Precision Silviculture Programme

A review of fertiliser and nutrient enhancers applied in the nursery or at planting for improved growth of *Pinus radiata* in New Zealand

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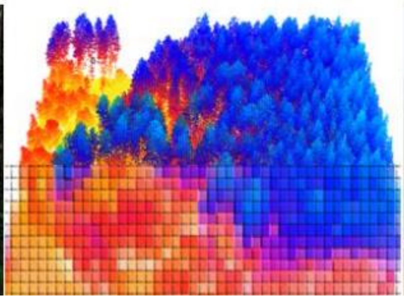


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FOREST GROWERS RESEARCH

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EXECUTIVE SUMMARY

The problem

Fertilisers or stimulants (nutrient enhancers) have been used at some sites for tree establishment in New Zealand. However, tree growth responses are varied. Current underpinning knowledge regarding the application of fertilisers or nutrient enhancers when establishing trees to improve tree growth in New Zealand remains incomplete. For example, there are variations in treatment methods and application rates, that are influenced by a combination of research findings, un-replicated grower experimental blocks, and local knowledge. The potential benefits of a nutrient treatment or stimulant use in the short period from when trees are lifted from the nursery to planting requires exploration. Current knowledge is primarily based on research recommendations targeting nutrient-deficient site types, limiting its applicability to a broader range of sites and outcomes, including productivity enhancement at sites without deficiencies. However, this knowledge can still inform fertiliser application at similar sites to those tested, provided factors like residual effects, management changes, genetic variations, climate change, and sustainability are considered.

This project

Through the Precision Silviculture Programme there is an opportunity to design or adopt new technology that can do multiple tasks, for example mechanised planting of a tree as well as adding fertiliser at the time of planting. The opportunity can be for a more targeted and precise application of nutrients and optimisation of resources. However, due to the uncertainties around site-specific nutrient treatment or stimulant options and benefits in the short period from lifting the tree to planting where mechanised operations are practical, there is uncertainty if including nutrient addition with mechanised planting should be pursued.

The objectives of this project were to review relevant literature on the growth response benefits of the application of fertiliser or nutrient enhancers to young trees leaving the nursery or at planting in New Zealand and identify knowledge gaps that can inform where to focus future research. Nursery practices specifically aimed at quality seedling production were out of scope for this review.

Results

The key results and knowledge gaps from the review are:

- *Previous research achieved past goals* - defining what was needed to overcome deficiencies on targeted sites but the research to define what is possible to optimize or maximise growth is limited.
- *Research is limited and old* – Much of the research into nutrient or stimulant treatments at planting was done over 20 years ago, with very little research into nutrient or stimulant treatments to trees leaving the nursery.
- *A growth response to a nutritional treatment can be mixed* – Past trials were targeted to nutrient poor sites where a growth response was considered more likely. As a result, there is limited ability to extrapolate to unrelated site types where responses may occur due to various other mechanisms such as different soil types/parent materials, soil depth, site history, genetic changes, and changes in weather patterns. There is also uncertainty on how long a growth response may last due to lack of data. Past trials also focused on a small group of nutrients which limits understanding of response opportunities outside of deficiency correction.

- *An economic assessment is limited* - As trials were not measured to rotation end, with a majority ending at five years, full rotation response is unknown and cannot be framed into an economic analysis.
- *Guidelines are available to foresters but are limited* – Foliage based nutritional deficiency indicators are available to inform foresters on fertiliser at planting needs. These guidelines are developed for the plant but only apply to sites where there is a nutrient deficiency. Guidelines are available for the seedling growing stage prior to lifting, but there are no guidelines on what nutritional treatment options could be applied to trees leaving the nursery. There is uncertainty in the forest industry around using fertiliser at planting and a high interest in understanding the benefits of nutritional treatment benefits for tree establishment.
- *Relevance of past research to forest establishment today* – There is still opportunity to expand knowledge on fertiliser and stimulant response in a more structured manner to represent present-day site conditions, genetic material, weed control practices, and alternative fertiliser sources (for example biuret and organically complexed fertilisers).

Recommendations

Recommendations on where the PSP would add value to the forest industry tree establishment practice are:

- *Predicting the likelihood of a growth response* – Investigation into and the development of a tool/model to predict the likelihood of a site-specific growth response that are relevant to nutrient treatments in the short time period of tree establishment. This cannot be achieved without the following:
    - *Collaborative effort* – Forest managers to host experimental trials and share data and results for maximum benefit to New Zealand's Forest industry.
    - *Precision application* - Including the ability to precisely apply nutrients or stimulants as part of mechanised planting (or lifting) tools would be highly advantageous for known responsive sites and to improve feasibility of mechanical planting operations.
    - *Targeted nutritional treatment experimental trials* – Supporting a designed network of research to test whether a site is responsive or not to nutritional treatment at establishment. Treatments to be determined in collaboration with industry.
- We need to understand what the seedling needs at the time of planting focusing on optimal formulations and application methods. This should also consider if the seedling meets the seedling quality standards and how these impact on nutrient requirement at the time of planting.
- *Broadening the range of treatments* – Including in the design a broader range of treatments than what have been tested in the past, for example, microbial inoculation, or a treatment combined with hydrogels.
- *Monitoring and data* – Explore rapid methods of data collection including the use of remote sensing and collection of other data, for example soil data, to support a more precise site/soil understanding of nutrient requirements and response potential.
- *Economic analysis* - the gains from applying fertiliser at time of planting need to be compared with later age application and the relative benefits compared. This includes comparisons between time cost of money due to adding fertiliser at various ages, risks, market uncertainties, and the economic gains from each application.

INTRODUCTION

New Zealand and its forestry industry invest substantially into forestry, supplying on time, fit-for-purpose timber to meet local, domestic and international wood product demands (MPI 2022). Key components of the harvested wood product supply chain require decades of development, such as production of high value genetic material in breeding programmes, maintenance of superior seed orchards and plant production in high performance production nurseries to meet the demand for planted forests. Approximately 1.76 million hectares are currently under timber production in New Zealand, 90% of which is *Pinus radiata* D. Don, accounting for 1.6% of GDP MPI (2022). The goal for New Zealand forestry is to sustainably manage planted forests over multiple rotations (MPI 2022) which can include the use of more conservative silviculture management or the addition of nutrients through fertiliser application. Forestry also needs to be a competitive land use or else other land uses will replace forestry.

Optimising seedling health and growing conditions from nursery to planting can impact young tree survival, growth, and uniformity, with significant consequences for productivity to rotation end (Balneaves, et al. 1996). The relatively brief time frame that occurs between nursery lifting and the few seconds it takes to plant each tree in the field can therefore have a pivotal impact on the economic return from past investment into genetic improvement and future investment into silviculture and harvesting that follows. The application of planned nutrition management within this short window of the forestry chain can offer an opportunity for the forest industry to improve New Zealand planted forests and has been a focus of research in the past (Davis, et al. 2015).

Soil quality varies widely over New Zealand, influenced by parent material, formation processes, and land use history. Initially, forests were planted on lands regarded unsuitable for agriculture due to poor fertility. Seven soil orders cover 94% of the planted forest estate (Figure 1) with Brown and Pumice soils making up 65% of the area Davis, et al. (2015). Many of these soils have previously supported multiple tree crops in addition to around a third of planted forests being on low-nutrient soils. More recent plantings occur on former pasturelands with higher fertility due to prior fertilisation. These factors highlight the need for site-specific management underscoring the importance of understanding and addressing the unique requirements of each site.

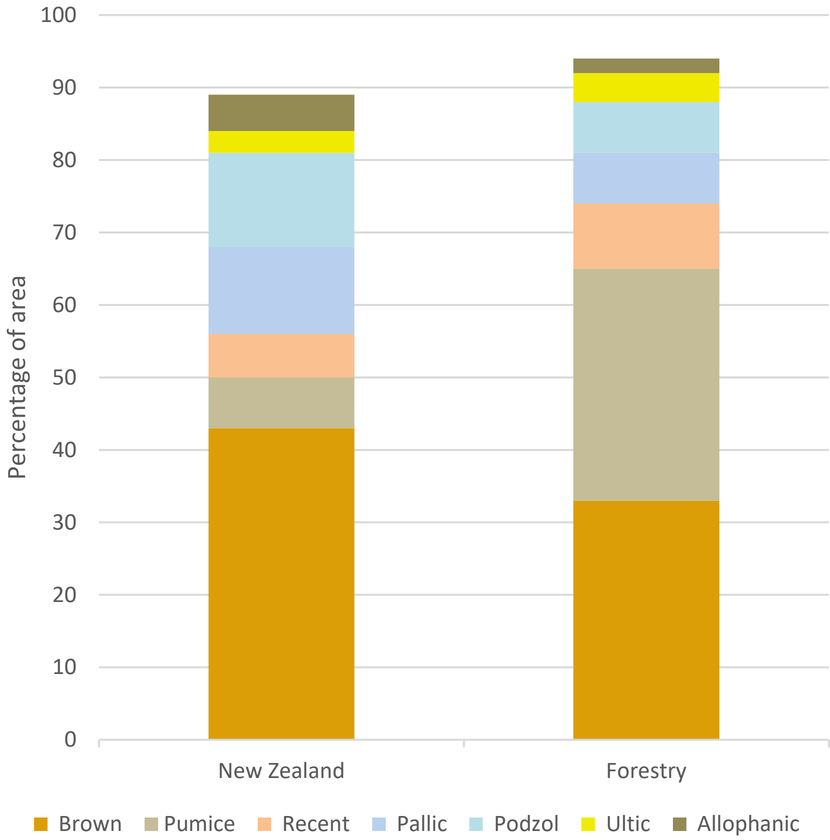

Figure 1: Seven major forestry soil orders by percentage of land area in New Zealand and under planted forests, after Davis, et al. (2015).

Fertiliser application in New Zealand forests is low with, for example, estimates suggesting less than 700 tons of nitrogen fertiliser used nationwide (Scion 2019). Additionally, the majority of forest stands are established without receiving any fertiliser (Smaill and Clinton 2016). Despite the use of fertiliser in some New Zealand planted forests, uncertainties regarding return on investment, if a site will respond to the fertiliser addition, and concerns about wood properties have limited the use of fertiliser as a nutrient management tool (Smaill and Clinton 2016).

There is a growing demand for the rapid deployment of resilient planting stock and site-specific forest management that will enhance early forest survival and growth. This trend is underscored by the increasing land area dedicated to new forest establishment (mostly post 1989 established to ex agricultural land) and continued reestablishment after multiple rotations (pre-1990 forests, Figure 2). This is coupled with a need to mitigate the impacts of climate change on early survival and growth of planted forests (Orwin, et al. 2015, Garrett, et al. 2021). Adoption of new technologies, planting stock type, and/or genetic material, and evolving requirements around licence to operate, may mean that what is current best practice may not be fit-for-purpose in years to come. For example, this could include adoption of more precise site-specific management that reduces risk to people through mechanisation or automation of silvicultural systems while improving tree survival, growth, and resilience to change, while still delivering an economic benefit at rotation end. Mechanical planting can also be integrated with site preparation activities (ripping and slash clearing) thus combine costs of site preparation, planting and addition of fertilisers in a single operation. However, it is important to compare this with the economic gains and the time cost of money resulting from spending on fertiliser additions, both at planting and during the mid-rotation period. This comparison should consider the risk exposure over various time spans and uncertainties associated with projected market demand.

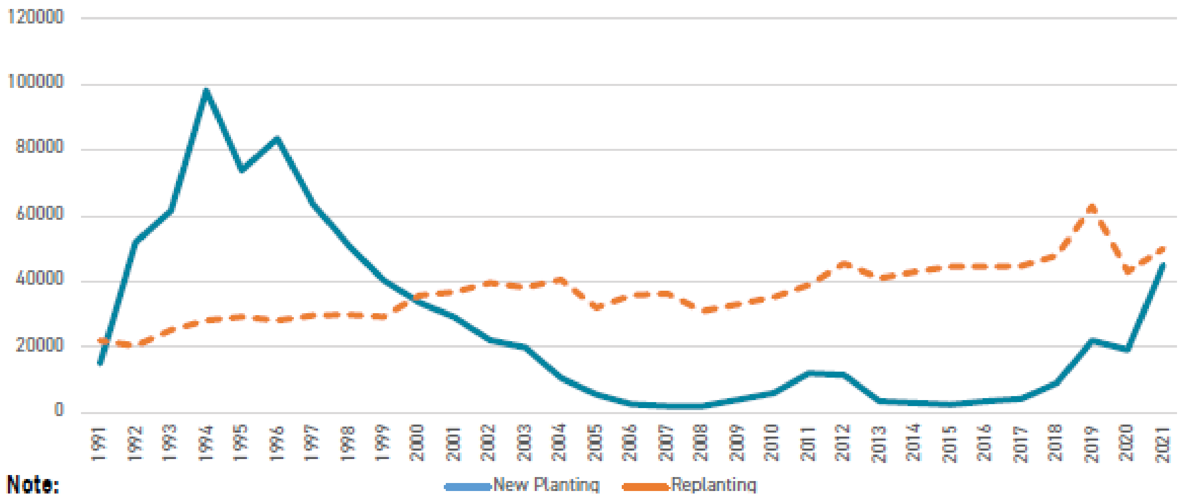

Figure 2: Estimated area (ha) of new planting and replanting, taken from MPI (2022).

The Precision Silviculture Programme (PSP), funded by Government and industry, aims to transform forestry management through taking advantage of opportunities offered by new technologies. Within the Planting and Establishment theme there is a need to understand the value of early nutritional silviculture with a view to the role of new technologies enhancing early tree growth through precision or targeted application. This could be for example, the application of fertiliser with technology that is also planting the tree (see the Bayne, et al. (2023) review on mechanised planting), or a nutritional treatment of a tree that has just been lifted from the tree nursery. Linking the timing of nutrition addition to an already mechanised operation would reduce establishment costs as well as target nutrient management goals. However, there is a knowledge gap in understanding if nutritional treatments within the short window of exiting the nursery to planting, results in a beneficial tree/forest growth response in the New Zealand context.

Objectives

The objectives of this study were to:

- Review existing literature on the growth response benefits of the application of fertiliser or stimulants (nutrient enhancers) to young trees leaving the nursery or at planting in New Zealand, noting any mention of responses having an economical benefit.
- Identify knowledge gaps in our understanding of site-specific growth responses,
- Recommend research than is needed to address the knowledge gaps with a focus on where the PSP programme would add value to the forest industry tree establishment practice.

METHODS

The review focus was on the growth response of *Pinus radiata* within the first year after planting to nutrient treatments for two key periods listed below when other forest management activities are occurring (e.g., planting). Growth response was defined as an increase in tree height, basal area, or volume, and any mention of an economically beneficial response. These as written here, were considered in increasing order of relevance to the interpretation.

Key periods:

- Within the tree nursery for the period just prior to and when the trees are lifted and packed ready for transport to the forest, and
- At the time of planting the tree into the field.

Two categories of nutrient treatments were considered:

- Mineral fertiliser, and
- Stimulants which enhance access to nutrients, for example, biuret and mycorrhizal fungi

Using the above search criteria evidence of a growth response of *Pinus radiata* to nutrient treatments at lifting from the tree nursery and at planting was obtained through a literature review on available, New Zealand relevant, literature, reports, research trial activity (Scion records), and local knowledge (Scion researchers and willing NZ forestry industry representatives).

Studies outside of this timespan and on other species were included if they contributed to general understanding around soils, site management and response potential. This included, for example, trials with fertiliser treatments out to 5 years where there were no other research data available. The findings of the review were then used to inform knowledge gaps of site-specific growth responses from the addition of fertiliser or nutrient enhancers for when young trees are lifted from the nursery and planted into the forest.

LITERATURE REVIEW SUMMARY

A brief history of nutrient additions at tree lifting and planting

Existing reviews available

Fertiliser addition in New Zealand's planted forests has been reviewed at various points in time, with two comprehensive reviews undertaken in the 70s and then in 2015 (Davis, et al. 2015, Ballard 1978). Davis, et al. (2015) carried out the most recent comprehensive review that summarised the development of New Zealand's exotic radiata pine tree plantation tree nutrition requirements and fertiliser application from tree nursery to planting, and to rotation end, summarising research between 1955 and 2010. **Both reviews generally summarise management practices of adding fertilisers in response to diagnostic nutrient deficiencies described in Will (1985), followed by research to maximise productivity on soils with known nutrient limitations.**

Research is limited and decades old

Research underpinning a growth response to a nutrient treatment of trees leaving the nursery gate and at planting is limited and mostly 20 years or more old (Figure 3). Much of the past research was focused on nutrient treatment at planting compared to application at lifting within the nursery, with more recent research targeted towards treatment of trees leaving the nursery gate (Figure 3). A more detailed history of nutrient addition research trials and a list of experimental trials specific to lifting trees in the nursery and at planting are listed in Appendix 1 and 2.

