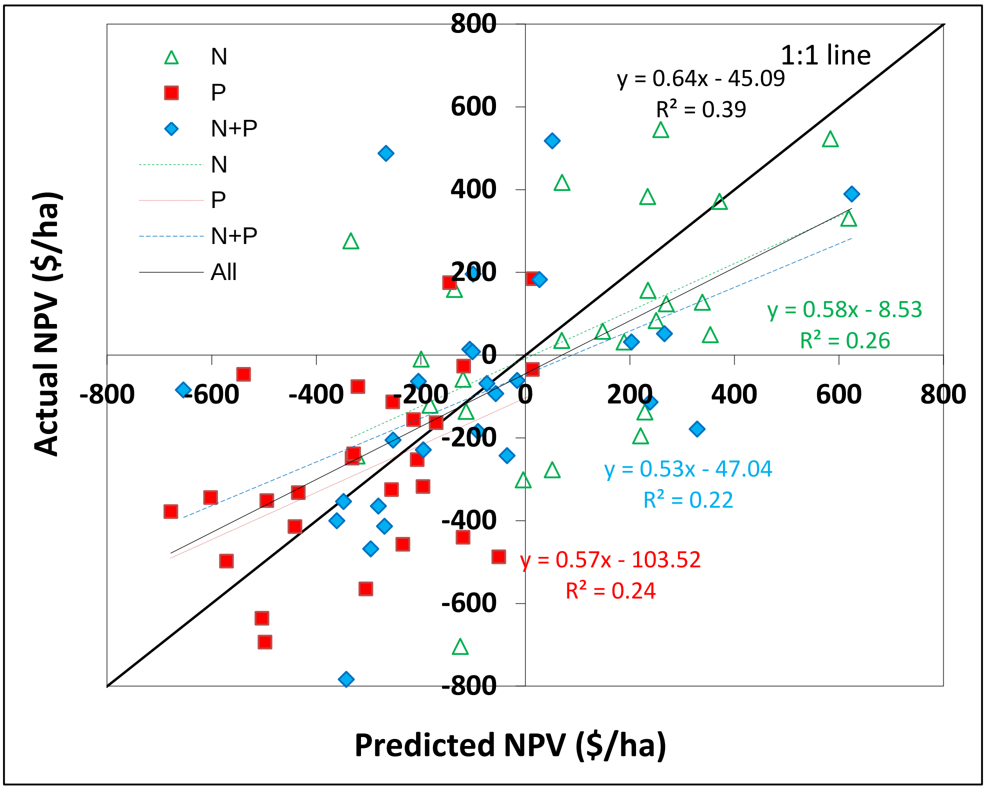


Figure 52: Relationship between actual and predicted NPV (i.e. the discounted estimated stumpage of standing trees minus fertiliser cost) across the 16 Green Triangle sites over 3-6 years after fertiliser was applied.

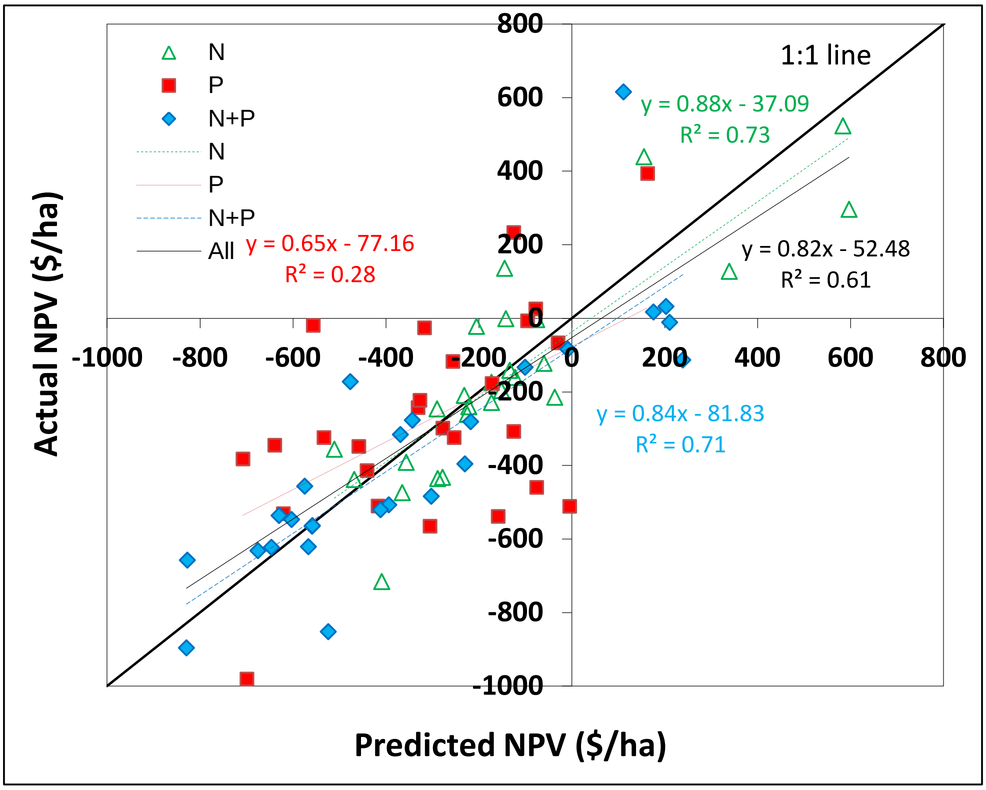


Figure 53: Relationship between estimated actual and predicted NPV (i.e. the discounted estimated stumpage of standing trees minus fertiliser cost) across the 16 Green Triangle sites over four years after fertiliser applied.

The capacity of ProFert to identify the optimum fertiliser treatment for a given stand was also assessed. NPV's of the predicted optimum core (N, P or N+P) treatment were compared with actual NPV's of those treatments at the expected age for clearfell for each of the 26 stands fertilised with one of the three core treatments. Out of the 26 stands included in the analysis, ProFert correctly identified the most profitable treatment for 20 (70%). All the treatments predicted to be profitable had positive NPV's by the end of the rotation, while NPV's of those treatments predicted to be unprofitable were zero or negative (Figure 54). Altogether, ProFert explained 47% of variation in actual NPV for optimum fertiliser treatments across the 26 sites and the predictions were unbiased with no significant difference between the line of best fit and the 1:1 line.

