Forest & Wood Products Australia

Research, development and extension investment plan

Research, development and extension priorities to achieve value gains through management of plantation nutrition.

2020

Adapted from *Investment Plan – A plantation nutrition investment plan for FWPA, 2019-2023,* prepared for FWPA by John McGrath (McGrath Forestry Services Pty Ltd) & Philip Smethurst (CSIRO), 2019.

This version of the Investment Plan, adapted by FWPA in December 2020, removes the cost and benefit estimates from the original Investment Plan, ***Investment Plan – A plantation nutrition investment plan for FWPA, 2019-2023*****, prepared for FWPA by John McGrath (McGrath Forestry Services Pty Ltd) & Philip Smethurst (CSIRO), 2019**

Author declaration of interest

Disclosure:
The authors, John McGrath and Philip Smethurst received income in the past year from RD&E carried out by the author in the technical areas addressed in this investment plan. The authors may receive income in the next five years from RD&E activities carried out by the author in the technical areas addressed by this investment plan"

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Executive Summary

This investment plan addresses the nutrient management RD&E required for hardwood and softwood plantations with the objective of optimising the value of timber from Australia's plantation resource. The maintenance or increase in wood yield (yield) of Australian forest plantations depends on effective nutritional management. As soils, climate, genotypes and management options change, the knowledge base for decisions about soil and residue management, fertilizer use, and weed control, for instance, needs checking and improvement to quantify the potential and realised gains in yield. The potential for finer resolution site-specific silviculture also offers opportunities to better match nutritional management to soil and climate variability. To address the research, development and extension (RD&E) needs for nutritional management, this investment plan was commissioned. The authors summarised background issues and some RD&E options, then interacted with nutritional experts and plantation managers, to finalise the plan.

Australia has a history of strong investment in nutritional research for softwood plantations, which has underpinned the viability of the industry. However, investment levels during the past decade particularly have declined, despite a continuing need for such research, especially in the more recently developed hardwood plantations. Concurrently, such investments by other countries have increased with a resultant substantial increase in realised wood yields per hectare. This plan recognises that softwood (mainly *Pinus* species) and hardwood (mainly *Eucalyptus* species) plantations have somewhat different needs that are reflected as different research priorities.

National averages of attained productivities are currently 16 m^3 ha^{-1} $year^{-1}$ for softwoods and 13-14 m^3 ha^{-1} $year^{-1}$ for hardwoods (B. Jenkin pers. comm.). Considering a range of levels of adoption from a likely level to full adoption, it is our opinion that these values could be increased 1-3 m^3 ha^{-1} $year^{-1}$ (6-20%) for softwoods over 30 years and 1-2 m^3 ha^{-1} $year^{-1}$ (7-15%) for hardwoods over 20 years (2 rotations) if the recommended investments in research are made and the results effectively adopted.

The priorities identified through this review and consultation process are summarised below:

Investment opportunity	Priority[1]	Common priorities for hardwood and softwood plantations
1	1	Fine-scale data (region-to-stand levels) on stand condition and history, soil properties, and climate, with links to yield predictions systems that indicate potential yield, likely attainable rain-fed yield, and the role of different factors including nutrition in closing the yield gap across multiple rotations
2	2	Knowledge capture and training systems (Delivery of R&D)
3	2	Cost-benefit (value) analysis of implementing research results when quantified
4	2	Nutrient value of slash in relation to fertilisation

Investment opportunity	Priority[1]	Common priorities for hardwood and softwood plantations
		Hardwood plantations
5	1	Methods for diagnosing nutrient deficiencies
6	1	Quantification of responses to fertilizer and the development of prediction systems and fertilizer recommendations
7	2	Operational management systems for conserving and managing slash
		Softwood plantations
8	1	Capture and adopt widely the considerable existing knowledge base on nutrient responses from establishment through to canopy closure and following thinning.
9	2	Nutrient requirements across multiple rotations, particularly for rarely studied for nutrients such as Ca, K and trace elements

[1] The priority rankings provide a guide to the order in which they could be addressed. If available funds are not sufficient to fund the full program, it is recommended that the focus of the program be on the issues identified as priority 1. These are the activities likely to deliver relatively major short-term yield increases for the plantation industry. It is noted that the longer-term issues will need to be addressed at some stage.

The two main barriers to improving plantation yield through improved nutrition management were identified as the lack of relevant knowledge on which to base improved management practices and ineffective transfer of that knowledge into management practices.

Strategies to address the availability of relevant knowledge were identified as:

- Development and retention of discipline expertise amongst researchers
- Balance the experimentation between short and long-term R&D and between applied and process based R&D
- Sustained levels of funding are required to ensure that the research capacity exits to implement and deliver the required programs

Strategies to address the transfer and utilization of relevant knowledge were:

- training in the principles and practice of nutritional management for plantation managers
- Integration of nutrition research with the full range of silvicultural management processes
- Targeting nutrient management actions based on available soil and climate databases and potentially using knowledge of different genotypes

Introduction

Background

To deliver the vision of the Grower Research Advisory Committee *to double the value of Australia's commercial forests by 2040,* FWPA is developing a suite of Investment Plans that enable industry investment in RD&E by providing a high-level business case for that investment in the period 2019-2024. This investment plan addresses the nutrient management RD&E required for hardwood and softwood plantations with the objective of optimising the value of timber from Australia's plantation resource.

Doubling the value of commercial forests will require both an increase in the yield and value from existing plantations and forests and the establishment of additional areas of plantation. The limited availability and access to land with high potential yield means that optimizing the yield of existing areas of hardwood and softwood plantations is a high priority. Additionally, new plantings will inevitably be in areas with lower rainfall and potentially poorer soils, and/or in close association with agriculture. Understanding the limits to yield and how they can be managed in non-traditional areas will be critical in optimizing wood production from these new plantations.

Due to the inherent low fertility of Australian soils, managing the nutrient status of plantations (including interactions with water availability) is a critical component of silvicultural management. Both the potential yield and realized yield are determined by the interactions between environmental conditions, genetics and management actions.

Much of Australia's softwood estate has been established on areas with low fertility. Significant increases in yield in response to fertilizer have been demonstrated in extensive areas of the softwood estate (see reviews by Nambiar 1995 and May *et al*. 2009). In contrast, the majority of hardwood plantations have been established on land that was used for agriculture for some decades and the nutrient status of these soils has been improved through agricultural fertilization and other agronomic practices. Under these circumstances responses to fertilizer have often been smaller and less general than in softwood plantations (Szota *et al*. 2014, McGrath and Mendham 2018).

Objectives

The Plantation Nutrition Investment Plan (PNIP) provides a high-level review of national and international research and operational practices relevant to forest plantation nutrition for the Forests and Wood Products Australia. This plan will direct investments to sustainably optimise value gains by

Optimising nutrition management;

- Establishing measurable stretch targets for maximising value gain across the sector;
- Outlining a pathway for investment in priority areas of research, development and extension ("RD&E") for the Australian plantation forest industry.

Methodology

To achieve the objectives listed above, Australian and International research personnel were consulted, and the relevant literature was reviewed to provide a position for the Australian plantation forest industry on:

- Deployment of previous and current forest nutrition RD&E, including those sponsored by FWPA in collaboration with other RD&E providers
- Relevant international RD&E not yet deployed widely in Australia;
- Quantification of yield and/or value gain made internationally in comparable or relevant forests and climates through nutrition management;
- The methodology for assessing the potential yield gains to Australia's plantation forest estate based on deployment of current R&D, international practices and potential future practices, and use this to provide an estimate of the likely potential yield gain and/or value of improved nutrition management to plantation forestry in Australia.
- Cost of implementing the Investment Plan;
- Industry and research provider capabilities, including the need to access and availability of RD&E expertise; and
- FWPA levy payers and other stakeholders' priorities for RD&E investment in this area.

This information was integrated and added to by the authors, and the plan drafted and revised in consultation with the FWPA.

Analysis of current state of plantation nutrition RD&E

The aims and priorities of an RD&E investment plan need to be developed in the context of the systems to which they apply, but useful examples and perspectives can be also be gleaned from similar systems elsewhere. In this section of the report we provide an overview of the Australian and International contexts that provide examples of achievements in yield by investing in nutritional RD&E. Presentations available from a recent international eucalyptus plantation conference (https://eucalyptus2018.cirad.fr/) provide further examples of RD&E efforts internationally (slides Eucalyptus 2018: Managing Eucalyptus plantation under global changes. Abstracts book - Agritrop (cirad.fr)).