Over the decades the focus of planted forest nutrient management, including nutrient management of trees leaving the nursery and at planting, has been to correct for a site nutrient deficiency (Davis, et al. 2015). Therefore, much of the research trials have focused on problem sites that are very low in a nutrient that has been identified through local knowledge or later through foliage nutritional testing (Figure 2). A spatial distribution of fertiliser addition at planting trials (and permanent sampling plots) is in Appendix 3.

Nutrients that have been a focus for nutrient amendment at planting are nitrogen, phosphorus and boron, with specific areas targeted for magnesium and potassium deficiencies (Figure 3). Both single nutrient amendments or combinations of nutrient treatments have been investigated using primarily nitrogen, phosphorus and boron. Of all fertiliser addition research carried out in NZ for growth improvement much of this has been done post 3 years of age and is discussed in the review of Planted-forest Nutrition (Davis, et al. 2015).

Menzies (1988) provides guidelines for optimal seedling quality and handling specifications at lifting. While this is out of scope it raises questions around whether such guidelines need review, and if the quality indicators can be related to field performance and further nutrient or stimulant requirements after lifting and at planting. Past research on the use of nutrient enhancers of trees before leaving the nursery explored various methods, with early research in the 1950s testing soaking the roots of lifted trees in mud and superphosphate, or mud and boron to prepare for phosphorus or boron deficient sites. There was no other research targeted towards nutrition addition to trees, or addition in the weeks prior to being lifted from the nursery as a means of building up nutrient reserves for field deployment. More recently, treatments of trees leaving the nursery gate have focused on mycorrhiza and Trichoderma inoculation, ethylene treatment and hydrogel root dips (Figure 3).

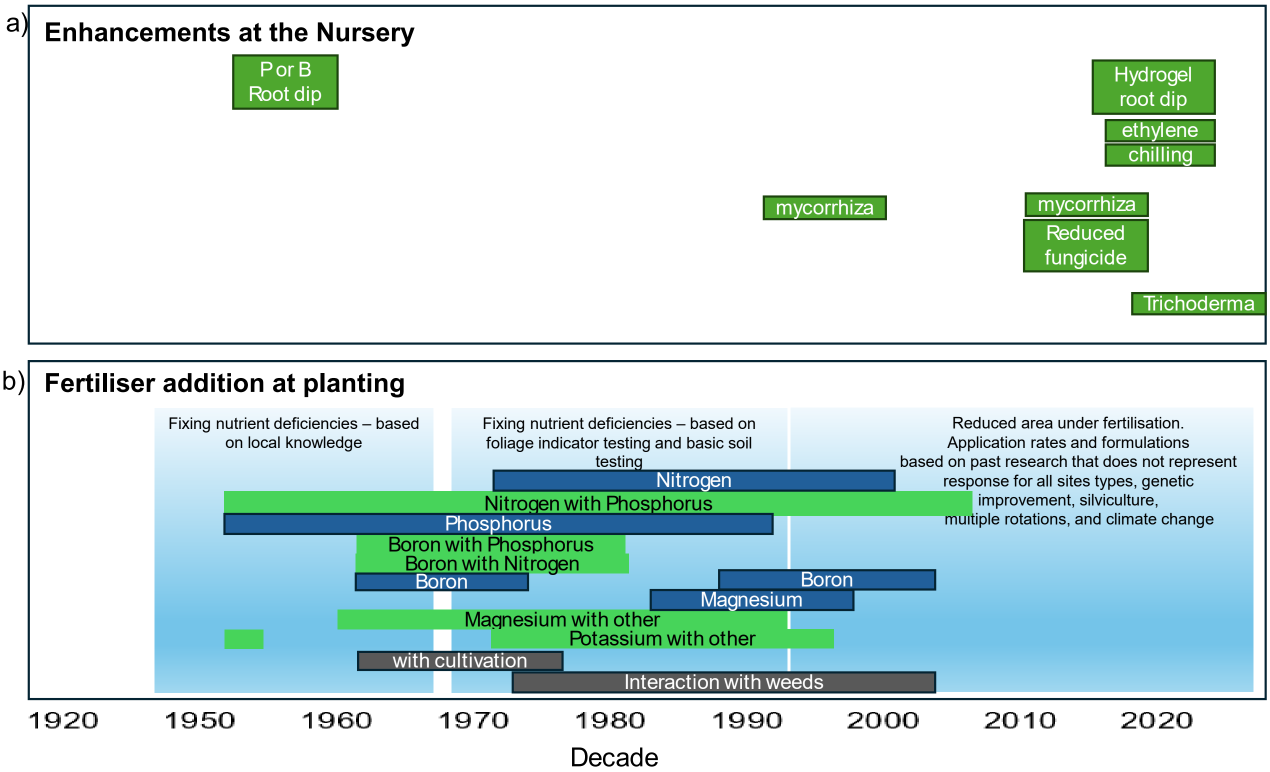

Figure 3: A brief history of documented New Zealand planted forest nutritional research with a focus on at planting for *Pinus radiata* a) at lifting the tree at the nursery, and b) at planting (note certain at planting research included experimental trials with fertiliser application out to 5

years). Elements included as a separate treatment are in blue boxes, combinations are in green. P=phosphorus, B=boron

Does nutrient addition increase tree growth?

Much of the past research in New Zealand on tree growth responses to nutritional treatment at any point through a rotation has targeted nutrient deficient sites, and even more so for at lifting or at planting. These sites are where a growth response is more likely to occur with a nutritional treatment. The most common nutrient additions targeted for research trials included applications of the narrow set of nutrients and their combinations mentioned above. This targeted nutritional research was able to demonstrate growth responses on nutrient deficient sites, however, these also demonstrated mixed responses. Also, the research trials were only measured over a short period with the majority terminated at three to five years, therefore, benefits of the treatment to rotation end are not well understood from a growth or economic perspective. Within the research trials there has been no research that has explored fertiliser application at planting across a wide range of sites that are representative of New Zealand's planted forests. However, a partial site understanding can be informed from a trial series that demonstrated response potential across a wide range in soil fertility from nutrient deficient to fertile (Beets, et al. 2019, Watt, et al. 2008, Ross, et al. 2009). This study cannot be directly related to fertiliser addition at planting as it applied fertiliser within the first year and continuously out to 4 years across a range of sites planted to 40000 stems per hectare. Fertiliser treatment included a range of elements and results do highlight the importance of fertiliser as a silvicultural treatment that can be used to improve site quality and tree growth, linking these responses to soil indicators (Watt et al., 2008).

The following sections list the growth response to nutrient treatment for when trees leave the nursery and at planting and summarises trials that have looked at the interaction between fertiliser and site management. A list of experimental trials at planting and their growth response are listed in Appendix 2. Research that has explored growth response with fertiliser application to young trees after planting have been included where these trials add value to understanding.

When nursery trees are lifted

Response to the application of fertilisers and stimulants (predominantly nutrient enhancers) in the nursery are varied and evidence of responses carried to field is limited to studies on a few sites.

- Growth responses in field occurred after soaking roots in mud enriched with superphosphate or boron followed by deployment to phosphorus or boron deficient sites. These treatments also induced greater mortality (Ballard 1978).
- Hydrogel + micronutrient drench dipping extended planting season and increased root water uptake, leading to improved survival and growth under dry conditions (Coker, et al. 2022).
- Ethylene application resulted in non-significant responses, and long-term chilling incurred negative responses (Smaill, 2022).
- Microbial additives such as mycorrhiza, Trichoderma and vermicompost produced positive growth responses in limited field experiments due to enhanced nutrient uptake and resistance to environmental stressors, but evidence of improved field performance is currently too limited to recommend wider application (Xue, et al. 2022, Liu 2005, Davis, et al. 1996, Whelan 2023).
- Evidence of conservation of native mycorrhiza in the nursery through reduced fungicide use resulted in better field performance, and points to a more cost-effective approach (Smaill and Walbert 2013, Smaill, et al. 2020).

At planting

Past research repeatedly confirmed and emphasised phosphorus, nitrogen, and boron as commonly deficient elements that can be corrected through fertiliser application at planting. Although potassium and magnesium deficiencies were found to occur in very specific areas these responses are difficult to predict and limited to very few studies. A similar observation is noted for the remaining macro- and micro-nutrients. The assumed lack of longevity of response to fertiliser addition, less than four years, remains questionable due to many past trials not measured to rotation end.

A summary of at planting response to fertiliser addition are described below and listed in Table 1.

Phosphorus

- Best growth responses occurred for soluble phosphorus forms in Northland and Coromandel weathered and leached clays, podsolised sands (Auckland region), pumice, brown soil, and pakihi podzol in Westland, and leached alluvial gravels in the Nelson region.
- Highly weathered clays of northern New Zealand are likely to require continued application at planting.
- Phosphorus can be placed near each tree at planting, but direct contact with the seedlings must be avoided to prevent mortality.
- Low phosphate rates showed comparable effectiveness to larger amounts, with responses often independent of the phosphate formulation. However, more soluble forms produced better efficacy.

Nitrogen

- Nitrogen fertiliser improved growth on podsolised soils, skid sites and strongly leached alluvial gravels and in certain areas also required the addition of phosphorus fertiliser with nitrogen fertiliser.
- Response to nitrogen was variable and limited on clay soils.
- Direct contact with seedlings can harm young trees resulting in mortality or reduced growth.

Boron

- Boron fertiliser was applied to reduce die-back on deficient leached alluvial gravels and granite soils in the Nelson region. Boron combined with phosphorus or nitrogen increased growth, but dieback was worse where nitrogen and phosphorus was not added with boron.
- Certain sand dune soils require nitrogen and boron.

Table 1: Aggregation of experimental treatment responses to elements or combination of elements added as fertiliser at planting or during the first establishment year. (These include other species). Full tables are in Appendix 2.

Elements added	Positive response	Negative response	No response
N	13	4	8
N P	16	2	8
N B			1
N S		1	1
N P B	1		1
N P Mg	1		2
N P K	1		
N B Mg	1		
N P B K			1
N P B K M g			
N P B K Mg S			4
N P K Mg Mn	1		
P	19	3	9
P B	4		1
P K	1		
P S			2
P Ca S	1		
P K Ca S	1		
B	4	1	2
K			1
K Ca S	1		
Mg	1		4
S			2

N = nitrogen, P = phosphorus, B = boron, Mg = magnesium, K = potassium, Ca = calcium, S = sulphur, Mn = manganese

As most past trials were targeted to responsive sites (nutrient deficient sites), there is limited ability to extrapolate to unrelated site types where, for example, a growth enhancement or increase in productivity could occur. Responses can occur as a type I (temporary growth rate increase) that brings a stand to a greater maturity level sooner, or type II (as a long-lived growth rate improvement) which is most desirable. This is due to complex relationships between: fertiliser application; the site; other vegetation; the physical, chemical, and biological properties of the soil; and tree genetics. This is evident in past research. For example, despite a potential for nitrogen fertiliser to enhance forest growth several factors have been demonstrated to limit this response. These were availability of other nutrients, previous land use and silviculture of the stand, soil compaction, weed competition, soil moisture, pests and pathogens, nitrogen fixing weeds, and genetics (Hawkins, et al. 2010), weather patterns, and the form and placement of the fertiliser (Smaill and Clinton 2016). This can increase the challenge in modelling and predicting growth and economic response to fertiliser addition (Smaill and Clinton 2016).

Interactions with site management

Past research also pointed to the control of competing vegetation and cultivation on certain soils as having the best response when combined with fertiliser addition. A summary of at planting response to fertiliser addition and site management are described below and listed in Table 2.

- Deep ripping is required to obtain optimal response to nitrogen application on skid sites. Total soil nitrogen measurements can be used as a guide with application in the second spring after planting.
- Weed control is necessary to avoid increasing weed growth competing with the young trees and to avoid a weed growth response that overrides that tree response to boron.
- The best response to fertiliser application occurred in combination with weed control and deep soil cultivation. This was found to be particularly important on compacted soils or burnt sites.
- Sites previously occupied by legumes and/or ex-agricultural sites do not require nitrogen fertiliser addition.
- Sites having undergone large quantities of biomass removal (particularly loss of the forest floor) or soil loss e.g. skid sites may require additional fertiliser application or respond differently to fertiliser application at planting due to depleted soil nutrients.
- Sites with large or excess nutrient capital, such as old farmland may not require fertiliser addition (and be able to maintain larger biomass removal rates).

Table 2: Aggregation of experimental treatment responses to elements or combination of elements added as fertiliser at planting or during the first establishment year and the interaction with site/soil management. Full tables are in Appendix 2.

Elements added		Positive response	Negative response	No response
Fertiliser with nitrogen fixing species	NoFert & Nfix	1		
	N & Nfix			1
Fertiliser addition after soil cultivation	N	2		1
	P			2
	NP	3		
	NPMg	1		
	NBMg	1		
Fertiliser addition with no weeding	P	4	1	2
	NP			1
	NPK			3
Fertiliser addition with weed removal	B	2		
	NPK	4		
	PKB	1		
Fertiliser addition of Mycorrhiza	NP			2

NoFert = no fertiliser added, Nfix = presence of nitrogen fixing plant species, N = nitrogen, P = phosphorus, B = boron, Mg = magnesium, K = potassium

Likelihood of a growth response at time of planting

Essential nutrients are needed for healthy growth and productive forests. The addition of fertiliser or nutrient enhancers can result in a growth response. However, the likelihood of a growth response for a specific site is not always certain. Forests are complex ecosystems. The effectiveness of nutrient treatment depends on several factors including, soil fertility and quality, climate, previous land management or use, harvesting impacts and site preparation management, soil moisture availability, genetic material, application method and timing and presence of pests and pathogens (Powers 1999).

Likelihood of a growth response to fertilisers or nutrient enhancers applied at the nursery or at planting was initially understood to be due to a lack of soil nutrient availability/supply. This is primarily driven by soil type (parent material and extent of weathering), organic matter content and previous land use. Use of soil maps, foliage and soil testing have supported identifying nutrient deficient sites that may be more likely to respond to nutritional treatment (Davis, et al. 2015). It is assumed that trees planted on fertile soil, for example previously ex-agricultural land or forests that have received past nutrient improvement, are less likely to respond than when planted on other less fertile soils. However, this hasn't been well researched.

A large proportion of planted forests (predominantly pre-1990) have grown over multiple rotations placing continued pressure on soils (Garrett, et al. 2021). For example, harvesting and residue management on nutrient poor sites may increase the need for fertiliser use to improve general site fertility. This, in addition to a gradual increase in land newly converted to forest on ex-agricultural sites in more recent years, implies that past management practices may no longer be applicable for present day sites (Figure 2). There are also various other mechanisms that may have potential to drive a (positive, neutral or negative) response which include limited access of small seedling trees to the bulk soil, soil in the planting mound or pit being less fertile due to subsoil inversion, and other physiological factors. Site preparation/cultivation and control of competing or site enhancing vegetation can also determine the response.

The strategic application of fertilisers plays a role in enhancing the productivity and sustainability of agricultural systems. It is important to note that if a site necessitates the use of fertilisers at the time of planting, it is highly probable that additional applications will be required throughout the rotation. This is since the quantity of fertiliser applied at the time of planting is small, and if the site is nutrient-deficient at this stage, it is likely to remain so. Fertilisers can be effectively utilised to augment the site's carrying capacity, thereby increasing yield potential. Additionally, they can serve as a valuable tool in bridging gaps in wood flow, among other benefits. Understanding the benefits of fertiliser use coupled with a tactical approach to their application is essential for optimising agricultural productivity.

There is a high need to be able to predict the likelihood of a site-specific growth response with a nutrient treatment for trees leaving the nursery or at planting. Given the variability in response magnitudes, the unpredictability of outcomes and a lack of data on broader site types it is currently not possible to expand upon past recommendations given in Table 3 (page 14). Further structured research work is required to predict any further. Steps towards this include assessing what models may be available that are relevant to treatments in the short time period from the nursery to planting. Moreover, including the complexities of a forest ecosystem through use of relevant indicators to ensure site-specific application is achieved or is even necessary.

A step forward in developing broader understanding and models will be to test response potential using a simple collaborative trial design over multiple sites. This approach was successfully applied in Brazil where under guidance each forestry company installed and shared data on plots stratified over a full site and soil range paired with existing permanent sampling plots and applied all nutrients required for tree growth (Stape, et al. 2006). More detailed process-oriented trials that include nutrient omission can be installed at key sites to further knowledge on interactions with tree belowground allocation, soil water, soil carbon, research on soil microbial processes that enhance nutrient access, uptake, and storage in the soil, and exploration of remote sensing technologies. Such trials can create a valuable understanding of site supply potential and should be part of a fertiliser research strategy. Thereafter specific elements and rates can be optimized. With such work, soil and site data would need to be captured to enable indicator testing and refinement and model development that is more precise and tailored to New Zealand soils and sites.