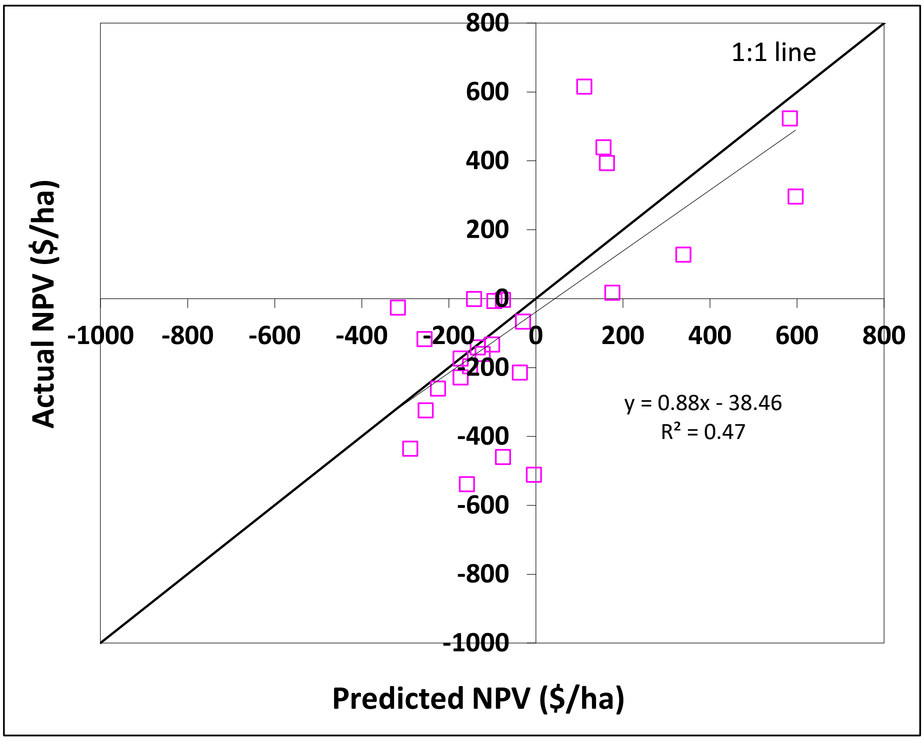


Figure 54: Relationship between actual and predicted NPV for predicted optimum fertiliser treatment for maximizing NPV each of the 26 stands in the Green Triangle.

Additional treatments

ProFert was able to accurately predict responses and profitability of an independent set of treatments from the Green Triangle sites not included in the development and calibration of the relationships. Predictions from ProFert explained 58% of the variation in relative (%) responses and 61% of variation in absolute (m^3/ha) responses to various fertiliser treatments across the seven sites included in the analysis (Figure 55, Figure 56). Furthermore the relationships were unbiased with slopes and intercepts very close to a 1:1 line.

ProFert was also able to explain most of the variation in estimated profitability of the fertiliser treatments (Figure 57). NPV predicted by the model explained 67% of the estimated actual NPV of the various treatments at the expected time of final harvest and there was no significant bias with the slope of the relationship being 0.93 and the intercept -$33.

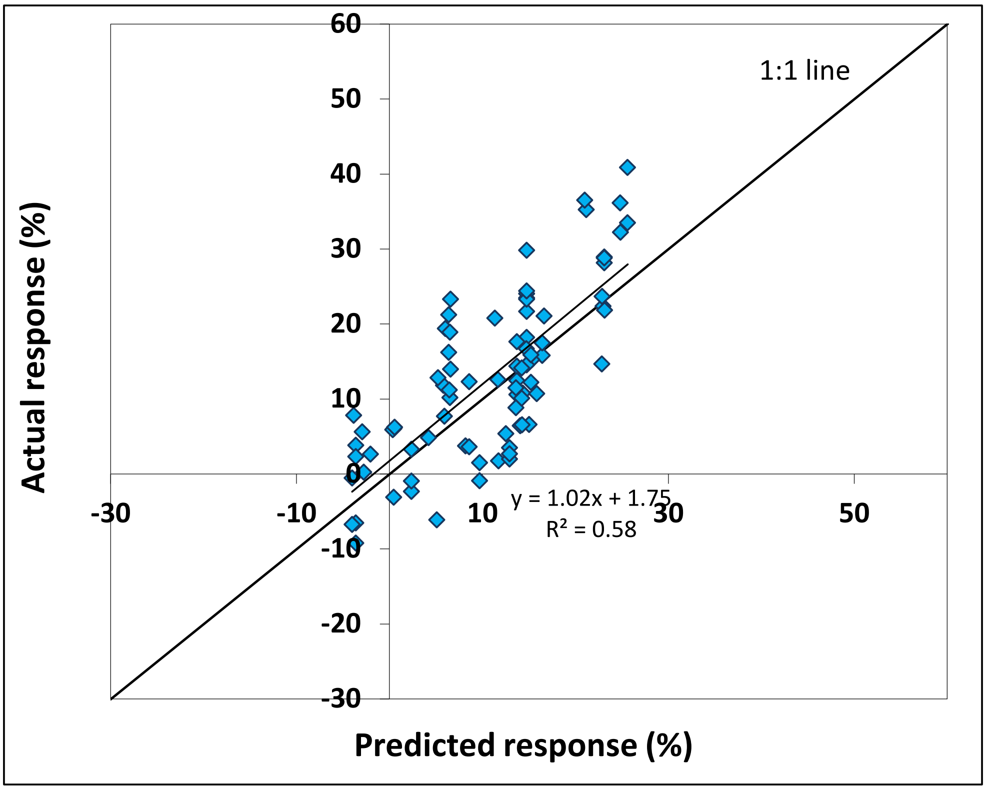


Figure 55: Relationship between actual and predicted relative (%) response to additional fertiliser treatments applied across 7 sites in the Green Triangle.