At this conference, 5 out of 65 presentations (8%) were by Australian government- or university-based researchers, but none had a strong Australian industry content. In contrast, industry was strongly represented in many presentations from other countries, particularly as cooperatives, and in a few cases in a private industry context.

In the following sections, we have attempted to focus on the nutritional components of yield, but this component is difficult to separate from other factors, as interactions are highly significant for realised yield (e.g. with water, genetics, pests and disease factors, the level of investment and the effectiveness of all silvicultural operations).

Australia

On an area basis, the 2 M ha plantation industry in Australia is comprised almost 50/50 of softwood plantations primarily grown for sawlog production and hardwood plantations grown for pulp. The softwood resource expanded steadily from the 1960's to the 1990's and was initially owned by State Governments, though most of this resource has now been privatized. The area of hardwood plantations developed rapidly from the late 1980's to the mid 2000's. These commercially owned and managed plantations are largely grown in areas with greater than 750 mm annual rainfall.

From a nutritional perspective the softwood and hardwood resources provide contrasting situations, with the softwood plantations established mainly on ex forest land with low natural fertility while the hardwood plantations were largely established on more fertile farm land. There was considerable research and development (R&D) on the nutrient requirements of the softwood plantations. This R&D effort came from the extensive resources focused on the development of these plantations by the State agencies that established the plantations, and by the considerable resources that the Commonwealth Government focused in these areas through CSIRO. A feature of the research environment during the expansion of the softwood plantations was strong coordination of public-good R&D through a series of discipline-focused Research Working Groups, with an overarching coordinating body. These coordinating mechanisms have ceased to exist with the privatization of the softwood resource and the development of hardwood plantations by commercial forestry companies.

A key message is that the combined effects of improved genetic material and silvicultural systems for softwoods (site selection, site preparation, weed control, nutrient management and within-stand competition) has been an improvement in plantation yield at the estate level (O'Hehir and Nambiar 2010).

There has been less focus on the development of nutrient management systems for the more recently developed hardwood plantations due to the decline in both State and Commonwealth resources available for plantation research that was not substituted by industry funding, and due to the higher fertility of the land on which these plantations have been established. Consequently, these plantation systems present different challenges. For the softwood resource, a major task is the effective provision of extensive knowledge gained through R&D programs directed at these plantations and the preservation of this information into the future. For hardwood plantations, there remain considerable knowledge gaps about the optimization of plantation yield through the conservation of existing nutrient resources and the enhancement of yield through fertilization.

International

Brazil

The forest plantation industry in Brazil has expanded many-fold during the past few decades, with investment in nutritional research underpinning a significant proportion of increased wood production per ha (yield). Across two decades, yield of eucalypt plantations steadily increased from about 26 to 40 m^3 ha^{-1} $year^{-1}$ (54% increase, Figure 1). In contrast, yield of pine plantations increased 48% over less than one decade to c. 37 m^3 ha^{-1} $year^{-1}$. Some current annual increments (CAI) in stem volume growth in Brazil are very high (> 90 m^3 ha^{-1} $year^{-1}$), which reflects the excellent soils, climate, management, and genetics generally experienced across the Brazilian plantation estate, a lack of pests and diseases, and a decrease in rotation length from 20 to 6 years (Stape *et al*. 2010; Figure 2). However, most new plantation areas being developed in Brazil are on sites prone to drought and frost that are expected to achieve somewhat lower productivities (Gonçalves *et al*. 2013). Some clones suitable for these sites are achieving MAI values of 35-42 m^3 ha^{-1} $year^{-1}$.

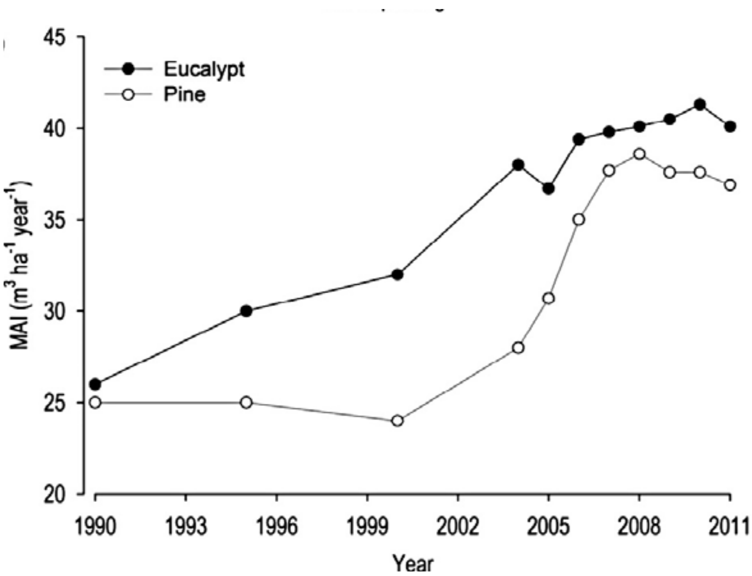

Figure 1. National average trends of yield for eucalypt and pine plantations in Brazil between 1990 and 2011 (Gonçalves *et al*. 2013).

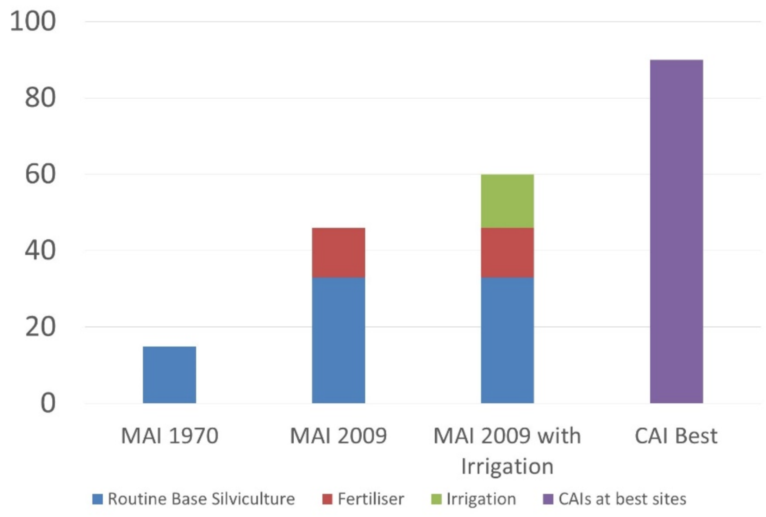

Figure 2. Some examples of eucalypt plantation yield (m^3 ha^{-1} $year^{-1}$) in Brazil achieved using fertilizer, irrigation and other factors compared to general yield achieved in 1970 (Stape *et al*. 2010).

These increases in yield reflect a sustained focus on development and implementation of new knowledge (Gonçalves *et al*. 2013). The research effort has been broad ranging, but largely a combination of silviculture and genetics, and based on substantial investments in internal (confidential) and external (collaborative, shared, publicly accessible) RD&E. External RD&E has been largely through industry cooperatives based at universities that have benefited greatly from the collaborative input of international researchers (mainly from USA and France).

While Australians could learn from the Brazilian experience, some aspects of it are not highly relevant to Australia, because there is an emphasis on tropical and sub-tropical genotypes, sites that are highly favourable to growth, and labour and other costs that are much lower than those experienced in Australia.

Portugal

Plantation forestry in Portugal could be a highly relevant comparison for Australia, as the industry is mainly based on temperate genotypes (especially *E. globulus* and *Pinus pinaster*) grown on sites significantly limited by low nutrient and water availability, and with labour and other input costs similar to Australia. Eucalypt productivities in research plots covering a range of growing conditions trended upward between 1982 and 2005, but this was accompanied by a decrease in the age from which MAI could be calculated (Palma *et al*. 2018). Overall, MAIs cover a similar range to those in temperate eucalypt plantations in Australia, but rotation length tends to be shorter, and there is more use of coppicing, which also influences yield. The doubling of yield over 25 years highlights the value of silvicultural R&D investment in this country, including nutritional management.