Considering benefits and risks

Allowing non-competing weed growth can also reduce nutrient leaching, and act as a temporary store of nutrients that are released when the weeds are controlled or outcompeted by the trees (Gadgil, et al. 1992). Some negative impacts can result from fertiliser addition (particularly nitrogen) in the nursery or after planting where trees are more prone to frost, insect, or disease damage. Weed or grass growth can also be stimulated, outcompeting trees (Barker 1978, Balneaves 1982). Impacts of these additives on insects and disease are, however, variable as certain reports reviewed in Barker (1978) indicate improved resistance to certain insects and pathogens (e.g. *Dothistroma pini).* This was further shown in Bulman, et al. (2008) for specific fungal pathogens. Nitrogen fertiliser addition can also result in oversized tree-tops and stimulate high root concentration in zones where fertiliser was added, negatively impacting wind stability due to an uneven root structure.

- Certain phosphorus fertilisers promote early root development and reduce the risk of frost damage and drought, while nitrogen fertiliser addition can increase risk of frost damage.
- Residual benefits of phosphorus fertiliser on severely phosphorus deficient soils in Riverhead Forest negated the need for fertilisation in the subsequent rotation.

The environmental impacts of fertiliser use in forestry, such as greenhouse gas emissions and runoff should also be considered. Several potential benefits of nutrient addition have been demonstrated in past research but are contrasted by various negative impacts and constraints such as lockup in the soil, leaching, and stimulation of weed growth. Nutrient management should prioritise the conservation of soil and maximise the retention of nutrients in the soil by retaining all the soil and as much organic matter on and in the soil as possible.

Past research and investment into enhancing tree quality from the nursery to the field is limited due to a range of factors. These include rising costs, a lack of clear understanding of potential gains due to variable responses across sites, past experimental trial designs that introduce excessive complexity without addressing present and future needs, the absence of a comprehensive database of soil characteristics at sufficient resolution, and concern around environmental impact (López-Díaz, et al. 2020). Cost can be an overriding decision criterion for any forest company, as costs incurred at establishment compound to rotation end, affecting cash flow. Cost-effectiveness of changes in nursery and planting practices therefore need to be evaluated by balancing the cost (and potential savings through reduced weed management or blanking) of additional practices (versus potential savings of not implementing) against value through discounted cash flow to rotation end. Full rotation cost-benefit analyses to support using or not using fertilisers and to motivate for further research will be unrealistic with the current dataset as responses were not measured to rotation end in past research. Only short-term economics may be considered, for example where fertiliser or stimulant use reduces other establishment costs such as reducing the need for blanking. Economic analysis also needs to include a comparative cost benefit of later fertiliser addition, such as at first or second thinning.

Indicators and growth response

Previous research in New Zealand has focused on identifying nutrient deficiencies and developing on-site soil and foliage indicators to support corrective treatments. Tree nursery nutrient requirements were developed using soil and foliage nutrient indicators to support application of fertiliser during seedling growth (Davis, et al. 2015). For planting in field, a likely response is determined using previous knowledge of the forest from foliar nutrient indicators, and/or extrapolation from forests on similar soils where a response was found in past research. Foliage nutrient indicators include tree crown visual symptoms and foliage nutrient testing to identify sites with nutrient deficiencies (Davis, et al. 2015, Will 1985). An understanding of nutrient deficiencies at planting, using foliage indicators, relies on previous rotation results, which may not be relevant to the following rotation. These soil and foliage nutrient indicators are still used today to identity nutrient requirements within the nursery, and to identify sites that have a nutrient deficiency after planting. Nutrient deficiency after planting can only be diagnosed after the trees have acclimatised and developed new mature leaves reflecting site conditions, which may be too late. In order to facilitate a decision support system that integrates site quality (soil, climate, topography), genetics, and management, it is necessary to develop knowledge and response data across multiple sites. This will allow for the creation of a matrix that indicates the likelihood of response, similar to that presented in Mead and Smith (2012). At present, this can only be accomplished for a limited number of sites that have previously conducted fertiliser trials and have shown indications of nutrient deficiency.

Past research underscored the importance of identifying reliable indicators for assessing soil and foliage nutrition in radiata pine plantations on nutrient deficient sites. As these indicators have focused on deficiencies they are limited to correcting for nutrient deficient sites. **As such, there is a need to develop indicators for predicting a growth response for all sites – improving productivity over care of correcting nutrient deficiencies.** There are examples emerging using other indicators (outside of soil and foliage) to cover the complexity of forest ecosystem nutrition. For example, the use of onsite foliage and soil natural abundance N isotopes (Garrett, et al. 2023). There is, however, a need to consider other co-limiting nutrients and to refine indicators and predictive models to enhance the effectiveness of site-specific nutrient management strategies in radiata pine plantations. Moreover, there is a need to target predictive models that apply to the time period of interest, (e.g., at planting) rather than applying a model that has been developed for another time period in the forest rotation.

What guidelines are foresters currently following?

Growers currently make use of fertilisers and application rates recommended for radiata pine at planting summarised in Davis, et al. (2015) which is based on the New Zealand Institute of Forestry (NZIF) Forestry Handbook guidelines set out in Mead (2005). These treatments are based on fertiliser addition at planting research over the past decades with responses summarised in Table 3. This research was developed in the 1980-90’s (Figure 2) over 3 decades ago and were targeted towards sites where a nutrient deficiency was identified. There are guidelines on treatment of seedlings during production and quality assessment specifications at lifting (Menzies 1988), but these may be outdated for use under modern nursery practices and are directly linked to field performance. There are currently no nutrient or stimulant based guidelines available to inform how to treat young trees once lifted from the tree nursery.

Table 3: Fertilisers and application rates recommended for radiata pine at planting taken from Davis, et al. (2015) based on Mead (2005).

Fertiliser	Nutrient content (%)							Quantity Applied
	N	P	K	S	Ca	Mg	Other	g/tree or as stated
Urea	46							25-60
Ammonium sulphate	20.5			24				60-100-180
Diammonium phosphate (DAP)	18	20		1				40-85
Magnesium ammonium phosphate (Magamp)	18	8				14		50
Superphosphate		9		11	20			60-100-180
Triple super		20		1	14-16			40-90
Reactive rock phosphates		11-16		0-1	32-38			500-1000 kg/ha
PARR phosphate		17			20			50-100
Potassium chloride			50					25-50
Potassium sulphate			42	17-18				50
Borax							11B	4
Ulexite							10B	4
Colmanite					19		16B	4

Recommended application rates developed on past research are likely to be beneficial when used on similar site types for which they were developed but will not be applicable to all other site types. They also cannot be widely prescribed due to increasing cost compounded over the rotation, changes in nutrient demand with improved tree genetics, natural and climate change related changes in weather patterns and silvicultural practices that differ from present day conditions. Foresters currently decide on fertiliser application if their sites have hosted past research or are on similar soils and growing conditions to past research sites. In addition, visual and laboratory-based foliar diagnostics from prior rotations may be used to indicate a fertiliser requirement. Some growers test response on un-replicated test-blocks as a guide for responsiveness of sites. Foresters may then base the cost decision on the expected probability of improved production or risk reduction (tree survival) and an expected economic gain at harvesting.

KEY KNOWLEDGE GAPS

Knowledge gaps identified through this review are:

- *Past research is targeted towards nutrient deficient sites* – Most past trials were targeted to nutrient poor sites known as responsive sites. The current management recommendations are therefore based on few trials that were concentrated on these poorest sites and limited soil testing. There are no targeted trials that have investigated growth responses across a range of sites. As a result, there is limited ability to extrapolate to unrelated site types where responses may occur due to various other mechanisms.

- No consideration of rotation number i.e. 2^{nd} or successive rotation requirements.

- *Uncertainty about the duration of the growth response* – A lack of data on response to rotation negates the ability to assess the economic benefit of the added fertiliser cost. Responses were believed to last for only 3 to 4 years as no data were collected to provide evidence of a continued response to rotation end. Fertiliser at planting was therefore thought to provide an early short-lived boost to tree growth, attributing only 4% to early growth.

- *Limited number of experimental research data* – The ability to interpolate and extrapolate research data with any amount of confidence requires data that covers a broad range of site and soil types. A lack of sufficient representation will result in levels of uncertainty in any predictive model larger than the response margin.

- *There is limited data on fertiliser addition at planting* and these data are biased towards certain elements for deficient sites. Comparatively less data is available on nutrients added after trees are lifted from the nursery. This makes it challenging when deciding where to focus research at tree lifting or at planting.

- *Narrow treatment options* – Past focus on a small group of nutrients also limits understanding of response opportunities outside of deficiency correction. Further work in understanding response needs to be through a balanced nutrient approach as certain elements may only be responsive when combined with other elements (For example: a growth response to boron can occur when added with nitrogen and phosphorus).

- *Relevance of past research to forest establishment today* – There is still opportunity to expand knowledge on fertiliser and stimulant response in a more structured manner to represent present-day site conditions, genetic material, and alternative fertiliser sources (for example biuret and organically complexed fertilisers).

- *Predicting the likelihood of a growth response* – Research results on the growth response to nutrient treatments are mixed. There is a high need to have a tool/model specific to predicting the likelihood of a growth response for early tree establishment.

A number of these research gaps were also highlighted through engagement with forestry companies during this review. Including, the lack of a broader understanding around fertiliser use echoed by various industry stakeholders, highlighting the need for further research on responses across broader site and soil types, including opportunities for optimising seedling treatment from nursery to planting. They also identified the lack of research on how seedlings should be treated from nursery to planting and how this can be used to optimise growth and ensure successful establishment. The integration of the additional chemical application with mechanised planting (including fertilisers, pesticides or other ameliorants) was seen as a major advantage by the forestry industry. This has potential to improve current practices and future proof machinery by incorporating mechanical application of chemicals in machine design thereby ensuring adaptability to evolving needs. These precision forestry practices can optimise fertiliser application by consistently targeting more precise application to the trees that require additional nutrition and using formulations with greater efficacy and lower costs while reducing negative impacts such as root scorch or soil fixation.

CONCLUSION

The use of fertilisers and stimulants in New Zealand forestry is integral to enhancing tree growth, health, and overall forest productivity. Current practices occur as a range of methods and application rates from nursery stages to establishment and mature stands. These approaches are based partially on research, internal company testing and local knowledge and experience. The insights from the various studies here provide a partial understanding of potential gain from fertiliser or stimulant used at planting or in the nursery and are applicable to a relatively narrow range of site types. This is due to most past trials allocated to sites that were known to be deficient in certain nutrient elements. Past research emphasises the importance of good silviculture when using fertilisers. A lack of soil cultivation on sites with impenetrable soil layers and/or a lack of competing vegetation control can negate the benefit of fertiliser. Use of mechanised fertiliser addition at planting as part of a precision forestry approach can optimise fertiliser application on currently responsive sites. A targeted and more precise application to the trees can aid in ensuring correct quantity and placement to limit negative impacts such as root scorch. The ability to mechanically apply any chemical with planting (for example: pesticides, hydrogels, fertilisers) will be highly beneficial and should be included in machine design irrespective of a need for fertiliser.

Currently methods to predict likelihood of response to fertiliser or stimulant use are based on generalised soil maps and limited data. Models to predict response can be beneficial but require complex research and site data. Maps with surfaces of response likelihood and magnitude are a better choice as these are simple to understand and are more likely to be taken up by the end users. Developing these will require updated research data across all commonly planted soil types and climatic ranges using new trials to explore response likelihood and magnitude.

RECOMMENDATIONS

Recommendations to address the knowledge gaps with a focus on where the PSP program would add value to the forest industry tree establishment practice are:

- *Targeted nutritional treatment experimental trials* – A network of trials of simple design across a range of site to test whether a site is responsive or not, and permanent sample plots monitored to rotation end. This can be followed by optimisation trials to find the best response with the greatest economic benefit.

- *Broadening the range of treatments* – Further opportunities exist to expand nutrient enhancement of seedlings in the nursery, testing less harsh fertiliser sources, and site-specific microbial inoculation. Research on alternative fertiliser sources that are more effective in the soil physical, chemical and microbial environment and easier to transport and apply mechanically. Research on soil microbial processes that enhance nutrient access, uptake, and storage in the soil. There may also be an opportunity to combine these with cellulose-based hydrogels.

- *Monitoring and data* – Exploration of remote sensing and spatial technologies to track response over time and interpolate to related sites. Plus, collection of other data, for example soil data, to support for a more precise site/soil understanding.

- *Collaborative effort*– A collaborative effort is needed to ensure maximum benefit from new targeted nutritional treatment trials and data. This includes for example, engaging and supporting new trials that have specific goals and design. Plus, sharing of data and results for the best outcome for New Zealand planted forests.

- *Cost benefit analysis* - Undertake an analysis encompassing the costs of nutrient treatment during planting and throughout the rotation. Assess whether the use of mechanised planting equipment reduces cost risks. Identify the optimal timing within the rotation to maximise benefits, enabling targeted planning of experimental trials.

- *Predicting the likelihood of a growth response* – Investigation into and the development of a tool/model to predict the likelihood of a site-specific growth response that are relevant to nutrient treatments in the short time period from the nursery to planting and using relevant research data. With consideration given to including the complexities of a forest ecosystem through use of relevant indicators to ensure site-specific application. Data from the specifically designed trials, described above, can be used to develop site-specific indicators and models.

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REFERENCES

1. MPI. 2022 A national exotic forest description as at 1 April 2022. Ministry of Agriculture and Forestry. TeuruRakau, Wellington, New Zealand.
2. MPI. 2022 Provisional estimates of tree stocks sales and forest planting in 2022. Ministry for Primary Industries. TeuruRakau, Wellington, New Zealand.
3. Balneaves, J., Menzies, M. and Hong, S. 1996 Establishment practices can improve longer–term growth of Pinus radiata on a dry-land hill forest. *New Zealand Journal of Forestry Science*, **26** (3), 370-379.
4. Davis, M., Xue, J. and Clinton, P.W. 2015 Planted-forest Nutrition. *Science publication*. New Zealand Forest Research Institute Ltd (trading as Scion). Rotorua, p. 134.
5. Scion. 2019 Fertiliser use. New Zealand planted forests environmental facts., p. 4.
6. Smaill, S.J. and Clinton, P.W. 2016 Overview of the issues affecting fertiliser use in New Zealand's radiata pine forests. *New Zealand Journal of Forestry*, **61** (2), 11-15.
7. Orwin, K.H., Stevenson, B.A., Smaill, S.J., Kirschbaum, M.U.F., Dickie, I.A., Clothier, B.E., Garrett, L.G., van der Weerden, T.J., Beare, M.H., Curtin, D., de Klein, C.A.M., Dodd, M.B., Gentile, R., Hedley, C., Mullan, B., Shepherd, M., Wakelin, S.A., Bell, N., Bowatte, S., Davis, M.R., Dominati, E., O'Callaghan, M., Parfitt, R.L. and Thomas, S.M. 2015 Effects of climate change on the delivery of soil-mediated ecosystem services within the primary sector in temperate ecosystems: a review and New Zealand case study. *Global Change Biology*, **21** (8), 2844-2860.
8. Garrett, L.G., Smaill, S.J., Addison, S.L. and Clinton, P.W. 2021 Globally relevant lessons from a long-term trial series testing universal hypothesis of the impacts of increasing biomass removal on site productivity and nutrient pools. *Forest Ecology and Management*, **494**, 10.
9. Bayne, K., Botero, J., Parker, R., Baker, M., Dixon, B., Schoonderwoerd, R. and Rolando, C. 2023 A review of the performance of the M-Planter in NZ. . *Technical report prepared for Forest Growers Research Ltd (FGR) Precision Silviculture Partnership Program*.
10. Ballard, R. 1978 Use of fertilisers at establishment of exotic forest plantations in New Zealand. *New Zealand Journal of Forestry Science*, **8** (1), 70-104.
11. Will, G.M. 1985 Nutrient Deficiencies and Fertiliser Use in New Zealand Exotic Forests. *New Zealand Forest Service, Forest Research Institute, Bulletin No. 97*.
12. Menzies, M. 1988 Seedling quality and seedling specifications of radiata pine. What's New in Forest Research. No. 171, 4 pp.
13. Beets, P., Kimberley, M., Garrett, L., Paul, T. and Matson, A. 2019 Soil productivity drivers in New Zealand planted forests. *Forest Ecology and Management*, **449**, 117480.
14. Watt, M.S., Davis, M.R., Clinton, P.W., Coker, G., Ross, C., Dando, J., Parfitt, R.L. and Simcock, R. 2008 Identification of key soil indicators influencing plantation productivity and sustainability across a national trial series in New Zealand. *Forest Ecology and Management*, **256** (1-2), 180-190.
15. Ross, C.W., Watt, M.S., Parfitt, R.L., Simcock, R., Dando, J., Coker, G., Clinton, P.W. and Davis, M.R. 2009 Soil quality relationships with tree growth in exotic forests in New Zealand. *Forest Ecology and Management*, **258** (10), 2326-2334.
16. Coker, G., Xue, J., Leckie, A., Henley, D., Glogoski, D., Dickson, G., Bayne, K. and Hill, S. 2022 Extending the Planting Season Managing delays in planting – the use of hydrogels. . *Te Uru Rākau*. New Zealand Forest Service
17. Xue, J., Bakker, M.R., Milin, S. and Graham, D. 2022 Enhancement in soil fertility, early plant growth and nutrition and mycorrhizal colonization by vermicompost application varies with native and exotic tree species. *Journal of Soils and Sediments*, **22** (6), 1662-1676.
18. Liu, Q. 2005 *Rhizosphere processes influencing soil and fertilizer phosphorus availability to Pinus radiata: a thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Soil Science at Massey University, Palmerston North, New Zealand*, Massey University.
19. Davis, M., Grace, L. and Horrell, R. 1996 Conifer establishment in South Island high country: Influence of mycorrhizal inoculation, competition removal, fertiliser application, and animal exclusion during seedling establishment. *New Zealand Journal of Forestry Science*, **26** (3), 380-394.