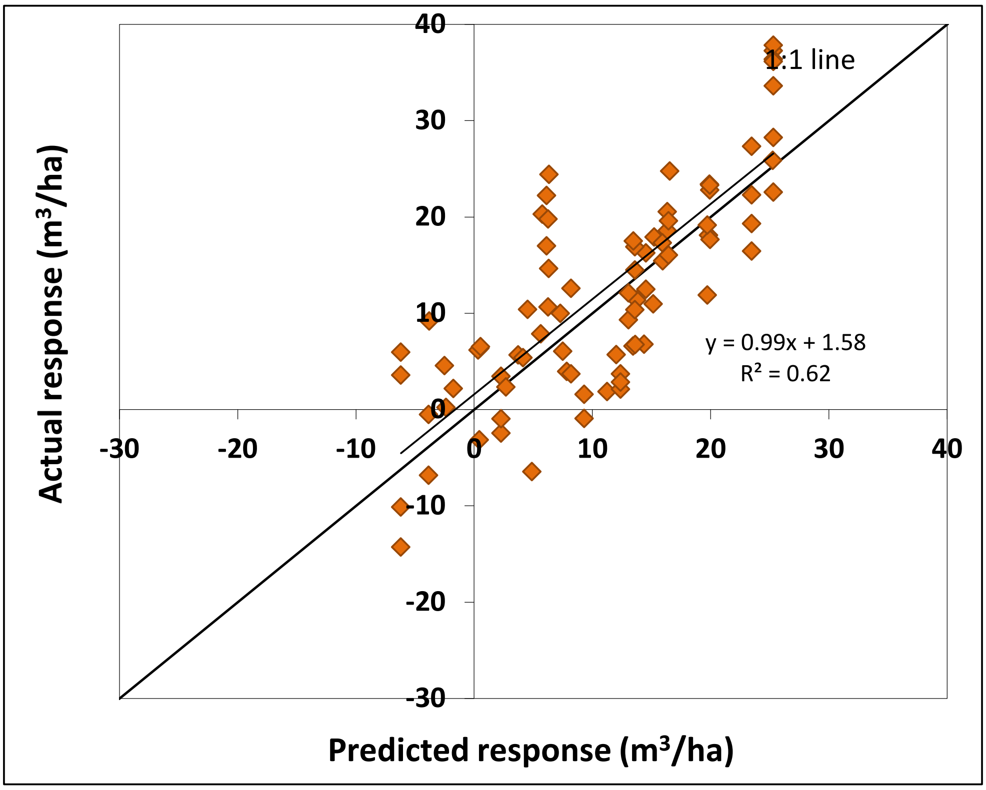


Figure 56: Relationship between actual and predicted increases in wood volume in response to additional fertiliser treatments applied across 7 sites in the Green Triangle.

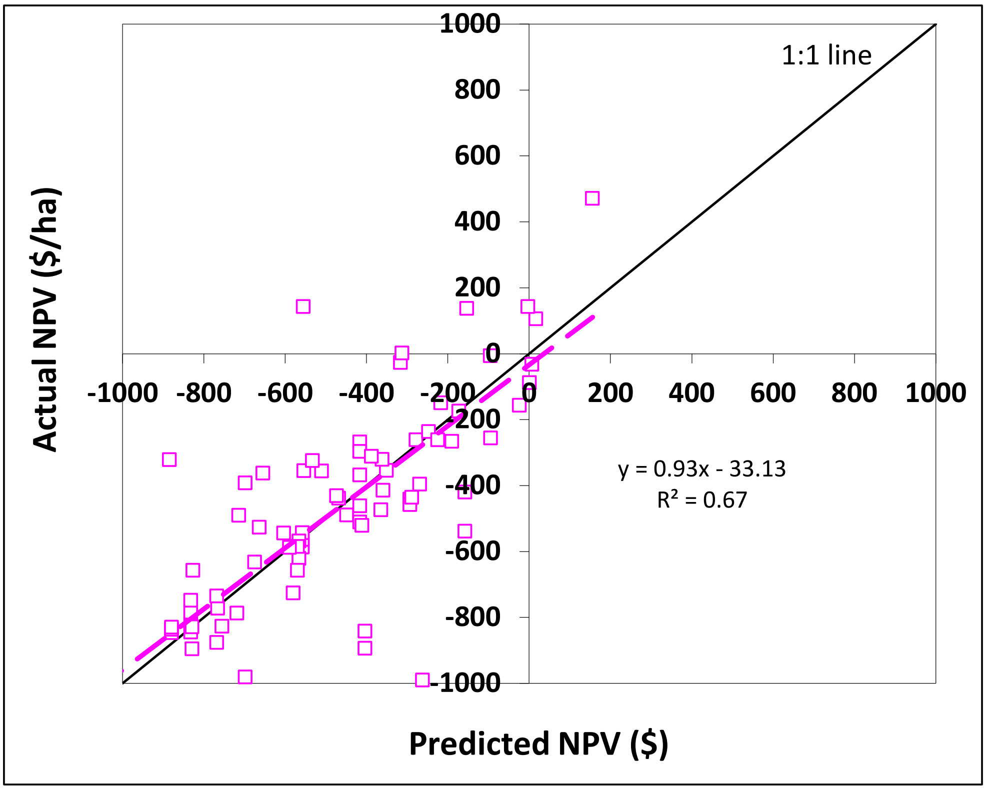


Figure 57: Relationship between estimated actual and predicted NPV of fertiliser treatments at the expected time of clearfell across 7 sites in the Green Triangle.

Repeat fertiliser applications

Across the multifactorial NxPxTime treatments in which N, P or N+P fertiliser were applied after 2nd thinning, 3rd thinning or both, ProFert explained 42% of variation in relative response and 30% of variation in absolute response (Figure 58, Figure 59). The variability in actual compared with predicted responses was relatively high as a result of the each treatment having only one replicate which increased the underlying variability in the data. Despite this variability, there was no evidence of significant bias in the predictions with the slope of the relationships equal to or close to 1:1 and intercepts close to zero.