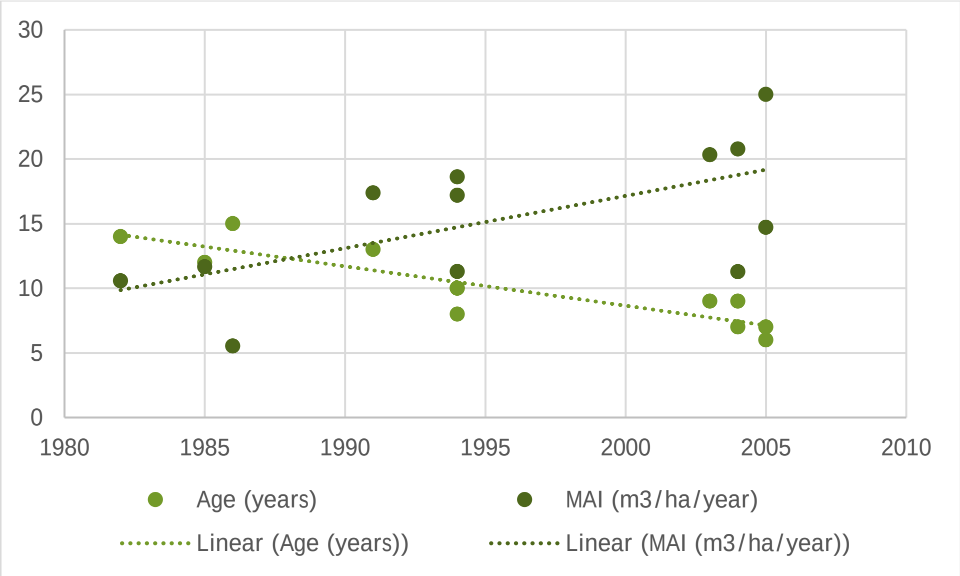

Figure 3. 23-year trend in yield and age of measurement in Portugal (Palma *et al*. 2018)

Private industry is a significant investor in RD&E in Portugal. While some of its research is probably private and confidential, some RD&E investment is via a cooperative with other companies and organisations from private and public sectors (RAIZ; http://raiz-iifp.pt/en/). Outputs of that research are available through publications or consultancies.

South Africa

Eucalypt yield in one of South Africa's major plantation companies increased on average from 7 to 22.6 m^3 ha^{-1} $year^{-1}$ over two decades across the entire estate (1981-2000) and reached 40 m^3 ha^{-1} $year^{-1}$ under some sub-tropical conditions (Morris 2008). A combination of silvicultural research and genetic improvement underpinned the knowledgebase for this increase in yield, while technical transfer was important for translating research into practice.

Tree breeding, plant propagation and site classification research is conducted largely in-house, whilst silviculture research and plant protection research is funded at several institutions mainly in collaborative initiatives with other forestry companies in South Africa (Dyer 2000 cited by Morris 2008). Another large plantation company in South Africa also runs substantial research centres and works with other research institutes. There are three main RD&E providers in South Africa based at universities or the national research agency (http://www.forestry.co.za/forestry-research).

USA

Pine yield increased in the south-eastern USA from 6 to 25 m^3 ha^{-1} $year^{-1}$ over six decades (1960-2000), which was associated with a halving of rotation length (40 to 20 years) (Fox *et al*. 2007a, 2007b). In early years this trend included naturally regenerating forest. Conversion to plantations achieved 8 m^3 ha^{-1} $year^{-1}$ during the first decade. Intensification since then achieved the remaining increase, with 19% of that increase attributed to site preparation, 25% to weed control, 25% to fertilisation, and 31% to genetic improvement.

There was substantial private and public investment in RD&E required to achieve this increase in yield, including significant collaboration with university-based cooperatives that provided a degree of public investment in university staff and facilities for planning, and implementation of the research program. These cooperatives in-turn conducted a large portion of the research in association with publicly-funded post-graduate training programmes. A lead example of this model is the Forest Productivity Cooperative, which is based at North Carolina State University, but with substantial bases also in South America and supported by a wide range of North, Central and South American plantation companies (https://forestproductivitycoop.net).

New Zealand

Pine yield increases due to breeding and site quality have been quantified in NZ at research sites (Kimberley *et al*. 2015). The effects seem to be additive rather than interactive, which means that genetic improvement and silvicultural research can progress separately and gains in each field are generally applicable (can be added) to estimate a combined effect. As such, for breeding that occurred from prior to 1978 to 1994, MAI at 30 years of age increased 13% for improved genotypes compare to unimproved genotypes, and a further 12% for highly improved genotypes. For site quality, the increases were 17% for moderate site yield relative to low site yield, and a further 26% increase for high site quality.

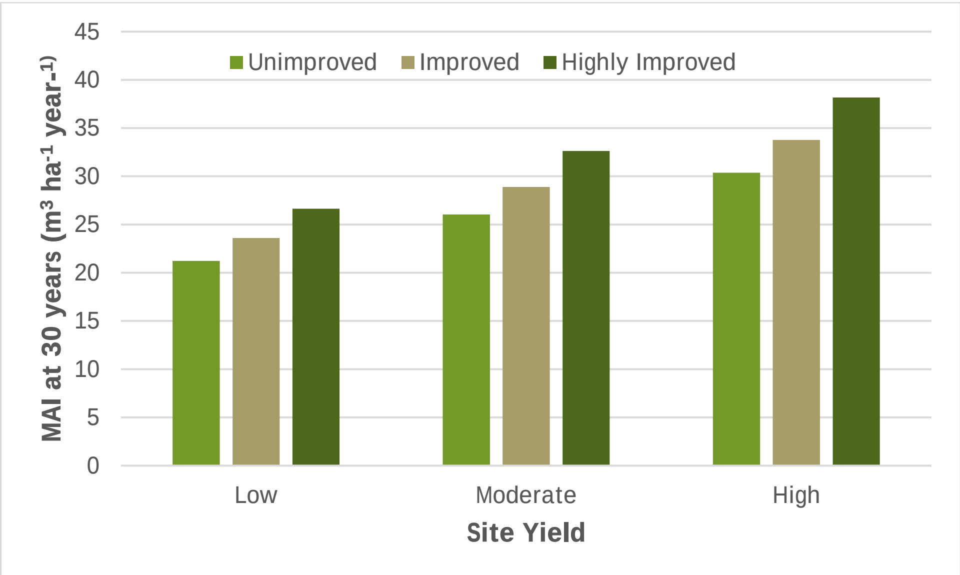

Figure 4. *Pinus radiata* yield as typically affected by genetic improvement on three sites of contrasting yield in New Zealand (Kimberley *et al*. 2015).

Currently, apart from confidential research by private plantation growers in NZ, research across a range of fields is conducted by a largely government-funded institute, Scion (https://www.scionresearch.com/home) and under a grower-led levy-based system (https://fgr.nz/about/research-structure/). Historically, most of the genetic gains and improvements in silviculture (including nutrient management) realised in today's plantations developed from research conducted by Scion and implemented by government growers prior to those plantations being privatised.

Key Attributes of Successful Collaborations Internationally

From the above international experience, we sought to identify key attributes that have underpinned their success in using research (including nutrient management) in achieving yield gains. These attributes are listed in Table 1.

Table 1. Key attributes of major collaborative research initiatives that have underpinned gains resulting from research into nutritional management and related areas of research

Technical scope	Industry involvement	Resourcing
• *Pinus* and *Eucalyptus*	• Quick knowledge transfer through workshops, seminars, in-field demonstrations, publication	• Support for numerous MSc and PhD training opportunities then for company or university employment
• Various technical programs related to silviculture	• Company teams working with university/researcher teams	• Support for significant on-going contributions from visiting scientist collaborations
• Multi-site, large scale experiments elucidating principles and potentials and including operational treatments for comparison	• Some IP protection within the collaboration and within companies	• Adequately funded with cash and in-kind from the industry; range of direct government funding support including in-kind time of university or government researchers and scholarships
• Applied and process research	• Shared data and experiences • Research and operational products and services provided to the industry • Complementary in-company applied and strategic RD&E – protected IP/knowledge, but IP drift occurs through staff changes, informal interactions and shared experiences	

The improvement in plantation performance due to better management systems based on research and development has been effectively delivered with a range of investment models. The development of successful softwood silvicultural systems in Australia was based on strong, coordinated, long-term investment by State and Commonwealth governments in both the research personnel and the resources to implement the R&D programs. Internationally the models vary considerably with strong government support remaining a feature of the New Zealand system. In the USA and Brazil industry funded (and in some cases industry-managed) cooperatives are common, while in South Africa much of the R&D is conducted directly by plantation companies.

Common features of the systems are strong and sustained support for the research programs and a substantial collaborative component. The long-term nature of plantations means that having on-ground custodians of the R&D programs is important in maintaining an effective trial base.