20. Whelan, H. 2023 Bioprotection for foliar diseases and disorders of radiata pine. *Report prepared for New Zealand Forest Growers Research. Project Overview January 2022 to December 2022*. Lincoln University. Lincoln, New Zealand.
21. Smaill, S.J. and Walbert, K. 2013 Fertilizer and fungicide use increases the abundance of less beneficial ectomycorrhizal species in a seedling nursery. *Applied Soil Ecology*, **65**, 60-64.
22. Smaill, S.J., Walbert, K. and Osorio, R. 2020 Reduced fungicide use in the nursery improves post-planting productivity of Pinus radiata for at least six years. *Forest Ecology and Management*, **475**.
23. Hawkins, B.J., Xue, J., Bown, H.E. and Clinton, P.W. 2010 Relating nutritional and physiological characteristics to growth of Pinus radiata clones planted on a range of sites in New Zealand. *Tree Physiology*, **30** (9), 1174-1191.
24. Powers, R.F. 1999 On the sustainable productivity of planted forests. *New Forests*, **17** (1), 263-306.
25. Stape, J.L., Binkley, D., Jacob, W.S. and Takahashi, E.N. 2006 A twin-plot approach to determine nutrient limitation and potential productivity in Eucalyptus plantations at landscape scales in Brazil. *Forest Ecology and Management*, **223** (1), 358-362.
26. Gadgil, R.L., Charlton, J., Sandberg, A. and Allen, P. 1992 Nutritional relationships between pampas grass (Cortaderia spp.) and Pinus radiata. *New Zealand Journal of Forestry Science*, **22** (1), 3-11.
27. Barker, J. 1978 Some silvicultural effects of fertilisation. *NZJ For. Sci*, **8** (1), 160-177.
28. Balneaves, J.M. 1982 *Grass control for radiata pine establishment on droughty sites*. New Zealand Forest Service.
29. Bulman, L., Ganley, R. and Dick, M. 2008 Needle diseases of radiata pine in New Zealand. *Scion Client Report*, **13010**, 1-81.
30. López-Díaz, M.L., Benítez, R., Rolo, V. and Moreno, G. 2020 Managing high quality timber plantations as silvopastoral systems: tree growth, soil water dynamics and nitrate leaching risk. *New Forests*, **51**, 985-1002.
31. Mead, D. and Smith, C. 2012 Principles of nutrient management for sustainable forest bioenergy production. *WIREs Energy and Environment*, **1** (2), 152-164.
32. Garrett, L.G., Lin, Y., Matson, A.L. and Strahm, B.D. 2023 Nitrogen isotope enrichment predicts growth response of Pinus radiata in New Zealand to nitrogen fertiliser addition. *Biology and Fertility of Soils*, **59** (5), 555-566.
33. Mead, D.J. 2005 *Fertilising*. The New Zealand Institute of Forestry: Christchurch, New Zealand.
34. Thomas, M. and Spurway, M. 1997 A review of specialised root systems, and their relevance in New Zealand nurseries. The International Plant Propagators' Society.
35. Haase, D.L., Rose, R. and Trobaugh, J. 2006 Field performance of three stock sizes of Douglas-fir container seedlings grown with slow-release fertilizer in the nursery growing medium. *New Forests*, **31**, 1-24.
36. Dyck, W.J. and Beets, P.N. 1987 Managing for long-term site productivity. *New Zealand Forestry, November 1987*, 23-26.
37. Smaill, S.J., Garrett, L.G. and Addison, S.L. 2023 Accelerator trial series in Pinus radiata stands in New Zealand: Trial establishment, site description and initial soil, forest floor and tree data. *Data Brief*, **47**, 108991.
38. Smaill, S.J., Clinton, P.W. and Höck, B.K. 2011 A nutrient balance model (NuBalM) to predict biomass and nitrogen pools in Pinus radiata forests. *Forest Ecology and Management*, **262** (2), 270-277.
39. Appleton, E. and Slow, L. 1966 *Nutritional disorders and fertilizer trials in Pinus radiata stands in Waimea county, Nelson*. New Zealand Forest Service.
40. Armitage, I. 1969 The establishment of second-rotation radiata pine in Riverhead Forest. New Zealand Forest Service.
41. Adams, J.A. and Walker, T.W. 1975 Nutrient relationships of Radiata pine in Tasman Forest, Nelson. *New Zealand journal of forestry science* **5**(1), 18-32.
42. Ballard, R. 1978 Effect of first rotation phosphorus applications on fertiliser requirements of second rotation radiata pine. *NZJ For. Sci*, **8** (2), 135-145.

43. Mead, D. and Gadgil, R.L. 1978 Fertiliser use in established radiata pine stands in New Zealand. *New Zealand Journal of Forestry Science*, **8** (1), 105-134.
44. Woollons, R.C. and Will, G.M. 1975 Increasing growth in high production radiata pine stands by nitrogen fertilisers. *New Zealand Journal of Forestry*, **20**, 243-253.
45. Davis, M., Ledgard, N. and Nordmeyer, A. 2001 Determining fertiliser requirements for the establishment of pines and Douglas-Fir in the South Island high-country. *New Zealand Journal of Forestry Science*, **31** (1), 18-33.
46. Payn, T., Skinner, M. and Clinton, P. 1998 Future nutrient requirements of New Zealand plantation forests. *Long-term Nutrient Needs for New Zealand's Primary Industries. Occasional report* (11), 97-110.
47. Mead, D.J. and Pimentel, D. 2006 Use of energy analyses in silvicultural decision-making. *Biomass and Bioenergy*, **30** (4), 357-362.
48. West, G. 1984 Establishment requirements of Pinus radiata cuttings and seedlings compared. *New Zealand Journal of Forestry Science*, **14** (1), 41-52.
49. Barton, I. 1985 Early growth and survival of Acacia melanoxylon: effect of weed control and fertiliser. *New Zealand Journal of Forestry Science*, **15** (1), 111-116.
50. Payn, T.W. 1991 *The effects of magnesium fertiliser and grass on the nutrition and growth of P. radiata planted on pumice soils in the central North Island of New Zealand.* Doctor of Philosophy University of Canterbury.
51. Richardson, B., Vanner, A., Davenhill, D., Balneaves, J., Miller, K. and Ray, J. 1993 Interspecific competition between Pinus radiata and some common weed species-first-year results. *NZJ Forestry Sci*, **23**, 179-193.
52. Olykan, S.T., Xue, J., Clinton, P.W., Skinner, M.F., Graham, D.J. and Leckie, A.C. 2008 Effect of boron fertiliser, weed control and genotype on foliar nutrients and tree growth of juvenile Pinus radiata at two contrasting sites in New Zealand. *Forest Ecology and Management*, **255** (3-4), 1196-1209.
53. Skinner, M., Hunter-Smith, J., Graham, J.D. and Kimberley, M.O. 1995 Weed control and the uptake of fertiliser P from various sources by young radiata pine at three sites. New Zealand Forest Site Management Cooperative Report No. 75.
54. Skinner, M., Kimberley, M. and Graham, D. 2000 The effect of boron fertilisers and weed control on the boron nutrition of young radiata pine. Results after 12 years. New Zealand Forest Site Management Cooperative Report No. 113.
55. Skinner, M., Graham, D. and Kimberley, M. 2001 The effect of fertilising weed control and silviculture on the growth of radiata pine at Hunua forest – Updating the results through to 2000. New Zealand Forest Site Management Cooperative Report No. 114.
56. Kimberley, M. and Clinton, P. 2000 Analysis of Eyrewell weed competition experiment at age seven. New Zealand Forest Site Management Cooperative Report No. 110.
57. Simcock, R.C., Parfitt, R.L., Skinner, M.F., Dando, J. and Graham, J.D. 2006 The effects of soil compaction and fertilizer application on the establishment and growth of Pinus radiata. *Canadian Journal of Forest Research*, **36** (5), 1077-1086.
58. Nish, F. 2021 *Assessing interactions between silvicultural treatment and site effects on carbon sequestration in Pinus radiata D. Don Plantations.* Bachelor of Forestry Science, Honours., University of Canterbury, New Zealand.
59. Yallop, K. 2021 *Effect of silvicultural regimes on carbon sequestration in Pinus radiata forest in Canterbury.* Bachelor of Forestry Science, Honours., University of Canterbury, New Zealand.
60. Smaill, S.J. and Garrett, L.G. 2016 Multi-rotation impacts of increased organic matter removal in planted forests. *Journal of soil science and plant nutrition*, **16**, 287-293.
61. Garrett, L.G., Smaill, S.J. and Clinton, P.W. 2015 Nutrient supply one rotation to the next. *New Zealand Journal of Forestry*, **60** (2), 16-20.
62. Smaill, S.J., Clinton, P.W. and Greenfield, L.G. 2008 Postharvest organic matter removal effects on FH layer and mineral soil characteristics in four New Zealand *Pinus radiata* plantations. *Forest Ecology and Management*, **256** (4), 558-563.
63. Smith, C.T., Lowe, A.T., Skinner, M.F., Beets, P.N., Schoenholtz, S.H. and Fang, S. 2000 Response of radiata pine forests to residue management and fertilisation across a fertility gradient in New Zealand. *Forest Ecology and Management*, **138** (1-3), 203-223.

64. Smith, C.T., Lowe, A.T., Beets, P.N. and Dyck, W.J. 1994 Nutrient accumulation in second-rotation *Pinus radiata* after harvest residue management and fertiliser treatment of coastal sand dunes. *New Zealand Journal of Forestry Science*, **24** (2/3), 362-389.
65. Garrett, L.G., Smaill, S.J., Beets, P.N., Kimberley, M.O. and Clinton, P.W. 2021 Impacts of forest harvest removal and fertiliser additions on end of rotation biomass, carbon and nutrient stocks of *Pinus radiata*. *Forest Ecology and Management*, **493**, 119161.
66. Addison, S.L., Smaill, S.J., Garrett, L.G. and Wakelin, S.A. 2021 Fertiliser use has multi-decadal effects on microbial diversity and functionality of forest soils. *Applied Soil Ecology*, **163**, 103964.
67. Addison, S., Smaill, S., Garrett, L. and Wakelin, S. 2019 Effects of forest harvest and fertiliser amendment on soil biodiversity and function can persist for decades. *Soil Biology and Biochemistry*, **135**, 194-205.
68. Hunter, I.R., Graham, J.D. and Prince, J.M. 1989 Response of radiata pine to varying rates of nitrogen and phosphorus fertiliser at five sites in New Zealand. New Zealand Forest Site Management Cooperative Report No. 37.
69. Mason, E.G. 1992 Decision-support systems for establishing radiata pine plantations in the Central North Island of New Zealand.
70. Hunter, I.R. 1991 An Atlas of radiata pine nutrition in New Zealand. Forest Research Institute, Rotorua, New Zealand.
71. Li, Y., Xue, J., Clinton, P.W. and Dungey, H.S. 2015 Genetic parameters and clone by environment interactions for growth and foliar nutrient concentrations in radiata pine on 14 widely diverse New Zealand sites. *Tree Genetics & Genomes*, **11** (1), 10.
72. Garrett, L.G., Sanderman, J., Palmer, D.J., Dean, F., Patel, S., Bridson, J.H. and Carlin, T. 2022 Mid-infrared spectroscopy for planted forest soil and foliage nutrition predictions, New Zealand case study. *Trees, Forests and People*, **8**, 100280.
73. Klomp, B.K. and M., D. 1986 The Effects of Ripping and Fertiliser on the Performance of 1-Year-Old Cuttings and Seedlings.. Project workplan description 1326.
74. Hunter, I.R. 1989 Growth to age 15 in the long-term rock-phosphate/superphosphate comparison trial: AK734. New Zealand Forest Site Management Cooperative Report No. 43.
75. King, J.M. 1988 Basal area and volume response of Pinus radiata to application of phosphorus fertilisers of varying solubility on sites displaying different degrees of phosphorus retention: 7 years after application. National Forest Fertiliser Co-operative Report No. 33.
76. Jacks, H. and Fitzgerald, R.E. 1971 Results of Soils and Nutrition Experiments in Nelson, 1971 (Unpublished report No. 34). Rotorua, New Zealand: Forest Research Institute, New Zealand Forest Service.
77. Phillips, G. 1987 An evaluation of the accuracy of the Auckland clays growth model with fertiliser effects. Project record 1528.
78. Hunter, J.A.C. 1990 The nitrogen and phosphorus central composite series of trials. Results after seven years. *New Zealand Forest Site Management Cooperative*.
79. Hunter, I.R. and Graham, J.D. 1982 Growth response of phosphorus-deficient Pinus radiata to various rates of superphosphate fertiliser. New Zealand Journal of Forestry Science 12, 49-61.
80. Skinner, M.F., Hunter-Smith, S.J., Graham, J.D. and Kimberley, M.O. 1995 Long-term studies on the use of superphosphate fertiliser for radiata pine on soils of low to medium P retention capacity in the North Island of New Zealand. New Zealand Forest Site Management Cooperative Report No. 74.
81. Skinner, M. and Graham, D. 1998 Phosphorus deficiency in second rotation pines at Riverhead Forest: the "Museum" plots revisited. Part 1: The re-establishment phase. *Internal report*. Scion.
82. Xue, J. and Graham, D. 2009 Boron Nutrition and Wood Quality trial series - Update Report for FR358/4.
83. Olykan, S., Payn, T., Beets, P. and Kimberley, M. 2001 Magnesium fertilisers affected growth, upper mid-crown yellowing, and foliar nutrients of Pinus radiata, and soil magnesium concentration. *New Zealand Journal of Forestry Science*, **31** (1), 34-50.

84. Hunter, I.R., Graham, D.J., Prince, J.M. and Nicholson, G.M. 1986 What site factors determine the 4-year basal area response of Pinus radiata to nitrogen fertiliser. New Zealand Journal of Forestry Science, 16(1), 30-40. .
85. Payn, T.W. 1991 The effects of magnesium fertiliser and grass on the nutrition and growth of P. radiata planted on pumice soils in the central North Island of New Zealand.
86. Skinner, M., Graham, D. and Kimberley, M. 2001 The effect of fertilising weed control and silviculture on the growth of radiata pine at Hunua forest – Updating the results through to 2000. New Zealand Forest Site Management Cooperative Report No. 114.
87. Skinner, M., Graham, D. and Kimberley, M. 2002 The effect of nitrogen, phosphorus and boron fertiliser in conjunction with weed control on the growth and nutrition of a pole stage stand of radiata pine from age 7 to 17 years in Mamaku Forest,.
88. Knight, P. 1978 Fertiliser practice in New Zealand forest nurseries. *NZJ For Sci*, **8** (1), 27-53.
89. Fisher, R.F. and Binkley, D. 2000 *Ecology and management of forest soils*. Third edition edn. John Wiley and Sons, inc. New York, 489 p.
90. Turner, J. and Lambert, M.J. 2011 Analysis of nutrient depletion in a radiata pine plantation. *Forest Ecology and Management*, **262** (8), 1327-1336.
91. Will, G.M. and Hodgkiss, P.D. 1977 Influence of nitrogen and phosphorus stress on the growth and form of radiata pine. *New Zealand Journal of Forestry Science*, **7** (3), 307-320.
92. Ameray, A., Bergeron, Y., Valeria, O., Montoro Girona, M. and Cavard, X. 2021 Forest carbon management: A review of silvicultural practices and management strategies across boreal, temperate and tropical forests. *Current Forestry Reports*, 1-22.
93. Giardina, C., Binkley, D., Ryan, M., Fownes, J. and Senock, R. 2004 Belowground carbon cycling in a humid tropical forest decreases with fertilization. *Oecologia*, **139** (4), 545-550.
94. Misra, R.K., Turnbull, C.R.A., Cromer, R.N., Gibbons, A.K. and LaSala, A.V. 1998 Below- and above-ground growth of *Eucalyptus nitens* in a young plantation: I. Biomass. *Forest Ecology and Management*, **106** (2-3), 283-293.
95. Cannell, M.G.R., Sheppard, L.J. and Milne, R. 1988 Light Use Efficiency and Woody Biomass Production of Poplar and Willow. *Forestry*, **61** (2), 125-136.
96. Sands, R. and Mulligan, D.R. 1990 Water and nutrient dynamics and tree growth. *Forest Ecology and Management*, **30** (1-4), 91-111.
97. Dickmann, D.I., Nguyen, P.V. and Pregitzer, K.S. 1996 Effects of irrigation and coppicing on above-ground growth, physiology, and fine-root dynamics of two field-grown hybrid poplar clones. *Forest Ecology and Management*, **80** (1-3), 163-174.
98. Payn, T. and Clinton, P. 2005 The environmental footprint of New Zealand's plantation forests: nutrient fluxes. *New Zealand Journal of Forestry*, **50** (1), 17-22.
99. Bown, H.E. and Watt, M.S. 2016 Stem and soil CO2 efflux responses of Pinus radiata plantations to temperature, season, age, time (day/night) and fertilization. *Ciencia e investigación agraria*, **43**, 95-109.
100. Mason, R.E., Craine, J.M., Lany, N.K., Jonard, M., Ollinger, S.V., Groffman, P.M., Fulweiler, R.W., Angerer, J., Read, Q.D., Reich, P.B., Templer, P.H. and Elmore, A.J. 2022 Evidence, causes, and consequences of declining nitrogen availability in terrestrial ecosystems. *Science*, **376** (6590), eabh3767.
101. Garrett, L.G., Smith, C.T., Beets, P.N. and Kimberley, M.O. 2021 Early rotation biomass and nutrient accumulation of Pinus radiata forests after harvest residue management and fertiliser treatment on contrasting types of soil. *Forest Ecology and Management*, **496**.
102. Clinton, P.W. Modelling competitive pasture effects on nutrient uptake by Pinus radiata.
103. Clinton, P., Garrett, L. and Smaill, S. 2021 Long-term site productivity research - 30 plus years in the making. *New Zealand Journal of Forestry*, **66** (2), 11-15.