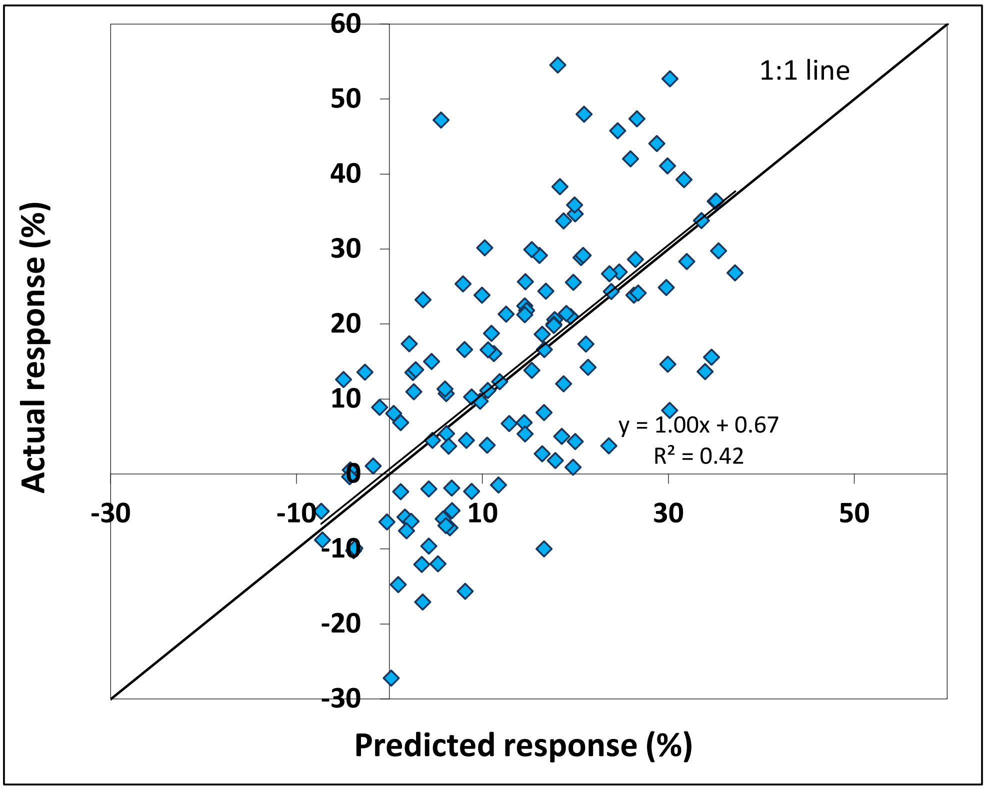


Figure 58: Relationship between actual relative (%) response to fertiliser and that predicted by ProFert across different combinations of fertiliser treatments applied to 10 sites in the Green Triangle at 2nd and third thinning.

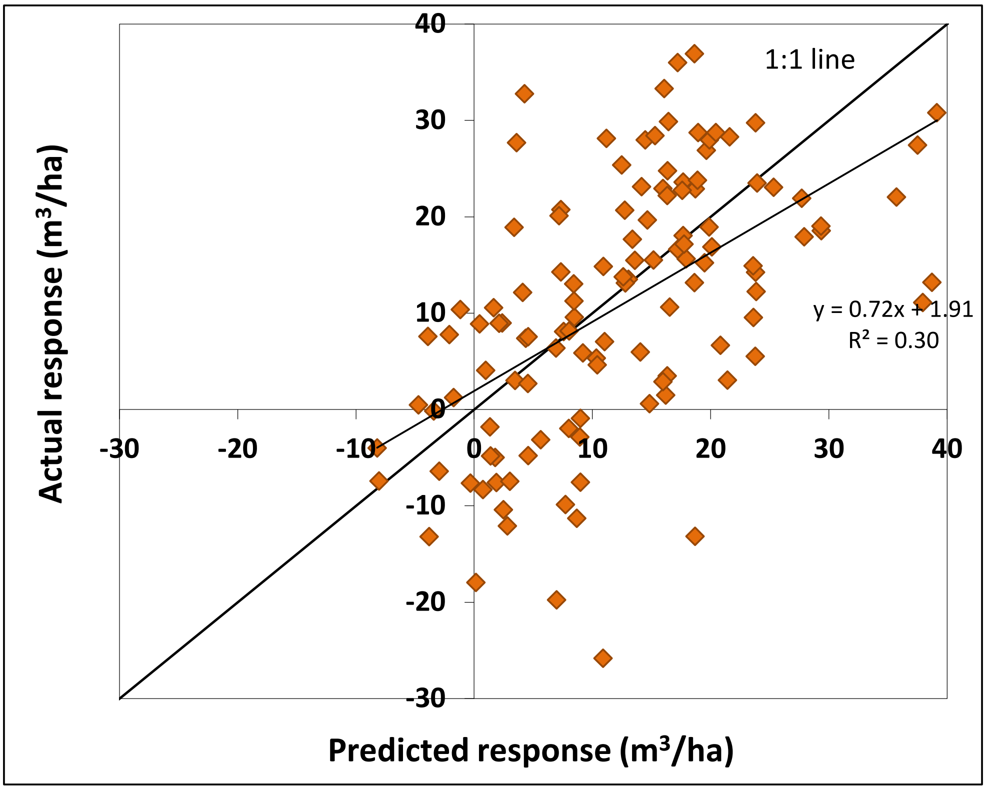


Figure 59: Relationship between actual absolute (m^3/ha) response to fertiliser and that predicted by ProFert across different combinations of repeat fertiliser treatments applied to 10 sites in the Green Triangle at 2nd and third thinning.

Data from Victoria

HVP provided data for operational fertiliser trials at additional two sites in Victoria where a range of fertiliser treatments were applied (Hopmans and Elms, 2014). These trials consisted of plots established in fertilised and unfertilised strips within thinned plantations aged 15 and 20 years.

One site (Flynn) was fertilised with N alone (200 kg N/ha as urea) and N+K (200 kg N/ha and 100 kg K/ha) in 2005. Six years later, NPK fertiliser (70 kg N/ha, 80 kg P/ha and 120 kg K/ha) was applied to half the fertilised strip and half of the unfertilised strip. A second site (Longford) was fertilised with N+K (200 kg N/ha and 100 kg K/ha) in 2005. Foliar N, P, K and S concentrations were measured on both controls and fertilised plots prior to initial treatment at both sites in 2005 and prior to the second application at Flynn in 2011. Initial volume and subsequent growth of both controls and fertilised plots was reported for the periods 2005-2011 (6 year response to initial treatment) and 2011-2014 (3 year response to second treatment at Flynn). Volume increments for both controls and treated plots were corrected for variation in initial plot volume (which accounted for up to 80% of variation in growth) using an analysis of covariance and relative (%) response to fertiliser calculated.

ProFert was able to explain 73% of variation in relative response to fertiliser based on foliar nutrient concentrations. The predictions were unbiased with no significant difference between the relationship between actual and predicted responses and a 1:1 line ($P > 0.05$).