Many of the attributes listed in Table 1 existed in the past for nutritional research in Australia, which led to substantial realised gains in yield. However, many of these attributes are currently weak or lacking, which represents a risk to achieving further gains in yield (see section Barriers to Achievement and Mitigation Strategies for comments on the impediments to achieving gains).

Estimating Yield and Yield gaps

In order to assess the potential gain in yield from silvicultural interventions it is necessary to understand the limits to production and the gap between potential and current production. For both softwood and hardwood plantations, defining this yield gap provides a framework for decision making based on the potential improvement in yields due to nutritional management and other factors.

A yield gap is the difference between potential and realised yield (e.g. van Ittersum *et al.* 2013, their Figure 1(a), and Rhebergen *et al*. 2018 reproduced as Fig 5 below). Potential yield is determined by genotype, climate, soil type and water supply. Thus, potential yield varies spatially and temporally, and can be influenced by soil nutrients and other site and management factors. However, it is generally impossible for managers to achieve the perfection in crop and soil management required to achieve potential yield, and generally it is not cost-effective to do so because yield response to applied inputs follows diminishing returns when yields approach ceiling yields (Koning *et al*., 2008; Lobell *et al*., 2009). Often 80% of the potential yield is defined as the exploitable yield, or practically achievable yield, and is used as the ceiling for production (van Ittersum *et al.* 2013).

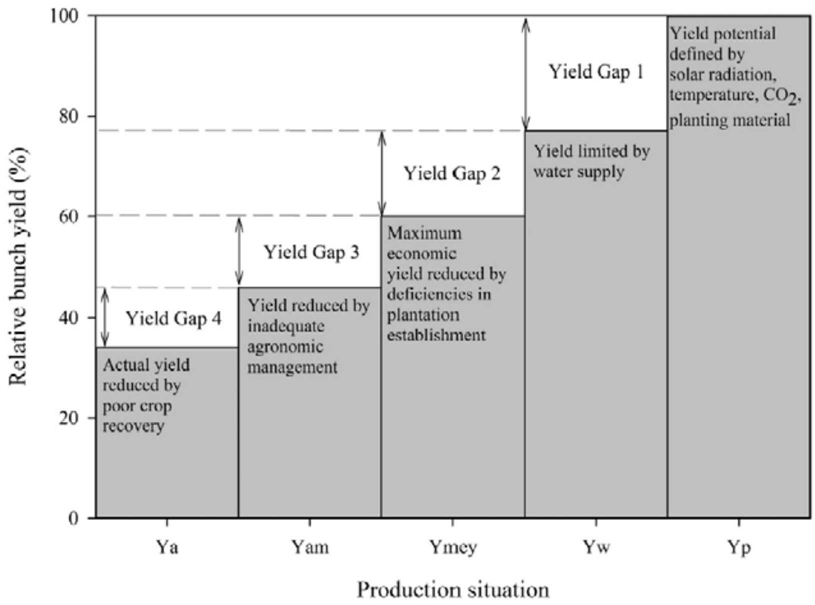

Figure 5. Modified yield gap model for perennial crops used to partition potential yield (Yp) and actual yield (Ya) into four gaps with the size of each gap depending on site specific factors (from Rhebergen *et al*. 2018).

For most of Australia's plantation resource, potential yield is limited by water (Yw), as it is unusual for timber plantations to be irrigated, except in limited circumstances where wastewater is available. However, data from irrigated plantations are useful particularly in calibrating growth models for the range of environmental conditions likely to be experienced. In the water limited environments in which most of Australia's plantations are grown, understanding the interaction between nutrient supply, water availability and other growth moderating factors (pests and diseases) will be critical in developing the knowledge required to define potential yield and hence estimate the yield gap.

In plantation forestry, the yield gap approach is a quantification that can contribute to site-specific (precision) silviculture. Using the yield gap approach provides managers with a useful framework for identifying potential gains that can be achieved through better nutritional management by

(1) quantify potential gains from improved silvicultural management,

(2) identify the most profitable target sites, and

(3) identify management actions that will close the yield gap.

Potential Australian plantation yield in relation to underlying factors

Nambiar (1995) assembled data for *P. radiata* from a range of silvicultural trials that assessed yield in relation to water and nutrient supply. These data came from both rainfed and irrigated trials. While the analysis was very useful in identifying the strong influence of both water and nutrient supply in determining plantation yield, the varied experimental designs and wide range of site conditions made it difficult to define the upper limits to yield. However, the relationships developed indicated that, under some conditions, very high yield could be achieved. The upper limits of growth under rainfed conditions appeared to vary from less than 20 m^3 ha^{-1} $year^{-1}$ to 35 m^3 ha^{-1} $year^{-1}$ over a rainfall gradient of 500-1200 mm yr^{-1}. In the Mt Gambier region of SA, productivities up to 55 m^3 ha^{-1} year^{-1} were measured, however it appears likely that these plantations had access to deep stored water (Benyon *et al*. 2007). In areas with strongly seasonal rainfall, soil water storage capacity appeared to be a critical limitation. Although the difficulty in determining soil water storage capacity relevant to deep rooted trees has been described as an intractable issue (Nambiar 1995, Running and Coughlan 1988), there has been a recent notable effort to quantify it for a *Eucalyptus grandis* plantation in Brazil (Christina *et al*. 2018).

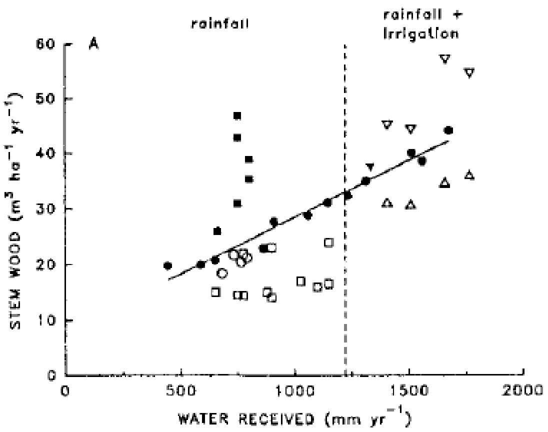

Figure 6 The range in amount of water received and mean annual increment (age 11-15 years) in *Pinus radiata* plantations (from Nambiar 1995).

Similarly, the relationships between yield and water supply for hardwood plantations in WA (White *et al*. 2009) clearly demonstrated that, in first rotation blue gum plantations, water supply provided the upper limit to plantation yield (Figure 7).

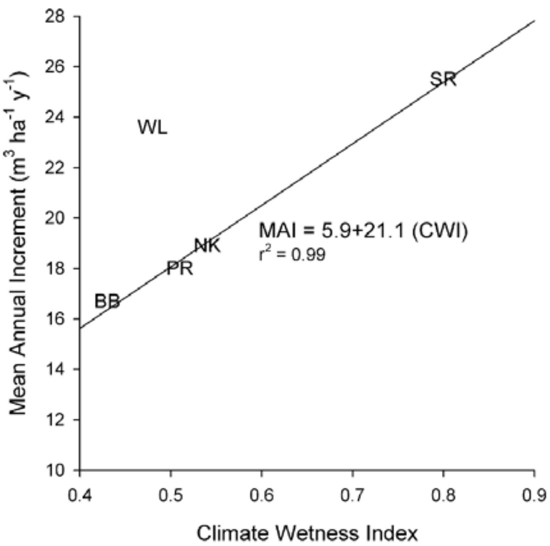

Figure. 7. Mean annual increment from 5 sites across southern WA provided with adequate annual fertilizer applications as a function of average annual climate wetness index (CWI = rainfall/potential evaporation) from planting to the time of measurement. The line is a linear relationship fitted by regression to the data for all sites except Wellstead (WL) (From White *et al*. 2009). The Welstead site had access to deep stored water

The additional stored water available to many hardwood plantations established on previous agricultural land results in yields that are higher than those achieved in subsequent rotations (Mendham *et al*. 2011). This needs to be accounted for when estimating sustainable potential yields.

The critical impact of weed competition on early yield of plantations and the response to fertilizers during establishment has been well documented (e.g. Smethurst and Nambiar 1989, Woods *et al*. 1992, Adams *et al*. 2003). However, the interactive impacts of weed competition and plantation density (stocking) on the effectiveness of later-age fertilization needs to be better understood and predicted. Similarly, nutritional interactions with pests and diseases need to be considered, because the nutrient status of tree tissues can change their attractiveness to these organisms, and tree recovery is influenced by nutritional status (Pinkard *et al.* 2006).