APPENDIX 1: A HISTORY OF NUTRIENT TREATMENT RESPONSES

Enhancements at the Nursery

Chemical and physical

Past research work explored various methods and enhancements at the nursery to improve tree growth, nutrient uptake, and overall performance of seedlings in various environmental conditions. One of the earlier methods during the late 1950s involved soaking the roots of lifted trees in mud and super-phosphate to prepare for phosphorus deficient sites. While this resulted in improved growth, it also led to increased mortality (Ballard 1978). A similar method tested with boron also demonstrated improved growth but increased mortality (while not mentioned, this may have been due to the solubility of the boron used). Continuation of this approach may yet have potential if alternative fertilisers are used to overcome root scorching. This approach was also used with hydrogels to extend the planting season and enhance crop productivity. This demonstrated that dipping tree roots into cellulosic hydrogels significantly increased root water uptake, leading to improved survival and growth under dry conditions two months after planting (Coker, et al. 2022). The potential for hydrogel applications to improve water retention and support tree survival during water limited conditions should be investigated further. This testing needs to include an understanding of the various hydrogel types, their methods of application and both the positive and negative implications for tree growth and cost (Coker, et al. 2022).

Research on post-planting impacts of long-term chilling and ethylene treatment in the nursery found that long-term chilling produced negative effects on post-planting survival and growth. Trees were planted late, outside the planting season in Tarawera forest with growth reported on 10 months after planting. The moderate application of ethylene consistently produced better, although non-significant growth rates in the forest (Smaill, 2022).

Mycorrhiza

The importance of mycorrhiza formed between mycorrhizal fungi and tree roots, as well as other mechanisms like nitrogen-fixing nodules and proteoid root systems, for enhancing nutrient uptake and resistance to environmental stressors was first highlighted in a review by (Thomas and Spurway 1997). The review discusses how these mechanisms can improve nutrient uptake, particularly phosphorus, and enhance resistance to pathogens, drought, and temperature extremes. This was demonstrated in a pot trial that applied phosphate rock fertilisers to radiata pine in phosphorus deficient allophanic volcanic ash soil, significantly increasing seedling growth and phosphorus uptake over a 10-month period (Liu 2005). This was further enhanced by the rhizosphere processes specific to radiata pine. The significance of specialised root systems differs by plant species, mycorrhizal associations, and relevance to nursery practices. The development of such associations may be reduced when fertilisers are added, as plants may allocate less energy to symbiotic relationships when nutrients are readily available through fertilisation. The use of vermicompost was found to enhance radiata pine tree growth in nursery pot trials without negatively impacting mycorrhiza. This increase was attributed to improved nitrogen and phosphorus nutrition due to enhanced root growth and soil enzyme activity, leading to better nitrogen and phosphorus nutrition for the trees (Xue, et al. 2022).

A study of ectomycorrhizal fungus *Hebeloma crustuliniforme* applied to the seedlings under nursery conditions also resulted in improved seedling health (Liu 2005). The benefit of healthy mycorrhiza was again demonstrated in a trial in Smaill and Walbert (2013) where although inoculation had no benefit, fertiliser addition plus reduced fungicide use enhanced tree growth. Reduced fungicide use in the nursery ensured that native mycorrhiza were preserved on trees leaving the nursery. Reduced fungicide was later shown to enhance field performance at six years after planting (Smaill, et al. 2020). In another study, while not nursery but seed related, seeds inoculated with mycorrhiza on a depleted grassland soil in a South Island dry site produced positive effects on two sites. These utilised locally collected sporophores of four ectomycorrhizal fungi species of *Pinus* spp. Inoculations were either as drilled into seeds or into the soil, with seed drilling producing best responses. Fertilisation here resulted in tree mortality (Davis, et al. 1996). Trichoderma mixtures applied at the nursery were shown to significantly enhance young tree growth and reduced foliar disease incidence in trials across Bay of Plenty / Waikato, Northland, and Gisborne regions (Whelan 2023). The study also cited improvements in tree uniformity and stem volume at various locations. Such use of added mycorrhiza is currently practiced by certain New Zealand seed producers as an optional seed coating on seed supplied to nurseries.

Beyond this work, there is very little work providing evidence of addition of stimulants or fertilisers in the nursery benefiting performance in the field. There may yet be potential to explore this given the positive response to dipping seedlings above, but with a need to reduce root scorch.
An example of this is shown in international publications such as in Haase, et al. (2006) who demonstrated slow-release fertiliser addition in the nursery improved growth for four years after planting.

A history of fertiliser addition at planting

Fertiliser addition at establishment for New Zealand planted forest began with nitrogen in the 1950s followed by research in the 1960s testing phosphorus added to deficient clay soils in Auckland and Nelson regions (Ballard 1978). Research followed a similar approach to international planted forest research, initially applying small quantities of nutrients to targeted forests in an aim to correct nutrient deficiencies or imbalances diagnosed though foliar and soil testing. During 1970 to 1990, research focused primarily on nutrient deficiencies with foliar and basic soil testing used as the tool to identify deficiencies. Research during this era investigated the impact of various phosphate rates and formulations in forestry trials gradually expanding across a diverse range of soil types in New Zealand. Positive growth responses were observed in trials on Northland and Coromandel clays, sandy podzol, pumice, brown soil, and pakihi podzol in Westland, expanding further over the North and South islands. In response to Barker (1978), research and fertiliser use grew to exploring a variety of additional benefits that included improved survival and growth, manipulation of wood properties, and improved flower and seed production expanding on this work. Exploration of additional benefits of fertiliser later evolved to research into methods for preserving or increasing soil nutrient status, and replacing nutrients lost during harvest removal in an effort to maintain long-term tree productivity and soil health (Dyck and Beets 1987). Fertiliser addition at planting, however, became more focussed on sites identified as most likely to respond, such as those with nutrient poor soils or soils with low bioavailability, expanding to investigate periods of high nutrient demand, testing key elements known to be responsive (Davis, et al. 2015).

A major component of past work after Ballard (1978) included continued testing of fertiliser formulations and methods of placement and timing of application to overcome negative interactions between the fertiliser and the soil; avoiding root scorch and optimising cost/benefit. Research on fertiliser formulations was beneficial at that time with certain formulations still in use today (for example urea as a nitrogen source, superphosphate as a phosphorus source). As certain formulations have become outdated due to costs, technology changes and environmental awareness, testing of formulations continues (for example biuret in Smaill, et al. (2023).

The focus of fertiliser addition post 2000 shifted from at planting to application later in the rotation in an effort to supply tree nutrient demand during rapid growth stages (Smaill, et al. 2011), a period during which demand outstrips supply (Figure A1.1).

An analysis of the Scion trials database provides a demonstration of the research activity around fertiliser addition at planting through time (Figure A1.1) and including these trials with records of fertiliser addition experiments in the Scion PSP database shows a general spatial distribution over the decades (Figure A3.1). Much of the field research was carried out prior to 2000 and forms the basis of present understanding. Research that included fertiliser addition at planting after 2000 was targeted towards enhancing site productivity over multiple rotations by optimising site resource supply and demand, and inclusion of other nutrient rich products at planting.

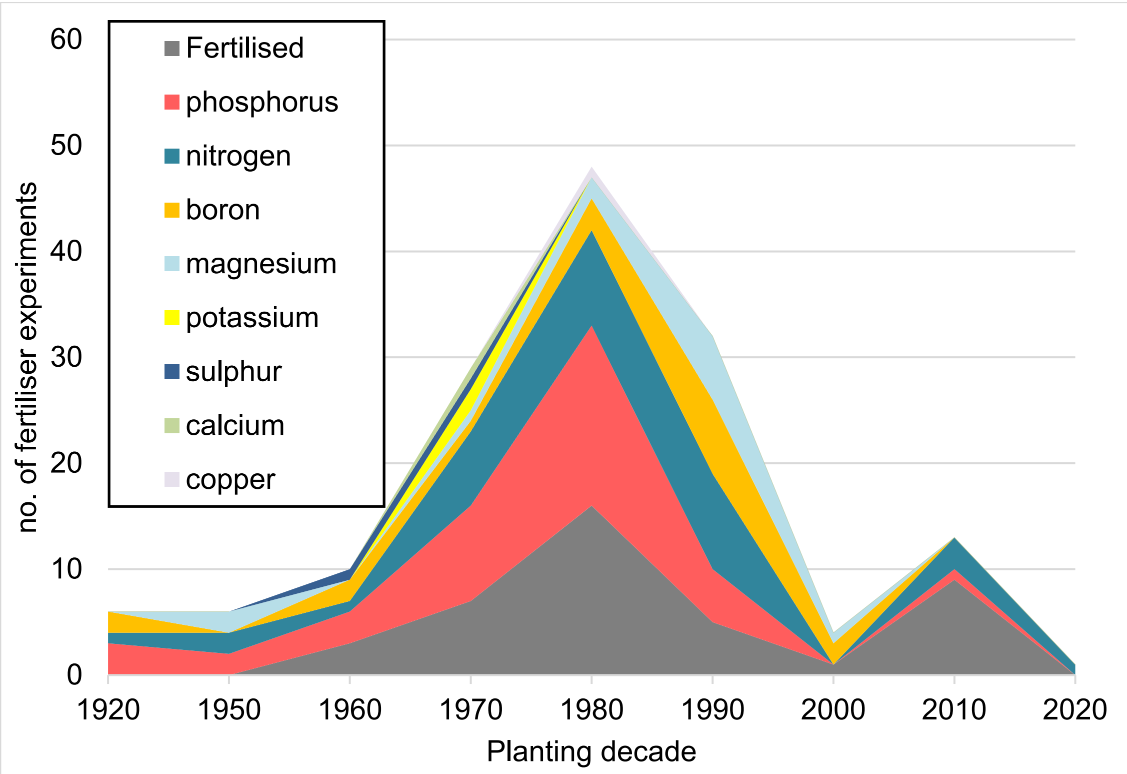


Figure A1.1: Number of trials captured in the Scion trial database mentioning fertiliser addition at planting by decade. Primary elements tested are represented as separate colours often include mixes with other elements. “Fert” implies that information on the element applied was not given in the database. Not all trials are documented or contributed to the review.

Addressing nutrient deficiencies (1960s)

Addressing nutrient deficiencies in New Zealand soils, particularly nitrogen and boron, was shown to have beneficial effects on tree growth and health when applied appropriately at planting or in the nursery (Appleton and Slow 1966). Evidence at that stage suggested that targeted fertiliser application, such as increasing boron levels through methods like spraying nursery beds and dipping seedlings, could improve early survival of radiata pine seedlings. The application of phosphorus as monoammonium phosphate (MAP) near each tree at planting was shown to enhance height growth. It was noted that placing fertilisers in the planting hole is a convenient method but requires careful consideration to avoid harming young trees as direct contact with certain fertilisers was found to harm young trees resulting in mortality or reduced growth. According to Armitage (1969), results from several experimental areas in Riverhead justified the use of chemical fertilisers for significantly accelerating the early growth of radiata pine trees. Adequate early hand topdressing with phosphorus fertiliser demonstrated positive effects on tree health and vigour. In 1967, manual topdressing using these fertilisers in different stands showed a reversal of the decline in tree health. These findings suggested that proper fertiliser application at planting could address health and vigour issues in trees, with different fertilisers showing varying degrees of growth improvement (Armitage 1969).

Research responses were used to emphasise the importance of considering other factors such as forest establishment, tree stock size, survival, planting methods, and the control of competing vegetation in addressing these challenges.

1970s era of phosphorus, nitrogen and boron fertiliser application

By the late 1970s approximately 600 ha were fertilised annually by manually adding phosphorus, nitrogen and boron 15 cm from the planted tree into soil opened with a spade slit three to eight weeks after planting (Ballard 1978, Adams and Walker 1975). The area of fertiliser application increased across New Zaland, despite being based on a few trials that were concentrated on poorest sites and having undergone limited soil testing (Ballard 1978). Phosphorus fertiliser application focussed on superphosphate (SP) application to weathered and leached clays and podsolised sands in the Auckland and leached alluvial gravels in the Nelson region. Such applications produced best results with weed control and deep soil cultivation. Responses were believed to last for only 3 to 4 years, but this was due to a lack of further measurements to rotation end. Nitrogen fertiliser was applied on podsolised soils, skid sites and strongly leached alluvial gravels as urea, or diammonium phosphate (DAP) where phosphorus was needed (Ballard 1978). Nitrogen was seen to be effective for up to 2 years due to a similar approach as above. Boron fertiliser was applied on as boronated (SP) to leached alluvial gravels and granite soils in the Nelson region, responses thought to last 3 to 4 years.

Formulations

Use of nitrogen fertiliser containing 3 : 1 mix was discontinued during the 1970s and phosphorus applied as (SP) was used at the highest application rate tested for routine management applications (Ballard 1978). This was adopted during the 1970s irrespective of site conditions, provided these were responsive sites of medium and poor quality. In addition, the cost of application was considered small compared to other establishment costs and the potential gain from use. Low phosphate rates showed comparable effectiveness to higher rates, with responses often independent of the phosphate formulation. Some trials, such as at Maromaku, required nitrogen for optimal results, while others did not respond despite low soil and foliar phosphorus levels. The solubility of phosphate forms influenced responses, with more soluble forms showing better efficacy on soils with medium or high soil phosphorus retention on certain sites. Alternative prescriptions were found to be required for skid sites such as in Kaingaroa Forest where optimal response was acquired with deep ripping and fertiliser addition in the second spring after planting with DAP fertiliser placed 15 cm away from the trees (Ballard 1978). Certain phosphorus (SP) fertilisers were shown to promote early root development and reduce the risk of frost damage and drought (Ballard 1978). However, it was observed in experiments in Kaingaroa Forest that mixed fertilisers containing nitrogen, phosphorus, potassium and magnesium increased frost damage in radiata pine seedlings on harsh sites by stimulating rapid succulent growth during the frost season (Ballard 1978). When considering choice of formulation, the addition cost of better quality formulations needs to be balanced with the response magnitude. Better quality formulations can improve solubility, handling, reactivity with the soil and availability for plant uptake, but may or may not translate to a better growth response.

Phosphorus and residual phosphorus

A study in the 1970s evaluated the residual benefits of phosphorus fertiliser on severely phosphorus deficient soils in Riverhead Forest and found that plots treated 19 years earlier exhibited a growth advantage in the subsequent rotation. Further phosphorus was added in the next rotation to residual phosphorus treatment plots and unfertilised treatment plots. Both showed better growth than where no addition had occurred. These results show that a single phosphorus application in either rotation can raise site productivity. A double application however caused a growth suppression. This slight suppression was attributed to the application accentuating a nitrogen deficiency induced by faster growth after phosphorus application (Ballard 1978). Such trials need to be replicated to further sites as they demonstrate a cost saving to fertiliser addition, and a potential growth reduction after double fertiliser addition if not balanced with nitrogen.