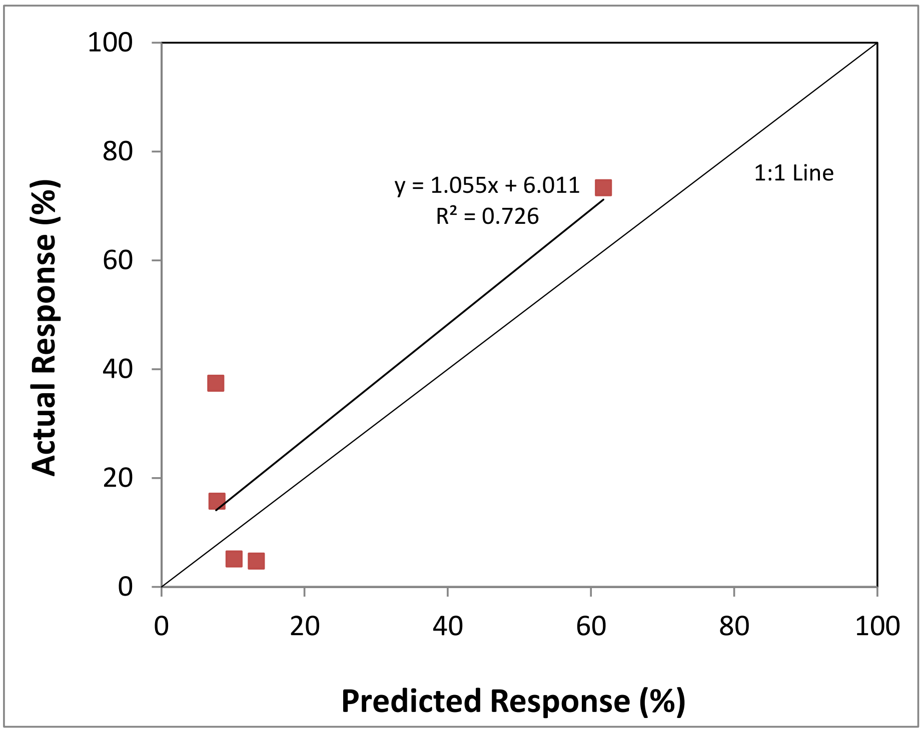


Figure 60: Relationship between actual and predicted relative (%) response to different combinations of N and P fertiliser applied after 1st thinning across 7 sites in Tasmania.

Comparison of ProFert with alternative models

Method used

To assess the benefits of using ProFert compared with other approaches, responses to fertiliser were compared for sites and fertiliser treatments selected using a range of criteria. The 16 stands from the Green Triangle were used for this comparison. Total increase in wood volumes, NPV and IRR at the end of the rotation were estimated for each site and treatment combination using actual measurements from each site to estimate growth at the end of the rotation using the approach explained in *Validation of model predictions.*

Approaches used to select sites and fertiliser treatments included:

- ProFert:
    - positive NPV (with a 10% discount rate);
    - IRR > 15%; and
    - wood production > 2 m^3/$100 spent on fertiliser
- Alternative methods:
    - all sites fertilised;
    - lower than expected growth (<75% predicted);
    - moderate growth (site quality 3-5);
    - older stands (> 20 years);
    - Foliar nutrients (N < 13 mg/g and P < 1.1 mg/g).

The alternative approaches were selected based on discussions with forestry managers and represent actual methods currently employed companies. It was assumed that the fertiliser treatment predicted to maximize NPV was selected for each site using ProFert. For alternative methods, the standard treatment was assumed to be N+P fertiliser (as urea plus triple super phosphate) except in the case where foliar analysis was used. In this case the fertiliser treatment was selected depending based on foliar N and P concentrations as follows:

- N < 11 mg/g: apply 200 kg N/ha as urea
- P < 1.3 mg/g: apply 80 kg P/ha as triple super phosphate

Results

ProFert provided consistently superior outcomes in terms of selecting sites on the basis of NPV or IRR compared with alternative methods. Using ProFert to select stands to fertilise and treatments to apply, average NPV ranged from $344/ha to $356/ha with between 19% and 27% of sites fertilised depending on which of the two approaches was used (Figure 61). Selecting on the basis of maximizing the wood yield per dollar spent on fertiliser yielded lower NPVs and IRRs than the other options. This is expected because this approach is designed to select sites based on wood production alone rather than profitability. If it is assumed that each site covered 100 ha, then the total profit from fertiliser application using the three methods ranged from $24,000 to $241,000.

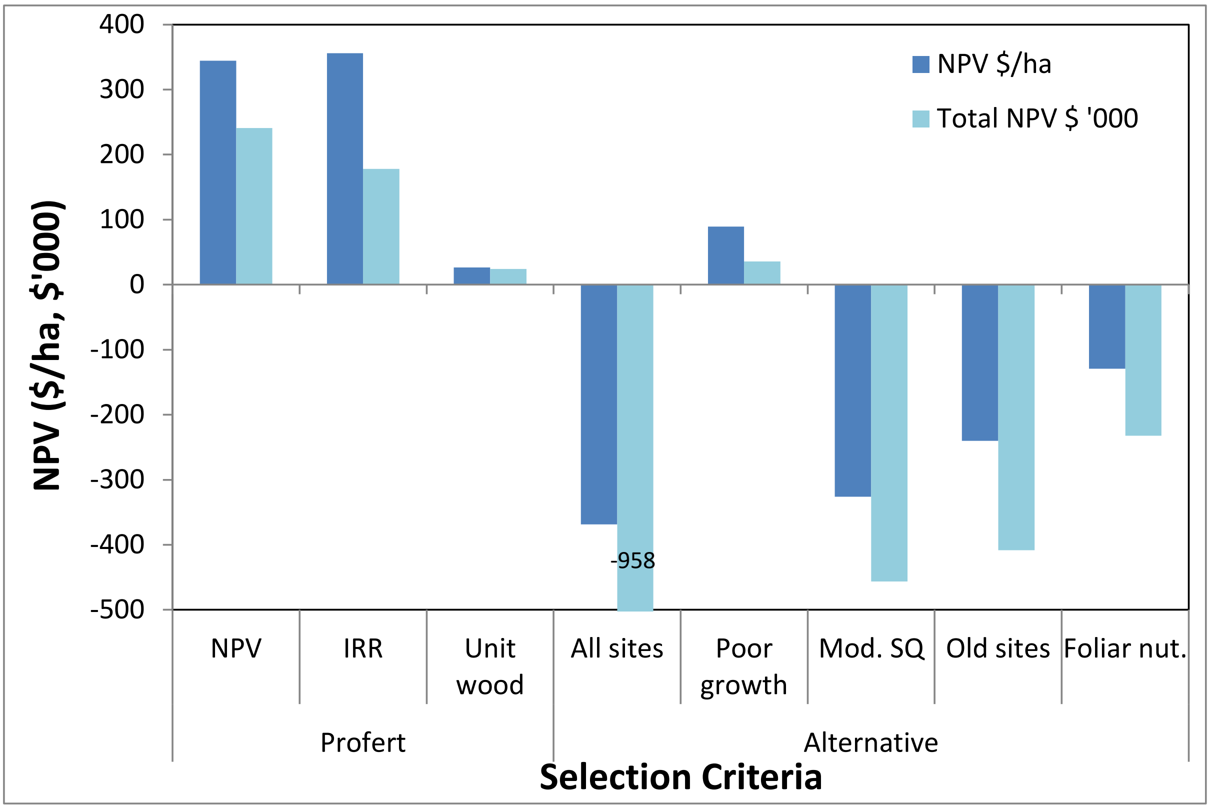


Figure 61: Estimated per ha and total NPV of fertilising sites selected from the 26 stands in the Green Triangle stands using ProFert compared with alternative methods.