Defining the limits to yield should be a key priority for silvicultural research in Australia. Identifying the factors that prevent plantations from reaching the potential climate (water) limited yield will be critical to identifying sites where yield can be enhanced with more intensive silviculture and those sites where it is difficult or impossible to increase yield. Water supply will be a key determinant of the response to fertilizer and the yield of potentially new plantation areas, and therefore any new research will need to include this issue.

The role of nutrient supply in enhancing yield

For both softwood and hardwood plantations there are many examples where yield has been increased with fertilizer application. In some cases, yield has been doubled by fertilization. For example, on the infertile soils in WA the yield of both blue gum (White *et al*. 2009) and radiata pine (McGrath *et al*. 2003) was at doubled to 25 m^3 ha^{-1} $year^{-1}$ in both studies, with combined N and P fertilizer applications and adequate water availability.

A useful comparison of the impact of improved fertility on plantation yield is the comparison of yield of adjacent plantations with different land use history in the central highlands of NSW. Total biomass and thinning yields at age 21 years were ~40% higher on the ex-pasture sites relative to ex-forest sites (Birk 1992).

A synthesis of an extensive series of post thinning fertilizer trials from the Green Triangle region showed that the combined response to N and P was in the order of 20-25% over 4 years (May *et al*. 2009). However, the highest N application rate in this trial series was 200 kg N ha^{-1} which may not have been sufficient to maximise production. Comprehensive rate trials and economic analyses are required to determine the optimum biological and economic fertilizer regimes.

The response to fertilizer varies strongly between sites with variations in water supply, inherent fertility and previous land use. This means that it is difficult to provide broad recommendations on the optimum fertilizer type, rate, placement and timing. The NSW radiata pine resource of ~300,000 ha provides a strong example of this, with the climate varying from temperate winter dominant rainfall through to uniform rainfall patterns and a wide range of soil types and elevation from sea level to over 1000 m

(Turner, pers. com.). Thus, an understanding of these key issues will be required to make informed predictions of likely fertilizer responses.

Recent reviews of blue gum nutrition (Szota *et al*. 2014, McGrath and Mendham 2018) indicated that while substantial responses could be achieved on some sites there were many sites that were unresponsive to fertilisation. As previously noted, higher fertility of ex-agricultural sites, on which much of the hardwood plantation estate is grown, will limit the role of nutrients at least during the first rotation. However, this is not consistent across Australia, for example, much of the Tasmanian hardwood estate was established on previously forested land. Mechanisms to identify both responsive and unresponsive sites will be important in increasing the value of these plantations. The recent synthesis of fertilizer response data by McGrath and Mendham (2018) has demonstrated that there are likely useful relationships between soil N and the responsiveness to nitrogen fertilizer. Further developing these relationships will likely deliver useful mechanisms for the diagnosis of nutrient deficiencies.

An important issue in determining the overall impact of improved nutrition is assessing whether there are any impacts of higher growth rates on wood quality. In the comparison of plantations grown on ex-pasture and ex native forest, the timber from the ex-pasture sites was of lower quality due to both heavy branching and lower wood density (Birk 1992). In a trial on a site that responded to both P and N in WA with a large and sustained increase in growth as a result of the application of P, the wood basic density did not appear to decline. This was consistent with the findings of Gentle *et al.* (1968) who showed little effect of P fertilizer on wood density. The high growth rates achieved when N was applied in combination with P were associated with a temporary reduction in wood density for the same period during which growth was increased by the application of N. Although application of P provided the greatest increase in growth, application of N reduced wood density to a greater extent than did the application of P (McGrath *et al*. 2003). In the WA study, wood density remained above the minimum basic density of 400 kg m^3 that has been set for clearwood to ensure satisfactory in-grade performance of framing members (Standards Association of Australia 1988). These studies highlight the need to assess the overall impact of the silvicultural treatments rather than limiting assessment to biomass or volume responses. As broadly applicable predictive relationships between fertilisation and wood quality have not yet been identified, it will remain important to measure such effects wherever possible before overall value impacts of fertilization can be fully quantified.

While the infertile nature of most Australian soils means that plantation yield is generally limited by nutrient deficiencies it is possible that nutrient toxicities may limit yield in some circumstances. The above example where high nitrogen availability on an ex agricultural site reduced the value of the timber (Birk 1992) demonstrates that nutrient toxicities can influence timber yield. Assessing whether toxicities influence plantation yield should be evaluated in circumstances where nutrient availability has been elevated.

Estimate of the quantum of yield gains achievable in Australia

Two methods were used to estimate the impact of implementing effective nutrient management programs on plantation yield. The estimated benefits from optimising nutrient management are delivered by avoiding losses of nutrients through poor plantation management, by reducing the costs of fertilizer programs through the accurate targeting of plantations that will respond to fertilizer applications and by increasing the productivity of plantations that are responsive to fertilizer. These issues are embedded in both the methods used to estimate the benefits of optimising plantation nutrition.

Method 1 uses estimates of overall (estate-wide) plantation yield (hardwood and softwood combined) based on trends in harvest volumes to estimate the impact of additional fertilizer applications in plantations on top of existing practice. Method 2 uses estimates of direct fertilizer responses for hardwoods and softwoods separately to estimate the gain for both optimal and likely operational implementation. These methods provide different estimated yield gains due to the different assumptions. However, both methods demonstrate that implementing effective nutritional management is likely to provide significant yield increases for the Australian plantation industry.

Method 1: Top-down estimate.

A study undertaken for FWPA by Braden Jenkin estimated that genetic and silvicultural R&D delivered an increase of 3 m^3 ha^{-1} over 15 years or 0.2 m^3 ha^1 $year^{-1}$ for the forest plantation industry overall (softwoods and hardwoods combined). We assumed that half of that increase was due to silviculture and half due to genetic improvement. If 50% of the silvicultural improvement was due to improved nutrient status; then this currently contributes 0.05 m^3 ha^{-1} $year^{-1}$ or an increase in yield of 1.5 m^3 ha^{-1} over a 30-year rotation. Investing in understanding fertilizer responses and developing effective prediction systems could double this to 3.0 m^3 ha^{-1} $year^{-1}$. When fully implemented, a 3.0 m^3 ha^{-1} $year^{-1}$ increase in MAI of softwood plantations would increase the total yield of wood by 90 M m^3 ha^{-1} over a 30-year rotation, and similarly such an increase in hardwood yield over 3 successive 10-year rotations would increase yield by 90 M m^3, or a total increase in wood production (softwoods + hardwoods) of 180 M m^3 over this period. This has not been discounted for reductions in effectiveness of implementation or level of uptake as it assumes that these issues are embedded in the progressive increase in yield.

Method 2, Direct estimates of fertilizer responses.

The direct benefit of extensive fertilizer programs were estimated from existing experimentally determined responses that have been discounted for the transition of knowledge into practice (estimated at 40% for Australian forestry) and that the recommended fertilizer programs would be implemented over 70% of the plantation area. These estimates assume that the impact of current R&D programs and the level of investment remains the same and that this is the baseline for further yield improvement. Without the current level of investment, it is likely that plantation yields would decline. **Details of Method 2 calculations are provided in Appendix 3.**

Estimates are provided for an Optimum response scenarios (Table (a), Softwood and Table (c,) Hardwood, Appendix 3) which assumes that the high levels of response requiring high rates of fertilizer are implemented, while the Likely Operational scenarios (Table (b), Softwood and Table (d), Hardwood, Appendix 3) assume that a lower level of fertilizer is applied and hence the responses are not optimised. Note that many calculated values have been rounded for clarity of presentation

Summary of estimates

The Top-down estimate (Method 1) for the increase in production over 30 years is 180 M m^3 split evenly between softwood and hardwood plantations. The direct estimates (Method 2 See Appendix 3) for the optimum fertilizer scenarios in both softwood and hardwood plantations would produce in excess of 64 M m^3 over 30 years. The Operational implementation scenario produces a combined total of 25 M m^3.

Summary of estimated gains in production from fertilizer application across the Australian plantation estate from both the Top Down and Direct estimates.

	Estimate Method: (million m^3)		
Plantation	**Top-Down**	**Direct estimate Optimum implementation**	**Direct estimate Operational implementation**
Softwood 30-year rotation	90	32	15
Hardwood 3x 10-year Rotations	90	21	10
Total	180	64	25

These estimates have been based on the assumption that the recommended R, D &E programs (including the transfer of knowledge to industry) are fully implemented. Lower implementation of the program will reduce the gains made from the program. In the short term not implementing the work on slash management may not have a significant impact on gains in yield, however over time this would likely lower the potential yield gains. In contrast any reduction in the focus on knowledge transfer will likely reduce the short-term yield gains. Of the four research areas identified and Priority 1:

- Yield predictions systems and yield gap analysis
- Methods for diagnosing nutrient deficiencies for hardwoods
- Quantify fertilizer responses and develop fertilizer prediction systems for hardwoods
- Capture and adopt the existing knowledge base on nutrient responses for softwoods

delaying work on the latter three would reduce the gains in the short term. Work on the yield prediction and yield gap analysis area will have an impact in the longer term.