Nitrogen and boron

Responses to nitrogen during the year after planting could be obtained on a few sites when applied in conjunction with phosphorus and boron. Applications that occurred sooner after planting tended to give a better response than later on, although this induced higher mortality. Mortality could be overcome by using correct placement of fertiliser (15 cm from the seedling) and using a less soluble nitrogen formulation. On clay soils, response to nitrogen tended to be small, short lived and varied, even on similar site types. It was therefore not accepted as standard practice at that stage for establishment of radiata pine (Ballard 1978). Boron fertiliser was shown in deficient soils to reduce die-back to negligible levels for 3 to 4 years after planting by placing boron fertiliser in the planting hole or at high rates close to the stem. Boron has little impact on growth, only tree form, but combined with phosphorus or nitrogen increased growth. Where boron was not applied phosphorus and nitrogen application increased the expression of boron related die-back due to increased growth rate. Based on the above responses to nitrogen and boron, there are precise application methods and site-specific application rates and formulations that need to be followed.

There was a substantial increase in fertiliser usage at establishment of radiata pine towards the end of the 1970s, particularly in areas with severe deficiencies in phosphorus and boron and those sites showing unsatisfactory initial growth (such as nitrogen with eucalypts). This necessitated a more complete understanding of long-term benefits of fertiliser application, including the impact on potential reduction in tending costs, damage by pests and pathogens, and weather extremes. The challenges at this time included the short-term effectiveness of spot applications, reliance on manual application posing cost and precision issues, and imprecise techniques for delineating responsive sites, highlighting the need for ongoing investigations into alternative methods and calibrated diagnostic techniques.

Research the 1990s

By the 1990s, the state of knowledge regarding fertilisation at planting confirmed and emphasised phosphorus, nitrogen, and boron as commonly deficient elements. Phosphorus was applied at establishment in specific regions, and efforts were underway to develop an effective means of quantifying radiata pine response to phosphorus fertilisation using soil tests. Nitrogen application occurred routinely at establishment and on skid landings throughout New Zealand, with potential considerations for using total soil nitrogen measurements as a guide. Knowledge regarding the potential response from fertiliser application during establishment based on past work (Mead and Gadgil 1978, Woollons and Will 1975) remained unchanged as 200 kg N ha^{-1} and a maximum response on pumice plateau to 460 kg N ha^{-1} (Davis, et al. 2015). These rates and responses were not improved upon and not prescribed due to cost. These responses may no longer be relevant due to changes in tree genetics, weather patterns and silvicultural practices. Boron deficiency was noted again in certain regions, and local observation and knowledge was considered as before the best indicator for predicting boron deficiency and crop response to boron fertilisation. Further elements were also investigated such as potassium and magnesium. Potassium deficiency was found to occur in very specific areas, and variations in the effects of potassium with boron fertilisation on deficient sites were challenging to predict. Magnesium deficiency was not commonly observed in very young stands of radiata pine in New Zealand during this period.

Into the new millennium, post 2000

Davis, et al. (2001) installed trials to test boron fertiliser addition a year after planting and found positive responses across three soils. No further gains were found when combined with other elements, nitrogen, phosphorus and sulphur and growth suppression occurred when nitrogen and sulphur were combined as fertilisers. It became commonly believed that radiata pine responded well to soluble phosphorus fertilisers such as (SP). There were limited data on the effectiveness of rock phosphate, although predicted to become the most used form of phosphorus fertiliser due to low cost, reduced phosphorus fixation, leaching and weed growth stimulation (Liu 2005, Payn, et al. 1998). Fertiliser at planting was thought to provide an early short lived boost to tree growth, attributing a only 4% to early growth (Mead and Pimentel 2006).

Use of fertiliser tablets

There has been a move to a wider use of fertiliser tablets that are inserted into the soil near the root zone (similar to granular fertiliser). They can contain a balanced blend of nutrients that are slowly released and can also be impregnated with pesticides or fungicides. They can range from small, coin-sized tablets to larger, palm-sized ones. A reduced soil contact can also be beneficial for limiting binding/sorbing of phosphorus with certain soils. A major advantage despite greater costs is that it is easier to transport and apply a more precise quantity of pre-formulated fertiliser using mechanised planting systems. No local trials were found for radiata pine in support of this, but various company data gives positive responses to the use of fertiliser tablets.

Exploration of interactions between fertiliser and other practices

Research also explored interactions with other silvicultural management practices and alternative cover-crops that include weeds, natural vegetation and planted nitrogen fixation species and nitrogen fixing weeds.

Weed management

Trials that investigated the interaction of cuttings and seedlings with grasses showed that a lack of grass control not only suppresses tree growth but negated the positive effect of fertiliser addition (West 1984). This was not found with *Acacia melanoxylon* (Blackwood) which gave a positive response to nitrogen and no interaction with weeds or other elements (Barton 1985). The impact of grass on suppressing growth and fertiliser response was also shown on magnesium deficient pumice soils where fertiliser addition of magnesium, boron, nitrogen and phosphorus had no effect on growth (Payn 1991). Interactions continued with investigation of interactions with water (irrigation), weeds and fertiliser showing growth to be either suppressed or improved (nitrogen fixing weeds) depending on species of weed retained, but with no fertiliser effect (Richardson, et al. 1993). Later boron trials at two contrasting sites confirmed this, with a positive response to boron

application (Olykan, et al. 2008). Weed control enhanced the response at a Balmoral site and reduced boron fertiliser was required at the Lake Taupo site after weed control.
Nitrogen fertiliser added to sites occupied by lupins (*Lupinus arboreus*) provided no further benefit during the first 4-5 years of growth due to sufficient nitrogen fixation by the lupins. A similar response could be obtained on sites occupied by gorse, but this varied as the gorse took up fertiliser and increased competition with the trees. Weed or competing vegetation control across various trials either enhanced responses to fertiliser addition or reduced the need for fertiliser addition. A lack of weed control in many cases negated the fertiliser response (Ballard 1978, West 1984, Richardson, et al. 1993, Olykan, et al. 2008, Skinner, et al. 1995, Skinner, et al. 2000, Skinner, et al. 2001, Kimberley and Clinton 2000).

Cultivation

Fertilisers at planting combined with cultivation obtained maximum growth on podsolised sands, most of which are known for poor drainage, low soil nitrogen, and at that time loss of organic matter and topsoil due to fires and erosion (Ballard 1978). Simcock, et al. (2006) showed interactions between fertiliser addition and ameliorative cultivation after compaction to have strongly positive response to cultivation at four years after planting when used in combination with nitrogen and phosphorus fertiliser. Fertiliser or cultivation alone had no positive impact on growth.

Effects on tree form and carbon storage

Studies have shown that fertilisers addition at planting has little effect on tree form due to its short-lived impact. Nitrogen application to radiata pine seedlings was found to increase basal diameter, branch number, and growth more than stem growth. Severe deficiencies of nutrients, especially boron, can cause tree malformation. Fertiliser application can have positive effects on soil carbon under good weed control (Nish 2021), wood properties, and forest productivity. A study over various experiments (Nish 2021) produced a carbon response exceeding national lookup table values in plots where weed control and fertiliser application were applied together. This contrasted with a study in Yallop (2021) finding no improvement in carbon stock due to fertiliser addition. The specific outcomes may vary depending on factors such as soil type, tree species, age, and silvicultural practices in addition to the availability of data for adequately describing the full range site types. Additionally, data used in each of these studies was sourced from experiments that were not designed for the specific objective of each study.

Single application of fertiliser at planting will be less likely to impact on wood quality to rotation end due to the very small quantity added, and the short-term early supply provided by the fertiliser overcome by later supply from decomposing residues. Faster tree growth and resulting reduction in wood quality due to improved site quality through optimal nutrient management may need to be offset through use of improved genotypes.

Move to a holistic nutrient management approach

During the past three decades and in more recent years response to fertilisation at planting has been generally uncertain in forestry soils, especially when considering the economic implications. Tools to predict the response to fertiliser addition at planting and over the whole rotation were required (see section 5, page 33). This needed to consider past work in the context of the availability of nutrients in the planting pit or mound, timing of planting after harvest, soil water recharge prior to planting and rainfall thereafter, soil temperatures, and disruption of soil structure and organic material in the planting pit or mound.

Impacts of biomass removal

More intensive forest management due to increased growth rates and larger biomass removal due to improved growth and biofuel collection are raising concerns around the impacts of these practices on soil fertility (Smaill and Garrett 2016). Research over the past 30 years has underscored the significance of nutrient availability for the long-term site productivity and soil health of New Zealand's radiata pine forests over multiple rotations (Smaill and Clinton 2016). Taking stock of past research this was recognised by Dyck and Beets (1987), and since then the focus has moved predominantly to understanding nutrient fluxes through the forest system and the impact of silvicultural management on these fluxes and tree production. Research in nutrition management continued to expand to investigate implications of more management practices, the ameliorative effects of fertiliser addition and alternative nutrient and soil management strategies (Garrett, et al. 2015, Smaill, et al. 2008). Trials established in different physiographic regions of New Zealand between 1986 and 1994 investigated the impact of various harvesting and residue treatments on the second-rotation performance of Pinus radiata, aiming to meet New Zealand's legal requirement for sustainable forest management. The studies found that residue retention, especially in nutrient-deficient sites, positively influenced tree growth, while fertiliser addition from planting and over the rotation mitigated harvesting-related reductions or improved growth. The benefits of organic matter retention in maintaining soil productivity, particularly on nitrogen deficient sites such as Pinaki Typic Sandy Recent Soil was highlighted (Smith, et al. 2000). Such trials pointed out the value of fertiliser addition to maintain productivity on sites after excessive biomass removal. Fertiliser addition without additional biomass removal was found to increase uptake of all other nutrients for elements not added to the site (Smith, et al. 1994). Intensive biomass removal trials at Woodhill, Aeolian sand, Tarawera basaltic tephra, and Berwick loess demonstrated a negative impact due to biomass removal (forest floor) at one site (Garrett, et al. 2021). Fertiliser addition was carried out at regular interval from planting to mid rotation using an approach that supplied nutrients for trees to have an unlimited balanced supply without root scorch. This resulted in improved tree growth and increased soil carbon and nitrogen stocks on sites with low initial soil stocks.

To test the ability to permanently improve site productivity a trial series was installed into radiata pine stands using current technology and knowledge to ameliorate gaps in site production (Accelerator Trial series, (Smaill, et al. 2023). Site enhancement at some of these trials included addition of fertiliser at planting continued in subsequent years based upon identified site limitations following continuous balanced addition with nutrient requirements predicted using the NuBalM model (Smaill, et al. 2023). This model does not indicate response likelihood of fertiliser added at planting. Fertiliser was added as nitrogen at two trial sites (Southern and Central Kaingaroa), and phosphorus at (Tairua), with other elements added as required. An alternative cheaper and more soil stable nitrogen source biuret was also tested as part of the nitrogen addition regime. Despite adverse effects on other agricultural crops due to accumulation in foliage biuret has produced a positive response in radiata pine growth. Early observations indicated a strong positive response to fertiliser addition, but this response does not directly relate to fertiliser at planting as the design was to regularly assess each site for any limitation and respond with an ameliorative practice (Smaill, et al. 2023).

Impacts on soil microbes

Trials at Woodhill and Tarawera forests investigated the impact of organic matter removal at harvest and fertiliser addition on microbial communities. The addition of fertiliser led to changes in both bacterial and fungal communities. Organic matter removal at harvest had persistent effects on the composition of fungal species in the soil, but no evidence was found for long-term effects on the composition of soil bacterial communities (Addison, et al. 2021). It was highlighted that fertiliser addition improved soil fertility but reduced diversity in both bacterial and fungal communities at Woodhill sandy soils and Tarawera recent soils (Addison, et al. 2019). Organic matter removal at harvest had lasting negative effects on fungal species composition, particularly affecting soil resilience and nutrient status, while bacterial communities remained largely unaffected (Addison, et al. 2019).

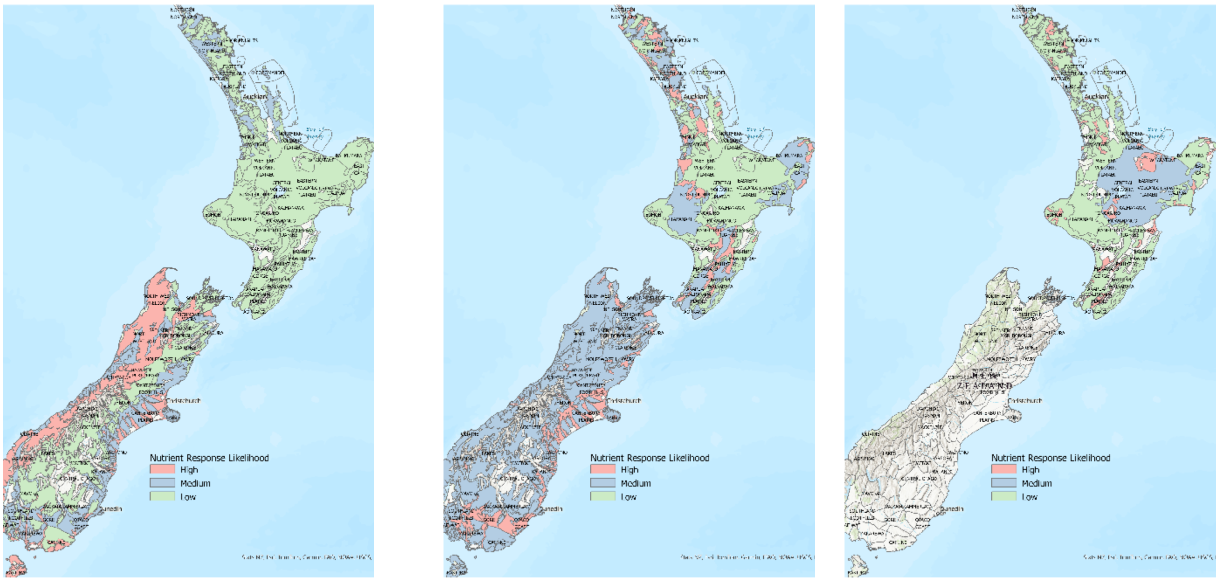
The work on nutrient removal and site improvement demonstrates the interactions between site type, historic land use, management intensity and fertiliser response/requirement. Removing larger quantities of biomass (such as for biofuel harvesting) on sites with low nutrient capital will deplete soil nutrients rapidly. Such sites may require additional fertiliser application at planting once the soil supply becomes depleted. Sites with large or excess nutrient capital, such as old farmland, may be able to maintain larger biomass removal rates without a need for fertiliser addition. Sites that can be permanently improved may no longer require certain fertilisers at planting, but this has not been tested other than the phosphorus retention trials mentioned previously.

Indicators and Modelling fertiliser response

Indicators of fertiliser response

Past research explored various indicators for assessing soil and foliage nutrition in radiata pine plantations with varying success. Early use of soil phosphorus retention levels showed promise during the 1970s and 1980s (Hunter, et al. 1989), but seemed to lack consistency in predicting the impact of the rate or type of fertiliser required , indicating the need for more accurate indicators (Davis, et al. 2015). Mason (1992) highlighted the significance of understanding the soil conditions for effective nutrient management and Hunter (1991) developed a soil nutritional atlas through a decision support system to identify potential deficiencies and fertiliser response based on location and soil types (Figures A2a, b, c). Li, et al. (2015) found that foliar carbon isotope composition and C:N ratio were correlated with growth and influenced by genetics, driven by soil nutrient levels in young trees. This suggested a potential for using these indicators for improved genetic selection and early nutrient management. Garrett, et al. (2023) demonstrated the link between nitrogen response likelihood and tree age using a natural abundance nitrogen isotope (δ15N) as a soil-based indicator. Despite variability in response to nitrogen fertiliser the study indicated that nitrogen fertiliser was most likely to induce a response if applied early in the rotation (< 15 years old), and that a response is more likely within one to three years after fertiliser addition. Stands with a more negative δ15N isotope enrichment were indicated as most likely to produce the biggest growth response to nitrogen fertiliser addition.

Although the research has yielded valuable insights into soil and foliage nutrition indicators, there are challenges in extrapolating previous findings concentrated on limited sites to broader contexts. A further study by Garrett, et al. (2022) tested mid-infrared spectroscopy for predicting forest soil and tree foliar nutrient properties and found that most key forest soil and tree foliar nutrient properties could be predicted. However, the method was unable to reliably predict other soil macro-nutrients and all soil and foliar micro-nutrients. This highlights the potential of using rapid analytical techniques for predicting certain nutrient properties of soil and foliage and should be explored further using additional wavelengths. There is opportunity to include rapid analytical methods in future research to expand the number of samples thereby reducing uncertainty in soil data, and for use as a rapid and low cost site assessment tool.



a) Nitrogen　　b) Phosphorus　　c) Boron

Figure A1.2: Atlas of response likelihood to fertiliser addition of (a) nitrogen, (b) phosphorus, and (c) boron (Hunter 1991).

APPENDIX 2: LIST OF ESTABLISHMENT FERTILISER TRIALS AND GROWTH RESPONSES

Summary of New Zealand experimental research studies that have tested the use of fertilisers to improve early tree growth.