In contrast, all but one of the alternative approaches yielded negative NPV's with losses ranging from $129/ha to $369/ha. In other words, using ProFert instead of these methods to select sites to fertilise on the basis of their NPV could have boosted profitability of fertiliser use by between $470/ha and $710/ha. The only method to provide a positive NPV was the selection of stands growing at less than 90% of their predicted growth rate. This approach yielded $89/ha ($260 less than that predicted from ProFert), but selected only 4 of the 26 sites (15%) for fertiliser application. For the other approaches (excluding fertilising all sites), the proportion of sites selected ranged from 54% to 69%. Assuming each site was 100 ha, the total NPV for options other than ProFert ranged from $36,000 to -$958,000.

The amount of wood produced per $100 spent on fertiliser and rate of return on the cost of fertiliser were also substantially greater for ProFert compared with alternative approaches. The average increase in unit wood production using the predictions from ProFert ranged from 3.8 to 3.9 m^3/$100 while the IRR ranged from 20% to 27% for the three options tested (Figure 62). In contrast, unit wood production under alternative approaches ranged from 1.9 to 2.6 m^3/$100 while IRRs ranged from -4% to 11%.

The alternative approaches tended to select a larger proportion of sites to fertilise, resulting in greater overall wood production. However, the cost was far greater with the average amount of wood produced for every $100 spent on fertiliser ranging from 1.9-2.6 m3 (equivalent to $39-$54 per m^3) compared with 3.9 m^3 (equivalent to $25 per m^3) for ProFert.

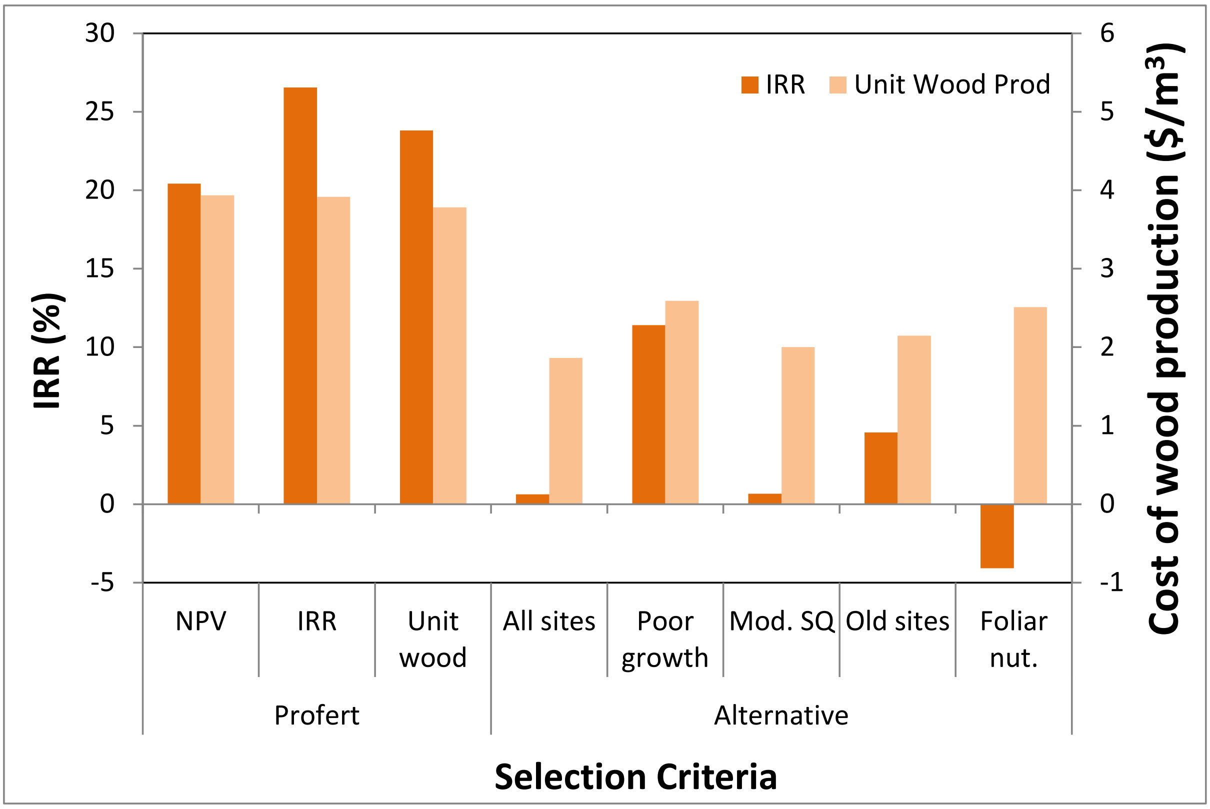


Figure 62: Estimated IRR for fertiliser application and amount of wood produced per $100 spent on fertiliser across sites selected from the 26 experimental Green Triangle stands using ProFert compared with alternative methods.

The results provide an interesting comparison of the effect of using different approaches within ProFert to select sites to fertilise. Boosting wood production can be higher priority than maximizing profit when, for example, there is a need to meet contractual obligations or even out fluctuations in production. However, across the 26 stands used in this example, maximizing profitability by selecting sites on the basis of positive NPV also maximized the amount of additional wood produced (16,000 m^3 assuming each site was 100 ha). When sites were selected sites on the basis of increasing wood production alone (i.e. > 3.5 m^3 per $100 spent) less wood was produced (14,000 m^3) and profitability was far lower ($27/ha compared with $344/ha).

These comparisons of ProFert with a range of alternative approaches demonstrate that the model provides superior predictions, at least for the sites in the Green Triangle. Both NPV per hectare fertilised and IRR were consistently greater than all other approaches, most of which failed to achieve profitable results. As a result of the improved capacity to predict response, the total amount of wood produced per $ spent on fertiliser was more than double that of other approaches.

Recommendations

Outputs from the Project

This project aimed to calibrate a new fertiliser decision support system, ProFert, for use in softwood plantations across south-eastern Australia. This objective was achieved with the collaboration and assistance of FWPA, and three forest companies HVP, Norske Skog and Timberlands.

The model was calibrated using datasets from three regions: the Green Triangle, Victoria and Tasmania using information from CSIRO, HVP and Norske Skog. As part of this process, new predictive relationships were developed which related response to fertiliser to both primary (those nutrients being applied) and secondary nutrient deficiencies. Furthermore, by using existing published data on responses to K fertiliser and relating growth of unfertilised trees to K concentrations, a new relationship predicting response to K from foliar K concentrations was developed.