As the data to undertake cost benefit analyses on the specific projects is lacking it is impossible to be precise about the impact of less than full implementation of the proposed program. However, in the longer-term, reductions in yield gains are likely to be proportional to reductions in funding.

Barriers to Achievement of Yield Gains, and Mitigation Strategies

There are two main barriers to improving plantation yield and value; the lack of knowledge on which to base improved management practices; and ineffective transfer of that knowledge into management practices.

As detailed research cannot be expected to be conducted for each individual spatial and temporal context of soil, climate, genotype and management factors, it becomes a source of uncertainty and contributes to less-than-optimal translation of research into practice.

Knowledge availability and generation

Development and retention of discipline expertise amongst researchers

Nutritional management expertise is crop-specific to some degree, which means that competent nutritional research expertise for forest plantations is best fostered in dedicated experts that invest in understanding forest plantation systems. Currently, this is far too infrequently achieved in Australia to expect the industry to be well-serviced for nutritional research skills in the future. Because the Australian forest plantation industry lacks critical size compared to several of the international comparisons made above, and because much nutritional research is pre-commercial, long-term collaborative frameworks supported by the whole industry should be considered to provide attractive career structures.

Balance of experimentation

As nutritional research is hugely diverse across species, sites, management, nutrient types etc., it is necessarily multi-faceted and incremental. The daily to multi-rotation dynamics of nutrient supply-demand relationships also adds a level of complexity.

Progress therefore depends on a balanced combination of different types of research, i.e. long- to short-term, and highly applied to strategic and process-based R&D, that can adapt to changing priorities.

Level of sustained funding

Although matching government funds are available for many projects (e.g. through FWPA), the low absolute level of funding available for nutritional research currently hinders the industry's ability to address the other barriers listed above and to meet the key attributes listed in the previous section that have underpinned the maintenance or increases in yield observed internationally. Engaging the plantation industry at a detailed technical level in the decision making process (i.e. co-development of projects) may be a way to improve the investment in this area as it will provide the industry with ownership of the research and the funding process.

A sustained level of funding is required for nutritional research at a substantially higher level than is currently the case.

Knowledge transfer and utilization

It has been estimated in some Australian plantation systems that potential yields defined through research are discounted by 40-60%, i.e. gains achieved in the field are substantially less than those suggested by research results, which was a consensus point at the industry workshop for this plan. This is likely an area that requires significant focus as it represents a strong opportunity to improve plantation yield. The magnitude of this discount factor could be better quantified, and socio-economic research could contribute to an understanding of why it is relatively high in Australian plantation forestry. Comments from South America, for example, suggest that translation of research into practice is more efficient there:

> "*Under similar conditions of climate, relief and soil, and intensive silviculture, a maximum productivity research-to-practice loss of 15% is expected due to normal handling failures, but for medium intensity silviculture the loss of productivity can reach 25%. The main faults are due to seedling/cutting quality, fertilizer distribution and weed control.*" Prof. J.L.M. Gonçalves, University of Sao Paulo
>
> *"Usually, we assume about 20% less productivity increase can be achieved operationally than the best response seen in research plots, but it depends greatly on the quality of operational practices and similarity of growing conditions."* Prof. R. Rubilar, University of Concepcion, Chile, and Co-director of the Forest Productivity Cooperative

This is a large opportunity for the Australian industry, as it suggests that yield could be substantially increased through better application of prescriptions defined through research, even without much additional research. This issue can be resolved by focusing on the following components.

Training

Specific training amongst forest managers and operational staff in nutritional management is rare at the tertiary level, and there is a high turnover of staff in forestry where this expertise is needed. This situation presents a barrier to appropriately prioritising nutritional research and management options, to understanding the need for change, and to designing practical responses. A new emphasis on training in the principles and practice of nutritional management is needed, using a combination of short-courses, seminars, workshops and field demonstrations. Significant past and current advances in knowledge developed by researchers need to be captured in hard and soft systems such as decision support systems, models and manuals. This knowledge then needs to be rapidly and effectively communicated to managers and operational staff as required. Researchers and managers need to work closely together in designing and conducting research so that the programs are jointly owned by both the two groups.

Integration of disciplinary research

Nutritional management is becoming more complex as the industry strives towards higher spatial and temporal resolution of information systems and management actions that improve the efficiency of wood production and predictability of its supply. Increasingly, nutrient management is not considered in isolation to other science disciplines (e.g. silviculture, genetics, protection, modelling, and data technologies) as industry strives for increased profitability and a low environmental footprint.

Future nutritional research should be embedded in multi-disciplinary approaches.

Resolution and accuracy of the resource base

Production forecasting methods are improving, but full use of these capabilities can only be achieved if data inputs to the projections are of comparable spatial and temporal resolution and accuracy.

Improvements in soil and climate databases would be beneficial in many cases. Genotype characteristics may need better specification for nutrient capture and use. Nutrient management actions would benefit from better targeting, accuracy and uniformity.

Co-development of projects

Increasing co-development of projects between researchers, managers and operational staff also has the potential to improve knowledge transfer during and after projects.

An outline of the priority RD&E needed from 2018 to 2023 and beyond

In this section, we describe the priority topics for investment in nutritional research common to and individually for hardwood and softwood plantations and indicate a level of priority (1 very high, 2 high). These and all other topics discussed at the industry workshop are listed in Appendices 1 and 2. They are also summarized in a table of priority research topics in the Executive Summary.

Common priorities for hardwood and softwood plantations

1. Potential Yield and Contributing Factors (Priority 1)

- Research that supports industry in understanding yield gap and the factors contributing to this, which should be multi-disciplinary and build capacity to identify where and when nutrient management will be beneficial economically
- Fine-scale knowledge of site potential – including climate risk – providing a basis for precision management
- Data-model fusion and AI approaches to improve forecasting capacity and identify uncertainty

To optimize the value of plantation silvicultural research in Australia it is critical that the limits to productivity be defined. Without a yield gap analysis, it will be difficult to assess progress towards the goal of the Grower Research Advisory Committee of doubling the value of timber production in Australia and even how to approach this task. The balance between increasing yield and value from existing plantations and establishing new plantations to achieve this goal depends on the capacity to improve yield. Quantifying the scope to improve plantation yield and value is the first step in this process. Defining the limits to yield and then estimating the yield gap will require data from both empirical experimentation and modelling. While the factors that limit growth are generally known, quantifying their contribution and the contribution that managing plantation nutrition can make is an important component of the yield gap analysis. A related priority is to better understand water use efficiency (yield per unit of water use) and its dependence on interactions between nutrition and genetics. The importance of this issue may increase if as predicted much of the area where plantations are currently grown become hotter and drier. Both empirical data on the variation in yield across climate gradients and the use of process-based models to predict the impact of climate change will be useful in studying these impacts.

The potential decline in nutrients that are not deficient in early rotations, particularly in plantations on previous farmland, including nitrogen phosphorus, calcium, potassium and some of the trace elements is an issue that needs to be understood, as nutrient deficiencies are likely to increase in importance in subsequent rotations if nutrient availability is not maintained or increased above the level required to sustain or increase plantation yield. Identifying the stage at which these nutrients limit plantation yield is an issue that requires additional research. This issue is common to both hardwood and softwood plantations.

Delivering knowledge of the factors that limit yield and the management actions needed to address the limitations to yield would be an important output of this initiative. It is important to note that many factors other than nutrient supply limit plantation yield and delivering this knowledge will require contributions from a broad range of specialists.

2 Knowledge Capture and Training Systems (Priority 2)

- Review and synthesis of past research
- Development of systems for capturing, storing and disseminating research, including the integration of research outputs into decision tools that are linked to industry operating systems
- Research into collaborative/alternative models for research delivery that improve uptake and develop capacity.