Table A2.1: Published/reported fertiliser trials with nitrogen (N) as the primary focus Compared with the control - = negative response, + = positive response, 0 = no response.

Age applied (y)	Period	Species	Treatment	Fertiliser Source	Site Soil	Response	Age assessed	Reference
0	1960s	*Edel*	N	Blood&bone	Tairua Forest NR	++	3	(Ballard 1978)
0		Prad	NP	3:1mix	Auckland/Nelson NR	+	5	
0			NPMg NBMg	MagAmp MAP	. Pumice (Skid Site)	++ ++	3	
0	1970s	Edel	N	Urea	Kaingaroa NR	+	1	
0		Prad	N		Whangamata Gravelly Loam Clay	0	2	
0			N		Waikare Clay, Loam Clay	0 mor t	2	
0			N		Rangiuru Clay, Loam Clay	0 mor t	2	
0			N		NR Podsolised Ohia Sand	+ mor t	2	
0			N		NR Podsolised Te Hapua Sand	+ mor t	2	
0			N		Pigeon Valley NR	+	3	
0			N		NR Pumice	+	2	
5			NP		NR NR	+		(Mead and Gadgil 1978)
0		Ereg	N Weed N+weed	Urea	NR NR	+ + ++	2	(Ballard 1978)
0		poplars	N Weeds N+weeds	AMS	Esk S.F. NR	+ ++ ++	3	
0		Prad	N NP	Urea SuperP	NR Pumice	+ ++	3	
0			NP	AMP	Tairua/Riverhead NR	++	2	
0			NP NPMg		Kaingaroa NR	+ 0	3	
0			Nfix Nfix+N	Lupin Lupin+urea	NR Deep Coastal Sand	+ 0	3- 7	
1	1980s	Prad	NP	DAP	Kaingora NR	NR		(Klomp and M. 1986)
4			N P NP	NR	NR Podsolised Sand	+ + +	4	(Hunter 1989)

4			N P NP		NR Northern Podsolised Clay	- - +	4	
4			N P NP		Southern Kaingaroa NR	- - +	4	
4			N P NP		Nelson Southern Granite	- ++ ++	4	
4			N P NP		Westland Pakahi	+ + ++	4	
0	1990s	Pnig	NPSKMg B	AmmNit, RP, Gypsum, KCl, Calmag, Ulexite,	Balmoral Fork	0	1	(Davis, et al. 2001)
0			NPSKMg B		Balmoral Pukaki	0	1	
1		DF	NPSKMg B		Mt Barker Tekapo	0	2	
0			NPSKMg B		Balmoral Tekapo	0	2	
1		Pnig	N P S NP NS PS	urea RP S	Balmoral Pukaki	- - 0 0 0 0	5	
1		DF	N P S NP NS PS		Balmoral Tekapo	0 0 0 0 - 0	5	
0+	>2000	Prad	N	Urea Biruet	Southern Kaingaroa Volcanic Deposits Loamy Sands			(Smaill, et al. 2023)
			N		Central Kaingaroa Volcanic Deposits Sandy Loam			(Davis, et al. 2001)

Prad = *Pinus radiata*, Pnig = *Pinus. nigra*, Ereg = *Eucalyptus regnans*, Edel = *Eucalyptus delegatensis, Eucs = E. botryoides, E. globulus and E. ovata, Dfir* =Douglas Fir
N = nitrogen, P = phosphorus, B = boron, S = sulphur
AmmNit = Ammonium Nitrate, RP=Rock Phosphate, SuperP = Superphosphate, AMP= ammonium polyphosphate, MagAmp = Magnesium-ammonium phosphate MAP = Monoammonium phosphate, CalMag = blend of calcium and magnesium nitrates, S = Elemental Sulphur
Mort = Tree mortality induced, NR = Not reported

Table A2.2: Published/reported fertiliser trials with phosphorus (P) as the primary focus. Compared with the control - = negative response, + = positive response, 0 = no response.

Age applied (y)	Period	Species	Treatment	Fertiliser Source	Site Soil	Response vs Control	Age assessed (y)	Reference
0	1950s	Prad	P PN PNK	RP SuperP+BB SuperP+BB+potash	NR Westland pakihi relic podsol-gleys	+ ++ ++	6	(Ballard 1978)
0	1960s		P	RP SuperP	Waikare clay loam	++	15	(Ballard 1978)
0			P PN	SuperP AMS		+ -		
0			PB&weed	-	Mapua hill NR	+ ++	7	
0	1970s		PCaS KCaS PK PKCaS	SuperP KCl CaS	Dun steepland NR	+ + ++ ++		
4			P	RP SuperP	NR Northern Clay	+	7	(Hunter, et al. 1989, King 1988)
4						++	7	(Hunter, et al. 1989, King 1988)
4						+	7	(Hunter, et al. 1989, King 1988)
4			P PN	MCP	NR Podzol brown (Pumice)	0 +		(Jacks and Fitzgerald 1971)
5,6			P	SuperP	Clay	Model		(Phillips 1987)
0	1980s	Amel	P N K Micros	SuperP urea Magamp	Hunua Ranges NR	+ 0 0	3	(Barton 1985)
0		Prad	P			+		
4			P PN	MCP	NR Podzolised sand	0,0	7	(Hunter 1990)
4			P PN	MCP	NR (ex pasture) Podzolised clay	0 +	7	
4			P PN	MCP	NR Pumice	0 0	7	
4			P PN	MCP	NR brown soil	++ 0	7	
4			P PN	MCP	NR Podzolised Pakihi	+ 0	7	
6			P	SuperP	NR northern clay	++		(Hunter and Graham 1982)
6			P	SuperP	NR northern clay	++	26	(Skinner, et al. 1995)
7			P	MCP	sandy podzol	+	7	
.	2020		P	SuperP	Museum Riverhead			(Skinner and Graham 1998)
.			P	SuperP	Tairua Volcanic deposit Sandy loam			(Smaill, et al. 2023)

Amel = *A. Melanoxylon,* Prad = *Pinus radiata,* RP=RockPhosphate, SuperP = Superphosphate, AmS= ammonium sulphate, CaS = calcium sulphate, BB = Blood and bone, micros = micronutrient suite N = nitrogen, P = phosphorus, B = boron, S = sulphur, K = potassium, Ca = calcium, NR = Not reported

Table A2.3: Published/reported fertiliser trials with boron (B) as the primary focus. Compared with the control - = negative response, + = positive response, 0 = no response.

<table>
<tr><th>Age applied (y)</th><th>Period</th><th>Species</th><th>Treatment</th><th>Fertiliser Source</th><th>Site
Soil</th><th>Response</th><th>Age assessed</th><th>Reference</th></tr>
<tr><td>0</td><td>1960s</td><td rowspan="3">Prad</td><td>B
NB
PB
NPB</td><td>NR</td><td>Rosedale hill
NR</td><td>0
0
++
++</td><td></td><td rowspan="3">(Ballard 1978)</td></tr>
<tr><td>0</td><td rowspan="2">1970s</td><td>B
PB</td><td>NR</td><td>Rosedale hill
Moutere gravels
Kaiteriteri & Pokoroa granites</td><td>-
++</td><td>4</td></tr>
<tr><td>0</td><td>B
PB
NPB</td><td>NR</td><td>Rosedale hill
NR</td><td>+
0
0</td><td>4-6</td></tr>
<tr><td>2</td><td rowspan="3">1990s</td><td>Pnig</td><td>B</td><td rowspan="3">ulexite</td><td>Ribbonwood
Sawdon</td><td>++</td><td rowspan="3">2</td><td rowspan="3">(Davis, et al. 2001)</td></tr>
<tr><td>1</td><td>Prad
Pnig
Ppon</td><td>B</td><td>Balmoral
Fork</td><td>+</td></tr>
<tr><td>1</td><td>Prad
P.nigra
Ppon</td><td>B</td><td>Balmoral
Pukaki</td><td>+</td></tr>
<tr><td>.</td><td>Current</td><td>Prad</td><td>B</td><td>ulexite</td><td>Tekapo
Pukaki Orthic Brown</td><td>0</td><td>6</td><td>(Xue and Graham 2009)</td></tr>
</table>

Prad = *Pinus radiata*, Pnig = *Pinus. nigra*, Ppon = P.ponderosa, N = nitrogen, P = phosphorus, B = boron, NR = Not reported

Table A2.4: Published/reported radiata pine fertiliser trials with magnesium (Mg) as the primary focus. Compared with the control - = negative response, + = positive response, 0 = no response. One experiment includes weed management

Age applied (y)	Period	Treatment	Fertiliser Source	Site Soil	Response	Age assessed	Reference
5	1980s	Mg	dolomite	NR (Mg deficient) Volcanic	0 (+foliar)	14	(Olykan, et al. 2001)
5		Mg	dolomite	Kaingaroa forest Mg deficient	0 (+foliar)		
6		Mg	dolomite	NR (Mg deficient) southern Kaingaroa	++	NR	(Hunter, et al. 1986)
0	1990s	Mg Mg+grass B grass removal	MgS04 MgO, Boric acid	Halls block Central North Island Yellow-Brown Pumice	0 0 0 +	3	
0		Mg B	MgS04	Kaingaroa Kiorenui Pumice	0 0	3	(Payn 1991)

B = boron

Table A2.5: Published/reported fertiliser trials with cultivation as the primary focus (all on radiata pine). Compared with the control (no cultivation) - = negative response, + = positive response, 0 = no response.

Age applied (y)	Period	Treatment	Fertiliser Source	Site Soil	Response	Age assessed	Reference
0	1960s	Rip&NPMg Rip&NBMg	MagAmp MAP	NR (Skid site) Pumice	+ +	3	(Ballard 1978)
0		PB Rip Rip&PB	NR	Rosedale hill NR	++ + +++	7	
0	1970s	N P NP Cul&N Cul&P Cul&NP	NR	Paerangaranga Te Hapua Podsolised sand	0 0 + 0 0 ++	2	
0		P N NP Cul&P Cul&N Cul&NP	NR	Rangiuru clay loam	0 0 + + 0 ++	2	
0	2000s	prep N NP prep&N prep&NP	NR	Riverhead Ultisol Mottled Yellow Ultic Whangaripo clay loam	0 0 0 + +	4	(Simcock, et al. 2006)

Rip = Soil ripping, Cul = soil cultivation, MagAmp = Magnesium-ammonium phosphate, MAP = Monoammonium phosphate, NR = Not reported

Table A2.6: Published/reported fertiliser trials with weed management as the primary focus. All trials are on radiata pine. - = negative response, + = positive response, 0 = no response. Gorse trial control are no gorse, weeding trial controls are no weeding

Age applied (y)	Period	Treatment	Fertiliser Source	Site Soil	Response	Age assessed	Reference
0	1970s	Gorse&PKB Gorse&NPKB	no Gorse vs with Gorse (no control)	Rosedale hill NR	++ 0	7	(Ballard 1978)
0	1980s	NoGrass NoGrass&NKP grass&NKP	urea potassic SuperP	Putaruru NR	+ + 0	5	(West 1984)
0		NoGrass NoGrass&NKP grass&NKP		Rotorua NR	+ + 0	5	
0		NoGrass NoGrass&NKP grass&NKP		Taradale NR	+ + 0	5	
0		NoGrass NoGrass&NKP		W Kaingaroa NR	+ +	5	
0	1990s	Weeding P NP Weeding&P Weeding&NP	TSP urea	Mariri Mapua hill soil	+ + + 0 0		(Skinner, et al. 1995)
		weeding P Weeding&P	RP SSP	Tairua Central Yellow Brown loams	0 + ++		
0		weeding P Weeding&P	TSP RP	Mangakahia Waimatenui clay/Omu clay loam	0 0 0		
2		weeding B	Borax ulexite colemanite	Rerewhakaaitu NR	NA	12	(Skinner, et al. 2000)
5		weeding P weeding&P	NR	Hunua Te Rango clay loam	+ 0 +		(Skinner, et al. 2001)
7		N P weeding&N weeding&P weeding&NP	Urea RP ulexite	Mamaku Mangowera sand, Otanewainuku sandy silt	0 + 0 + ++		(Skinner, et al. 2002)
0		-Noweeding Noweeding&P	NR	Eyrewell Forest NR	- --	7	(Kimberley and Clinton 2000)
0		weeds irrigation non-limiting fert	Multiple	Rotorua pumice (yellow-brown Ngakuru loam)	0	1	(Richardson, et al. 1993)
0		weeds irrigation non-limiting fert	Multiple	Rangiora Wakanui silt loam	0	1	
0	2000s	weeding weeding&B	ulexite	Lake Taupo Waipahihi sand Immature Orthic Pumice	+ +	4	(Olykan, et al. 2008)
0		Weeding weeding&B	ulexite	Balmoral stony sandy loam Typic Orthic Brown	+ +	4	

SuperP = Superphosphate, TSP = Triple Super Phosphate, RP=RockPhosphate

APPENDIX 3: MAP OF FERTILISER AT PLANTING TRIALS

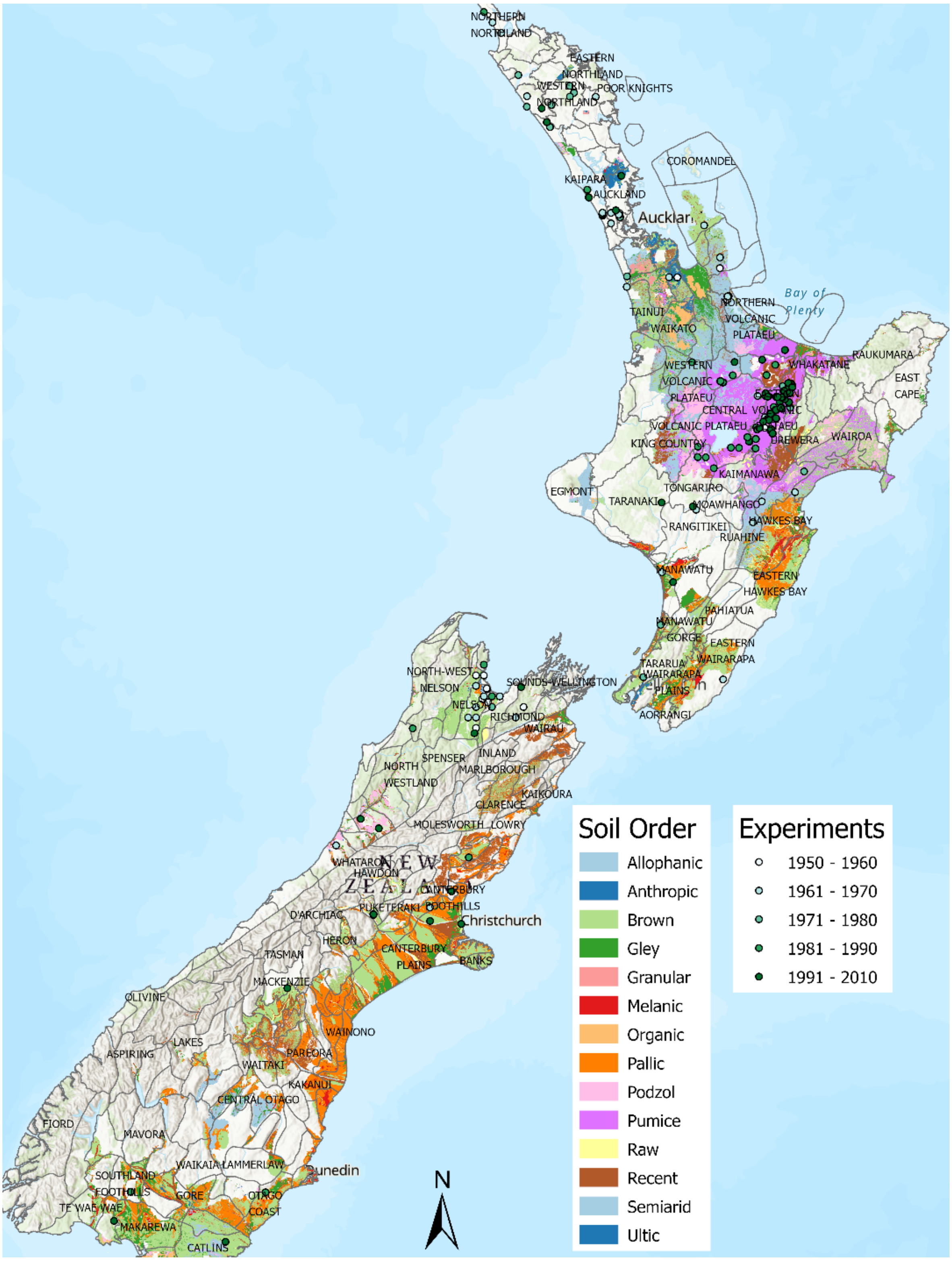


Figure A3.1: Fertiliser at planting experiments locations per planting decade (using locations captured in the Scion PSP database), showing NZ soil orders and Eco-Regions.