Responses to N, P and K fertiliser were related to foliar N and P concentrations prior to treatment across all regions. However, relationships based on data from the Green Triangle and Tasmania differed significantly from those based on Victorian data. The reason for this difference is not clear although it could be related to different soils or climate, other nutrients not accounted for in the experiments, or different rates of application (for N) or periods over which the response was measured (for P). Therefore, two predictive relationships were included in ProFert for N and two for P with one pair applicable to Victorian plantations and the other generally applicable to plantations in other regions.

Results from HVP confirmed earlier findings from the Green Triangle that the form of N fertiliser applied can have a major impact on growth response. Responses to urea alone, which tends to be prone to N loss through volatilisation, were around 25% lower than those to ammonium based forms of N for both regions. However, the results also supported an earlier finding that applying P together with urea could reduce these losses.

ProFert was also modified to make it fully compatible with outputs from the existing growth and yield systems used by the three collaborating organisations. The types of systems and their outputs differed substantially and so the model was designed to be highly flexible and able to take a range of different input data. A user manual was created to assist with its adoption and use.

Validation of the model was performed against independent data from operational fertiliser trials and fertiliser treatments not included in the development of response prediction relationships. These data included additional results provided by HVP as well as additional treatments included in the dataset from CSIRO. Results from the validation process demonstrated that ProFert could provide accurate and unbiased predictions of growth responses and profitability of fertiliser treatments across a wide range of site and stand conditions. The model was able to explain 58% of variation in relative response, 62% of variation in absolute response and 67% of variation in profitability of N, P and N+P applied at different rates and forms of fertiliser applied across 7 sites in the Green Triangle. The model also explained 72% of variation in response to N, P and K fertiliser treatments applied operationally at two sites in Victoria. There was no evidence of systematic bias in the predictions with the slope and intercept of the lines of best fit not significantly different from those for a 1:1 relationship.

Comparisons between actual and predicted profitability indicated that ProFert could substantially improve the profitability of fertiliser use. Predicted NPV of the optimum treatments explained 47% of variation in estimated NPV at the time of final harvest. Furthermore, a comparison of the profitability of selecting sites to fertilise and treatments to apply using ProFert compared with a range of alternative approaches indicated that the former was superior at identifying sites profitable to fertilise. The average actual NPV of sites selected using ProFert was around $340/ha (representing an internal rate of return of 20%) compared with -$370/ha to $70/ha (with internal rates of return ranging from -4% to 11%) for alternative methods.

Adoption and use of ProFert

ProFert is able to take growth data from a variety of sources to estimate the growth of unfertilised plots and responses to N, P, K and S fertiliser using foliar and soil data. Increases in product yields are estimated using harvest regime and product recovery data while overall profitability is estimated using input fertiliser, harvest and transport costs and product values.

The model was modified in consultation with potential end users from industry to ensure that it could be readily used in conjunction with existing growth and yield systems and that its outputs were what was required in order to plan fertiliser programs and justify decisions. It was specifically designed to accept outputs from growth and yield systems used by HVP and TPPL (YTGen) and Norske Skog (an in-house system developed specifically for its plantations) for most of its inputs. Other key inputs required to predict response are usually routinely collected or readily available and include foliar N, P, K and S concentrations, soil type (sand or clay/loam). The model is also flexible, allowing the user to predict growth responses for stands with limited background data using only current age and volume, foliar N and P and soil type. Both graphical and tabular outputs are provided and include: response to fertiliser, increases in pulplogs, sawlogs and other logs, key nutrient limitations, optimum fertiliser regimes and a range of indicators of predicted financial performance. These features of ProFert were chosen to ensure that it could be readily adopted and used by industry.

Preliminary testing and validation of ProFert indicate that it should provide accurate predictions of fertiliser response across the estates of HVP, Timberlands and Norske Skog. This also demonstrated that it represents a major improvement on existing approaches and systems in terms of predictive capacity and financial performance. These results indicate that ProFert is a versatile and potentially valuable tool for forest managers to use when selecting sites for fertiliser application. Additional work is needed to further validate the predictions of the model within plantations across south eastern Australia as well as in other regions. However, given the low level of accuracy achieved by alternative approaches and the fact that there are no similar tools available which allow the full financial performance of fertiliser decisions to be analysed, it is recommended that ProFert be adopted for the management of nutrition of softwood plantations across southern Australia in its current form.

To assist with the adoption of the ProFert by plantation growers, a User Manual has been developed for the tool. This manual includes detailed step-by-step instructions on how to operate ProFert and interpret the results. Because of the differences in growth and yield inputs, the tool has been customized for use by each collaborator. Therefore, the User Manual includes company-specific instructions for its use.

In addition to the user-manual, one-on-one training has been undertaken with each of the three collaborating organisations as part of the project. This training ensured that end-users were familiar with its operation and outputs. It also allowed any issues to be identified and rectified. Subsequent on-going communication with each of the collaborators has helped rectify other issues and ensure that the tool could accept the input data used by each system. At the completion of the project, the model was being used operationally by one collaborator and was undergoing field testing by the other two organisations.

A webinar explaining the project and introducing the model has been produced and is available on FWPA’s website. This outlines the key results of the project and explains the use and outputs from ProFert. It is expected that this will make it easier for potential users to understand the potential advantages of using the tool. A generic version of ProFert will also be available together with the main report and user manual on FWPA’s website which will allow potential users to test the model and explore its capabilities.

Further work

Although every effort has been made to ensure the relationships used in ProFert accurately reflect the latest available research relating to plantation responses to fertiliser, uncertainty still exists regarding its the predictions. This is because differences in environmental factors influencing the fertiliser trials means that there can be substantial differences in fertiliser responses between regions and years which cannot be readily accounted for. This appears to be the case for the datasets used in the current project where differences in rainfall, other nutrient deficiencies, soils and other factors resulted in different relationships for predicting responses to N and P fertiliser response across the different regions. In addition, most of the datasets used to calibrate ProFert have been from mid-rotation (15-30 year old) stands, whereas younger stands form a key component of most operational fertiliser programs. Therefore, it is strongly recommended that additional data sets be accessed and new fertiliser trials be established across a wider range of regions and stand ages in order to validate the relationships and compare actual responses with those predicted by ProFert.

Establishment of fertiliser experiments

A series of fertiliser experiments using the same fertiliser types, rates and forms should be established across softwood plantations in several different regions (e.g. Victoria, Tasmania, NSW, Queensland and WA). Since the results from the current project indicate that foliar nutrients are likely to be the most robust and accurate predictors of response, foliar sampling of the trees would need to be undertaken prior to fertiliser being applied.