Reiterating earlier comments in this report, past and current advances in knowledge developed by researchers need to be captured in hard and soft systems such as decision support systems, models and manuals. This knowledge then needs to be rapidly and effectively communicated to managers and operational staff as required in training systems. Research that supports industry in understanding yield gap and the factors contributing to this, which should be multi-disciplinary and build capacity

3 Cost-Benefit Analysis (Priority 2)

- Conduct cost-benefit analysis on yield gains from nutritional management

As yield gains in response to nutritional management are quantified, and product values known, cost-benefit analysis needs to be conducted that accounts for the delay between nutritional expenditure and revenue gained. These analyses will need to be done both for the national estate and on a site-by-site basis.

4 Nutrient value of slash in relation to fertilisation (Priority 2)

- Determine the extent to which fertilisers can augment or substitute for nutrients contained in hardwood and softwood slash
- Implications of slash management strategies across multiple rotations for nutrient management

There is a strong understanding of the principles behind the role of slash conservation in maintaining nutrient resources. However, we currently lack the knowledge of slash nutrient interactions with fertilization because nutrients in slash will probably not be adequate to maximize yield in many cases. There are also commercial and logistical pressures to remove and even sell forest residues from some sites that prompts this issue. If non-nutrient slash values are significant, direct substitution with fertilizer is unlikely, but this aspect has not yet been adequately quantified. Specifically quantifying of the value of nutrients and how effective nutrient replacement (fertilization) is in either maintaining or replacing nutrients removed in biomass should be a priority. Potential values of slash management also extend multiple rotations, for which there is little information that is directly applicable to Australian plantation systems.

For hardwood plantations

A recent review of this area for FWPA (McGrath and Mendham 2018) has provided useful direction in determining the priority areas for R, D&E in hardwood plantations, with which the following priorities are consistent.

5 Diagnosis of deficiencies (Priority 1)

- Systems for diagnosing nutrient deficiencies, including traditional soil and plant analysis methods, and new sensor technologies

Soil analysis shows some promise as a diagnostic tool, particularly for nitrogen, but they are not widely applicable yet due to the limited nature of the data available. While soil phosphorus also appears to have some predictive value, the data are limited. For other nutrients very few data exist. Agricultural experience with trace elements indicates that soil analysis is of little use in such cases.

While a number of studies have found little relationship between foliar nutrient concentrations and responsiveness to fertilizer there is some work that suggests a useful index of nutrient status can be developed by combining nutrient concentrations and tree size (T. Baker pers. comm. 2018). Further work is required to define the most useful methods of diagnosing nutrient deficiencies in hardwood species, including the potential use of new ground-based and remote sensor technologies. Transparency and peer-review is needed to define and justify the range of applicability of diagnostic systems.

6 Developing fertilizer recommendations (Priority 1)

- Systems for diagnosing nutrient deficiencies, including traditional soil and plant analysis methods, and new sensor technologies
- Experiments and tools to support site-specific nutrient recommendation and management, including decisions around type, timing, frequency and placement of fertilisers throughout the rotation
- Research to determine the long-term effectiveness of slow-release fertilisers

Fertilizer can correct or ameliorate nutrient deficiencies and needs to be applied at a time that is suitable for plant uptake. Ideally fertilizer would release nutrients slowly so that release was commensurate with tree demand or be applied at regular intervals. Synchronisation of nutrient supply and demand is important because application of a high dose in one event may exceed the capacity of the plantation to utilize it and lead to leaching or volatilisation losses. Slow-release fertilizers may help to match the supply and demand. Mineral fertilizers can be placed where they will be most effective, for example, close to the base of newly planted seedlings, so that nutrients are highly available to the plants.

7. Slash management for nutrient conservation (Priority 2)

- Develop an operationally effective management option for hardwood slash.

Practical slash management options exist for pines (e.g. equipment), but the development of technologies for hardwood slash management remain a very high priority. Nutrient removal via soil erosion is not a research issue, as the evidence base is strong that erosion should be prevented using standard erosion prevention measures, e.g. minimal soil disturbance and soil protection using vegetation and residues.

For softwood plantations

8. Delivery and preservation of the considerable knowledge base on nutrition is the key issue for softwood plantation RD&E. **(Priority 1)**

- Synthesis of existing softwoods knowledge on nutrient deficiencies into new knowledge systems

While there has been considerable research on diagnosing nutrient deficiencies and identifying sites that respond to fertilization, at establishment, pre and post canopy closure and following thinning, across Australia's softwood estate this knowledge has not been consistently captured or applied. The decline in research capacity across the plantation industry means that the previously available corporate knowledge base that existed in this area is unlikely to be available in the future.

Two current FWPA/Industry projects in the softwood area, that cover all the main softwood growing regions in Australia, aim to capture and deliver the available information and in the process will also identify key knowledge gaps. An important part of this initiative will be the provision of this knowledge through systems that do not rely on high level nutrition expertise.

9. Nutrient requirements across multiple rotations, particularly for rarely studied for nutrients such as Ca, K and trace elements (Priority 2)

- For particular contexts, define multi-rotation responses to nutrients that are likely to have fertilizer carry-over or run-down effects

A better understanding of site-specific nutritional responses and their longevity are areas that both managers and researchers have identified where additional knowledge would improve softwood plantation yield. At a broad level, nutrients that limit yield vary between regions. For example, phosphorus, sulphur and boron are consistent issues in NSW and eastern Victoria, while in other regions plantations are known to respond to fertilization with nitrogen, phosphorus and a range of trace elements. Future nutrition research needs to be tailored to specific regions so that the outcomes are optimized. This focus will require consideration of nutrients such as Ca, K, S and trace elements in combination with N and P.

Refining traditional techniques of nutritional diagnostics such as foliar and soil analyses remains a priority. Determining whether nutrient deficiencies can be identified remotely either using specific spectral signals or by measuring biomass or leaf area needs to be assessed.

Time frame for the delivery of the yield gains from the recommended R&D program

- For softwoods, where the task in largely the implementation of existing knowledge, then the lag between the research programs and implementation could be relatively short and will depend on the level of industry uptake
- For softwoods a useful strategy to expedite the delivery of improvements in yield would be to preferentially fertilize responsive stands later in the rotation - potentially after 2nd thinning which may be within 5-8 years of harvest.
- For hardwoods where there is a greater need to undertake additional R&D that could take 3-5 years, implementation would occur after that. However, some existing knowledge can be implemented without additional research, for example from the reviews by McGrath and Mendham (2018) and Szota *et al*. 2014). This could provide yield benefits for the current rotations.
- Profiting from the growth advantage from nutritional management will be quickest for short rotation hardwood plantations, as the lag between fertilization and harvest is shorter. In contrast, or softwoods, early rotation fertilization could take 3 decades to fully capture the financial benefit.

Prioritisation

If the funds available for this area are not sufficient to fund the full program, it is recommended that the focus of the program be on the issues identified as priority 1 in the Outline of the priority RD&E needed from 2018 to 2023 and tabulated in the Executive Summary. The issues categorized as priority 1 relate to activities that will deliver relatively major short-term yield increases for the plantation industry. It is noted that the longer-term issues will need to be addressed at some stage.

Benefits of implementing the required RD&E from 2018-2023

The estimates provided in this report indicate that overall plantation yield could be increased by between 25 and 180 M m^3 over 30 years. In addition to the increase in yield, an additional increase in profitability will result from a reduction in nutrition-related unnecessary or poorly justified costs that would otherwise have been made (e.g. some fertilizers applied unnecessarily to new land).

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Appendix 1: Previous Relevant FWPA Reports

Nutrition-related research has previously been funded by FWPA. Reports during the past decade are listed in Table.

Report	Author Surnames	Title	Relevant Conclusions	Relevant Recommendations
VNC422 01617 2018	McGrath J and Mendham D	Optimising Blue gum plantation productivity through improved fertiliser regimes.	1. Significant gains in productivity and profitability possible by targeted fertilisation 2. Diagnostic techniques allow the identification of responsive sites 3. Understanding the limitations imposed by water supply is critical to optimising plantation performance. 4. Knowledge delivery requires effective and usable tools for managers	1. Additional work on developing diagnostic techniques is required 2. Quantify the costs and benefits of retaining slash 3. Effective knowledge delivery tools are critical but can only be developed when sufficient data on the diagnosis and fertilizer responses are available
PNC342-1415 2017	May B, Elms S, Hopmans P, McKay L, Hetherington S, Bruce J, Edwards K, Hanssen R	ProFert-Pine - A fertiliser tool for softwood plantations in southern Australia	1. Improved capacity to predict growth responses to and profitability of fertiliser. 2. Provides economic justification for fertiliser decisions 3. Allows responsive stands to be better targeted, improving growth rates, reducing wastage and reduced environmental impacts. 4. Enable better understanding and management of specific nutritional limitations	1. Additional data sets be accessed and new fertiliser trials be established across a wider range of regions and stand ages. 2. Responses to operational fertiliser applications be monitored. 3. Test and validate model use in other agencies and regions
PNC326-1314 2017	Stone C, Osborn J (eds)	Deployment and integration of cost-effective, high spatial resolution,	1. Several satellite and airborne technologies appear accurate and cost-effective enough to consider operational implementation for assessing plantation physical characteristics, e.g. stem volume and foliation.	