APPENDIX 4: AN OVERVIEW OF RESPONSE POTENTIAL

This section describes the pathway from nursery to planting where nutrition or stimulant use can make a difference.

The various sites into which trees are planted differ in their weather patterns, soil water availability, nutrient stock, nutrient supply potential, soil root access and soil microbial populations. All of these factors combined with plant quality and genetics can also contribute to successful establishment and tree growth.

1.1.1. Nursery plant production

Plants are grown and dispatched from nurseries having followed standard practices developed though research to ensure healthy green plants of appropriate size, colour, nutrition and proportions, having been correctly hardened off for field deployment. Certain nurseries include additional inoculants such as Trichoderma coated seed that can enhance seedling performance in the nursery and in certain cases after planting in field (forest company consultation). Current best operating practices outlined in (Knight 1978) remain effective for achieving nursery objectives to produce “universally” high-quality plants at low-cost. Trees extracted from the nursery have their roots trimmed to fit in a box, which results in large variation in root mass prior to being taken to field and planted. This usually occurs over a few days, but a protracted delay between nursery extraction and planting is not uncommon (forest company consultation). Opportunities for improvement in the nursery space still exist in line with new technology developments to improve efficiency and productivity and to optimise on continuous genetic improvement. Research into producing plants to meet site specific requirements or enhancements for site-specific conditions seems lacking and is a current gap in knowledge (forest company consultation).

Nursery to planting

At planting, trees are exposed to new environments in which they must overcome transplant shock, site conditions that differ from the nursery, and a limited access to water and nutrients. Due to an undeveloped root system at this stage, they rely on plant tissue storage and any additive applied before leaving the nursery or applied at planting. These can include an addition of water and/or fertiliser to provide readily available access for the small root system and/or products that can reduce transplant stress related to water loss, nutrients and energy use, and stress hormone production. Products tested in this regard have included slow-release fertilisers, hydrogel, microbial inoculation, potassium silicate, selenium, ethylene, chilling/cold storage, among others.

Post planting seedling and soil conditions

The period immediately after planting presents a contrast between abundant soil nutrient supply and the limited access of the small trees. The tree root system is undeveloped or heavily trimmed and lacking mycorrhizal associations thereby unable to access the large pool of available soil nutrients. (Mycorrhiza association with tree roots provide the ability for enhanced nutrient and water uptake (Plassard and Dell, 2010)). While soil typically contains a large total nutrient quantity compared to plantation biomass nutrient pools, only a small fraction is immediately accessible to trees (Fisher and Binkley 2000) (see Figure A4.1). The size of this accessible nutrient pool depends on factors such as the volume of soil available to roots, nutrient uptake depth, soil density, concentrations of plant-available nutrients, and rhizosphere processes (Liu 2005, Turner and Lambert 2011). In addition, soils in the planting pit or mound may not exhibit the same nutrient status as the surrounding soil due to soil disturbance or variation in soil composition during preparation. This includes changes in soil bulk density affecting water holding capacity and soil root contact, mixing of low nutrient subsoil with topsoil, mixing of high C : N residues with the soil in the planting mound potentially locking up soil nitrogen. Although young trees have a lower overall nutrient demand compared to later stages of growth, they require nutrients for initial growth and early development.

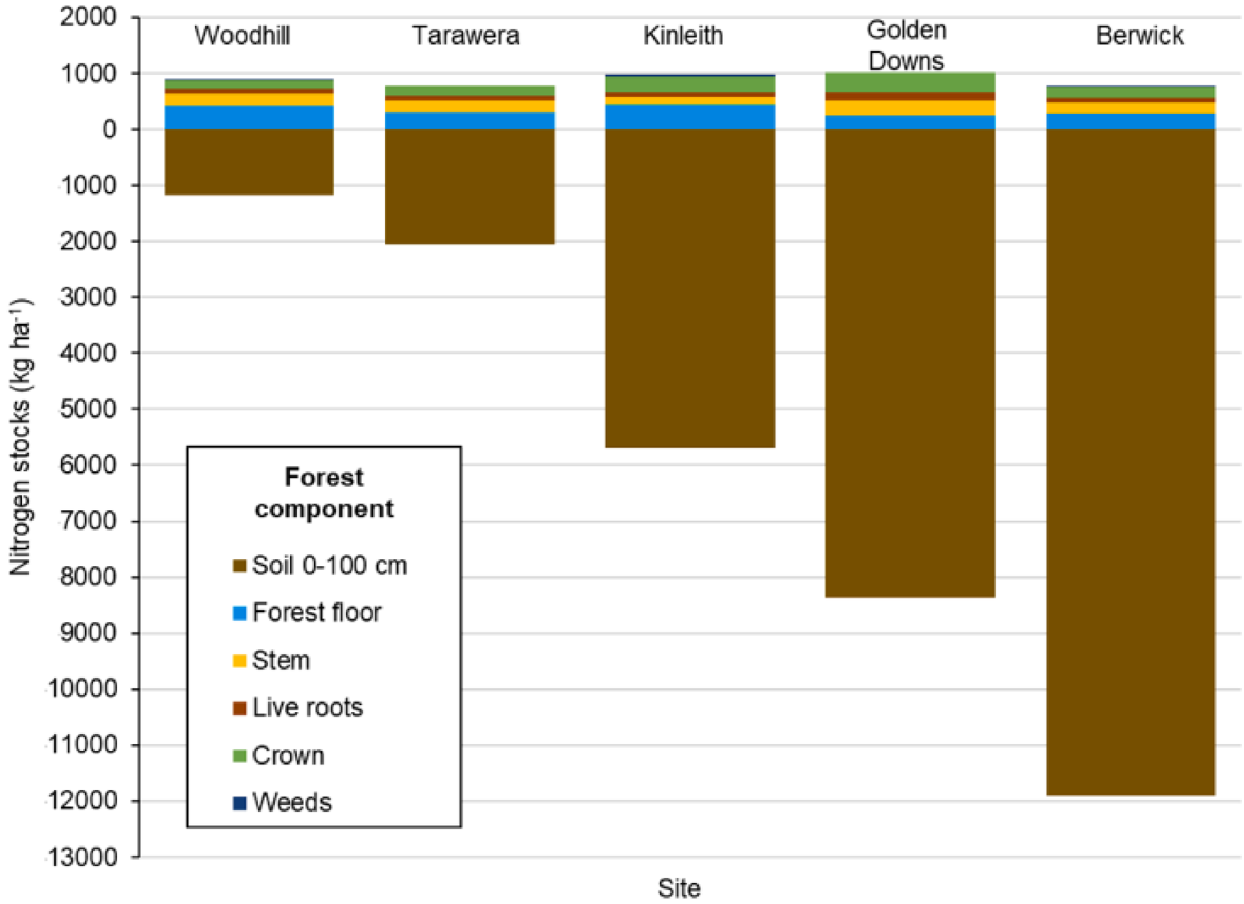


Figure A4.1: Showing how different sites have contrasting nutrient availabilities in soils compared to aboveground components (Garrett, et al. 2021). This highlights the importance of conservative management on low nutrient soils with less conservative management required on soils with more nutrients.

Energy balance

In the weeks immediately after planting, trees rely on stored carbohydrates, water and nutrients for initial root and foliar growth. Trees with adequate nutrients and water can optimally balance growth and energy use; avoiding excessive respiration due to inefficient nutrient and water uptake and overcome growth constraints due to water and nutrient stress (Will and Hodgkiss 1977). This principle has been demonstrated in ecosystem respiration in temperate, boreal and tropical forests in Ameray, et al. (2021), emphasizing the impact of optimal nutrient and water availability on overcoming growth constraints and minimizing inefficient respiration. This raises questions about the degree of root trimming and whether seedlings with more roots perform better in the short term. Nutrients that are readily available and optimally concentrated in close proximity to the roots require less energy to access due to a reduced requirement for early root growth and respiration.

This reduced energy cost for nutrient uptake allows more growth resources and energy to be directed to aboveground components and structural roots. A shift in resource allocation due to fertiliser addition is evidenced in various studies that also suggest that stimulation of faster growth might be linked to faster physiological maturity rather than gross primary production. (Giardina, et al. 2004, Misra, et al. 1998, Cannell, et al. 1988, Sands and Mulligan 1990, Dickmann, et al. 1996). Due to a combination of the above a response to fertiliser addition can occur in soils that have abundant bulk soil nutrient supply, even where specific nutrient deficiencies are not apparent.

Potential Benefits of fertiliser addition

Adding fertiliser, or any other product to enhance soil or plant water status or soil root contact at planting, may aid in overcoming the temporary limits of root access to water and nutrients and to enhance growth. A growth boost at this stage can allow more rapid root growth and canopy development of the small seedling, enabling earlier access to the bulk soil water and nutrient stores. Applying fertiliser at planting can also be a pathway to maintain or improving site quality over multiple rotations by replacing, in part, nutrients removed during harvesting particularly on sites low in nutrients or where excessive biomass has been lost or removed (Garrett, et al. 2015, Smaill, et al. 2008, Payn and Clinton 2005). Additionally, the application of fertiliser (nitrogen) can offset temporary nitrogen lockup and affect soil microbial activity and accelerate the decomposition of organic material in the soil. Nutrients immobilised by microbes will eventually be mineralised and released back to the soil.

1.1. Rotational response to nutrient addition at planting

Research has been invested into understanding patterns of nutrient supply and demand over the growth of a planted forest. Responsiveness to fertiliser addition is generally related to a physiological growth stage, seasonality, balance between elements in the soil and tree, and the availability of other plant growth resources that are affected by competition for water and light. Response to elevated CO_2 may also be modulated by nutrient availability (Bown and Watt 2016, Mason, et al. 2022). Garrett, et al. (2021) described nitrogen supply and demand during various growth stages according to the dynamics of tree demand and supply from soil, decomposing biomass, and nutrient cycling, linking this with the likelihood of response to nitrogen fertiliser addition. This understanding of biomass, nutrient allocation and soil nutrient dynamics in New Zealand radiata pine plantations was developed into a multi-rotation Nutrient Balance Model (NuBalM) that can be used to predict likelihood of response to nitrogen and phosphorus addition throughout a rotation thereby enabling precision nutrient management and maximisation of site productivity and sustainability (Smaill, et al. 2011, Clinton 2011). The productivity of trees should be defined here as their ability to generate a sustainable maximum economic return on investment, encompassing factors such as production costs, quantity, and quality of products (Davis, et al. 2015). The NuBalM model is effective for predicting nutrient requirement for trees that are established based on the difference in nutrient accumulation between actual growth rate and optimal growth rate (nutrient balanced research based). Fertiliser addition can compensate for the difference between actual and optimal nutrient uptake and any shortfall in supply from the soil (soil sampling) and decomposing residues. The model does not include an economic assessment, but this is highly feasible. This model however cannot predict response to fertiliser at planting, as trees at planting do not having access to the bulk soil/residue nutrients, relying on supply from the immediate planting mound/pit and internal reserves.

During early growth after establishment, large quantities of nutrients are released from decomposing residues and a low tree growth demand within the first three to four years limits the likelihood of response to nutrient addition (Garrett, et al. 2021). Once tree roots have colonised the topsoil layers they have access to a large pool of available soil nutrients, provided residues and forest floor are retained and the site is not deficient in any element (Garrett, et al. 2021). Nutrient demand is greatest during the canopy development stage of stand growth (about age 6, Figure A4.1, Table A4.2) that follows during which demand can potentially outstrip supply. This however does not consider the potential for nutrient imbalances, particularly later in the rotation.

Soil supply, decomposition of residues and nutrient cycling within the trees during this stage are at a minimum. The imbalance of supply and demand during this stage presents an opportunity for response to fertiliser addition but depends on the quantity/intensity rates of nutrient release from decomposing residue, inherent soil fertility, and the ability of tree roots to capture soil nutrients. Nutrient demand then declines as the stand approaches canopy closure (about age 10, Figure A4.2, Table A4.1) and is increasingly met through cycling processes from internal nutrient cycling prior to litterfall, forest floor litter decomposition, and fine root turnover. In the absence of known nutrient deficiencies, nutrient cycling after canopy closure, enhanced nutrient mobility in *P. radiata* root rhizosphere (Liu 2005), and a reduced soil nutrient demand for low-nutrient wood growth limits the likelihood of a fertiliser response. A response to fertiliser addition during this stage may be more likely after a disturbance event, such as thinning or pruning. The above research while not directly addressing the objectives of this review highlights the importance of considering the needs of tree genotype, management practices and the soil and site conditions. This understanding is apparent in the research outcomes outlined in the review in Appendix 1.

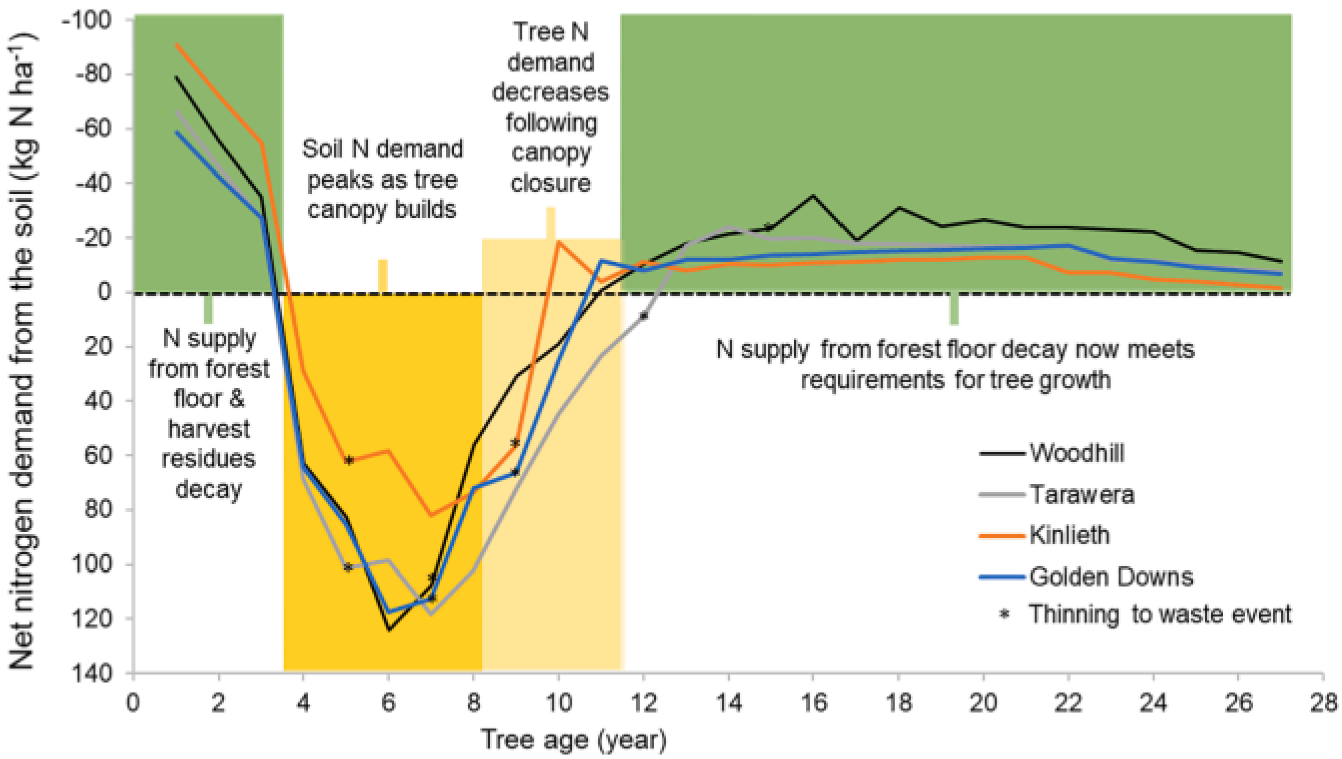


Figure A4.1: Tree crop nitrogen demand over a rotation for the stem only (SO), whole tree (WT) and whole tree plus forest floor removal (FF) treatments at Woodhill Forest estimated using NuBalM with thinning occurring at age seven and 15 years in Garrett, et al. (2021) and Clinton, et al. (2021)

Table A4.2: Tree crop nitrogen demand over a rotation and supply source.

Growth Stage Demand	**Establishment Planting to age 1 Low demand Low access**	**Early growth Age 1 – 4 Increasing demand High access and availability**	**Canopy development Age 4 – 12 Maximum demand Low availability**	**Canopy closure Age 4 – 12 Decreasing demand Low-increasing availability**	**Steady growth Age 12 -> Low demand Higher availability**
Supply from	Seedling reserves Limited root accessible soil	forest floor and residue decay	Low supply from soil and decay	Low supply from soil and decay Onset of cycling of litter	Nutrient cycling
Response	uncertain	less likely	most likely	likely	Post thinning response
Research	Few studies deficient sites	Few studies deficient sites	Majority of fertiliser studies Can be modelled		Some post thinning/pruning studies