Stand age should cover both mid-rotation (post first thinning to 25 years) and younger stands (aged 2-5 years). Each stand should be relatively uniform (i.e. with even stocking and basal areas) as variation in initial basal area can be a key potentially confounding factor (May *et al.*, 2009a). The impact of this problem can be minimised with careful design of the experiment, sufficient replication and appropriate analysis of the results.

Foliar sampling should take place in mid-winter when foliar nutrients tend to be most stable (Fife and Nambiar, 1982). Nutrients analysed should include all macro nutrients (N, P, K, Mg, S, Ca), as well as key micro-nutrients (Fe, Mn, Cu, B, Cu). Composite samples should be taken from the same aged needles (e.g. youngest fully expanded needles) and from the same part of the crown (e.g. third whorl from the top) from at least 10 trees and should be combined on an equal-weight basis.

It is important to carefully select fertiliser treatments which could be used operationally, but which also avoid potential problems which could confound the results. It is suggested that urea be avoided because of the potential volatilisation losses and interaction between urea and P fertiliser. The experiments should also be designed so the individual responses to N and P fertiliser can be separated. Furthermore, there should be a minimum of four replicates per treatment. A potential set of treatments would be:

- Control: no N or P fertiliser
- N: 200 kg N/ha as ammonium sulphate;
- P: 80 kg/ha as triple superphosphate; and
- N+P: 200 kg N/ha and 80 kg P/ha as ammonium sulphate and triple superphosphate.
- N+P+K: as above with the addition of 200 kg K/ha as KCl.

Growth responses to fertiliser should be measured for a minimum of six years after application with an optimum of 12 years to fully capture responses to P. In addition, annual foliar sampling should be carried out for at least five years post treatment to verify growth responses to fertiliser and identify any induced nutrient deficiencies. Relating responses to foliar N, P and K concentrations would provide a means of validating the existing relationships used in ProFert and measured responses could be related to those predicted by ProFert to test its accuracy. This would provide a means to check and improve the relationships used in the model to ensure it can be used with confidence across different regions.

Monitoring operational fertiliser responses

In addition to or as an alternative to establishing fertiliser experiments, responses to operational fertiliser applications should be monitored. One option for doing this is to leave strips of plantation unfertilised when applying fertiliser operationally. Plots can then be established in both the fertilised and unfertilised strips and subsequent growth monitored and compared with predictions based on foliar sampling. This method is potentially cheap, but underlying variability in growth is likely to be greater requiring a larger number of replicates. As with the fertiliser experiments, underlying differences in plot basal area would need to be accounted for and between plot variability in soil, stocking and basal areas minimised. A drawback of this approach is that it would not allow responses to N or P fertiliser to be separated. However, this could be balanced by reduced costs allowing a larger number of sites to be included.

Acquiring additional datasets

The predictive models used in ProFert also need to be tested and validated for use by other agencies and in other regions. Many existing datasets on fertiliser responses exist which could be used to test the model and ensure that its predictions are robust for use across Australia. Providing access to these datasets so that ProFert can be validated for use in other regions should be a high priority for the plantation forest industry. Such datasets would need to have sufficient information on foliar nutrients, growth responses, standing volume, soil, stand age and response periods to allow them to be used by ProFert.

Calibration for use in other plantation types

Although ProFert has been specifically designed for use in softwood plantations in south eastern Australia, it can be readily adapted for use in other plantation types including hardwood plantations. The flexibility in its structure and capacity to accept different response prediction relationships for different nutrients and outputs from different growth and yield systems mean that it is highly versatile. The underlying principles relating to secondary nutrient deficiencies, response longevity, nutrient interactions and effects of fertiliser on stand nutrient status and response to future applications are generally applicable to all plantations. Therefore, it is recommended that results from fertiliser experiments from hardwood plantations and other softwood species be used to calibrate ProFert for use in these plantations.

Conclusion

This project aimed to modify, calibrate and operationally test a new tool for predicting response to fertiliser in softwood plantations. This was achieved using datasets provided by HVP, CSIRO, Norske Skog and TPPL, developing new relationships and processes used in the model, changing the model to accept outputs from existing growth and yield systems, extensively testing it by comparing outputs against available data and working with end users to ensure it operated correctly and provided the required information.

Datasets used in the project include results from:

- over 250 fertiliser treatments applied across 16 sites located in the Green Triangle;
- 35 fertiliser treatments applied across 19 sites across Victoria;
- Results from two operational fertiliser trials in Victoria;
- 21 treatments applied across 7 sites in Tasmania;
- results from studies by Hall and Raupach (1963), Raupach and Hall (1973) to predict response to K; and
- other published and unpublished studies including Bruce *et al.* (2001), Hopmans and Elms (2014) and May *et al.* (2009a) and Reuter and Robinson (1997).

Using these datasets and studies new relationships for predicting response to N, P and K fertiliser have been produced and a novel approach developed to accounts for the effects of secondary nutrient limitations on primary responses. The effects of different N rates and forms, predicted changes in response over time based on these data have been included in the model. In addition, results from additional sites and treatments have been used to validate ProFert's predictions.

The resultant model represents a significant improvement on existing systems which rely on a mixture of simple predictive relationships, generalised responses based on soil type, climate or stand age, visual diagnosis and stand growth rates to identify potential responsive stands. In contrast, ProFert's outputs are based on quantitative relationships and growth models with explicit assumptions which can be readily modified. Furthermore, its outputs include a financial analysis of the results. Comparison of a range of different approaches indicated that ProFert can increase profitability of fertiliser use by up to \$260/ha to \$710/ha compared with other approaches.

Despite these improvements, additional work is required to further validate the relationships and to confirm its accuracy for use in different regions. Therefore, it is recommended that further operational or experimental fertiliser trials be established in conjunction with deployment of the model. This would allow its predictions to be tested operationally and would produce additional data which could be used to develop more robust response relationships for N, P and K fertiliser.

Regardless of these uncertainties, ProFert is expected to substantially improve the capacity of forest growers to predict growth responses to and profitability of fertiliser use as well as provide economic justification for fertiliser decisions. This will allow responsive stands to be better targeted, improving growth rates and reducing wastage and unwanted environmental impacts associated with fertilising unresponsive stands. Equally importantly, it will enable managers to better understand and manage the specific nutritional limitations on growth. As a result, adoption of ProFert should increase the plantation productivity and increase the economic return on both fertiliser use and plantation ownership generally.

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Researcher’s Disclaimer

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