Report	Author Surnames	Title	Relevant Conclusions	Relevant Recommendations
		remotely sensed data for the Australian forestry industry		
PNC305-1213 2015	Stone C, Melville G, Caccamo CG , Rombouts J, Rawley B	Operational deployment of LiDAR derived information into softwood resource systems	5. LiDAR-based inventories may not be cost-effective if they were to be refreshed annually but where they to take place every two or three years it appears to be cost-effective. 6. LiDAR acquisition costs are scale and terrain dependant but these costs are decreasing with the use of more powerful sensors by LiDAR data providers.* 7. We have demonstrated that the cost of LiDAR data can be recovered, in part, through reduced field sampling costs (labour). 8. There are many intangible benefits arising from LiDAR such as the numerous DTM-derived surfaces, accurate mapping of NSA and mapping of woody weeds. *Note recent advice is that costs are relatively static, but resolution in increasing rapidly	1. Develop small area estimations and 'conditional' sampling whereby a new subset of reference plots is selected to augment an existing set of reference plots
PNC288-1112 2015	Battaglia M, White D, Musk R, Short T, Bruce J, O'Grady A, Wiedemann J, Edwards J	The extent and causes of decline in productivity from first to second rotation blue gum plantations	2. Reduced soil nitrogen supply was observed on all 20 plots, but only affect 2R productivity on one of the sample plots as water and pests were became most limiting. 3. On sites where 1R site fertility was low, however, or in second and subsequent rotations, soil nutrition is highly likely to become a more seriously limiting effect. 4. If the same genetics are applied, and the same weather conditions and silvicultural	2. Balancing forest production and drought risk combined with careful stewardship of soil resources are fundamental in the south west Western Australian environment to sustaining productivity. 3. Without management of these resources, we will not realise the benefits of improved genetics, or forest management technologies.

Report	Author Surnames	Title	Relevant Conclusions	Relevant Recommendations
			practices prevail, 2R production can be expected to be lower on virtually all areas and all site types within the existing Western Australian bluegum estate. This reflects the change from the first to the second rotation in site resources. 5. The first rotation benefited from high levels of fertility associated with prior land use and from substantial stored soil water resulting from land clearing. The effect will be most significant, in percentage terms, on low fertility sites with deep soil, where the change could on average exceed a 25% decrease, and possibly more if secondary insect attack occurs. 6. Burning or removal of forest residues will increase second rotation decline on sites currently nutrient limited- and on all sites will decrease the pool of available resources in subsequent rotations. Slash burning, or removal offsite of residues, is not likely to be a sustainable practice.	4. Evidence shows that this 1R nutrient and water capital can be invested in increased production realised through multiple rotations, or it can be squandered in a downward spiral of site resource depletion and decreased growth potential.
PNC304-1213 2014	Szota C, Hopmans P, Bradshaw BP, Elms SR, Baker TG	Predictive relationships to assist fertiliser use decision-making in eucalypt plantations	1. Significant increases in yield can be achieved through targeting sites highly responsive to fertiliser. Mid-rotation N-only applications at sites with low N-status/high N-demand have significant potential to yield greater volume at end of rotation. Methods were developed to identify those sites more likely to respond to fertiliser applied at establishment, based on basic soil tests and/or foliar nutrient concentrations in combination with long-term climate data.	1. More work is required to develop models which can predict response to mid-rotation applications of N.

Report	Author Surnames	Title	Relevant Conclusions	Relevant Recommendations
Investment Plan 2012	Sands R	Maximizing Product Yields and Values From Current Forest resources	1. Precedence will be given to research that considers (a) the economic and wood flow analysis of later age fertilization, (b) the economic evaluation of alternative fertilization strategies, (c) the potential to redeem non-performing plantations, and (d) the assessment of nutrient requirements of mid-rotation and second rotation hardwood plantations. 2. In particular research that quantifies and models responses in softwoods together with economic and wood flow analysis. 3. Invest in the nutritional management of hardwood plantations. 4. There is a need for more robust predictive fertiliser response relationships that can be applied over a range of conditions. 5. Decision support systems need to be based on trials rigorous enough to detect and model the variability in fertilizer responses. There are insufficient fertilizer trials to cover the required range of climates and soils. 6. Remote sensing (see later) has the potential to characterize some of the key variables at less cost than field measurement. 7. Removal of harvest residues carries a risk of degrading site productivity, particularly on low productivity sites. Where a subsequent rotation is contemplated, harvesting residues carries significant nutritional risk.	
PRC202-1011 2011	Turner J, Lambert M	Analysis of Nutrient Depletion in a Radiata Pine Plantation	1. Removal of the forest floor led to a decrease in productivity, primarily though the loss of nitrogen, and this was largely overcome by replacement fertilisation. 2. Such trials established over a range of site types, could be used to identify sites more sensitive to nutrient losses and/or to identify specific nutrients of concern on specific sites. 3. Harvesting of only wood was estimated to lead to a negligible effect on wood production. However, more-intensive harvesting, especially whole tree harvesting will potentially have significant impacts on tree growth. 4. The raking treatment reduced foliage nitrogen, and this was correlated with	

Report	Author Surnames	Title	Relevant Conclusions	Relevant Recommendations
			reduced growth while other nutrients such as boron and sulphur were reduced but not to a degree that affected growth or health.	
PN03.3907 2009	May B, Carlyle C, Lowther R, Keeley P, Bernie C, Gritton D, Michael M, Nickolls K, Mattay J	A decision support system for maximising profit from nutrient management of mid-rotation radiata pine	1. While a single P application can boost subsequent responses to N, there appears to be no benefit in applying P more frequently than once every 2 thinning cycles at most sites. 2. For N and N+P treatments, thinning ~6 years after fertiliser application may be required to maximise wood production. 3. In contrast, there was an ongoing increase in the cumulative response to P. 4. The patterns in temporal response mirrored the differing effects of N and P on nutrients in soil and foliage 5. Applying N alone to plots previously fertilised with P increased average stand value by 12 times more compared with applying N to unfertilised plots. 6. Leaf area index (LAI), foliar N, and forest floor N and P were the most useful indicators of potential responsiveness to N, P or N+P fertiliser. 7. Age and site quality index could be used as alternatives to soil or foliar variables for predicting response to N or N+P fertiliser, but will be important to validate them when applying it outside the range of systems tested in this study 8. The model developed (NP-Opt) provided forest managers with a means to substantially improve fertiliser efficiency and profitability by assisting with targeting of potentially responsive stands, optimising	1. Over multiple thinning cycles, applying N alone after each thinning and N+P after every other thinning is likely to be the most profitable fertiliser strategy. 2. Improved targeting of responsive sites and optimising fertiliser combinations for specific sites are both important in order to maximise profitability. 3. The selection of soil or foliar indicators for predicting response should take into account the underlying variability in the indicator, the cost and ease of sampling, as well as the strength of the predictive relationship. 4. Alternatively, basic stand information such as volume, age or, if known, current growth rate may provide a more convenient means of identifying potentially responsive stands. 5. Since the empirical relationships on which the model was based were developed from radiata pine plantations of the Green Triangle, its application outside that region and for other species needed to be tested.

Report	Author Surnames	Title	Relevant Conclusions	Relevant Recommendations
			fertiliser and harvest regimes to maximise wood yield and net present value.	6. Quantify longer-term responses and interactive effects between multiple fertiliser applications. 7. Validate the model against alternative sites and management scenarios. 8. Modify it to suit other species and regions, 9. Improve the efficiency of data collection for predicting growth response. 10. Determine the impact of a long-term decline in soil N availability on stand nutrient and growth. 11. Integrate model outputs into process-based growth models such as Cabala and 3PG. 12. Improve methods for diagnosing nutrient deficiencies such as ground, aerial or satellite-based remote sensing of leaf area and foliar nutrient concentrations
PNC074-0708 2009	Sims N, Hopmans P, Elms S, McGuire D	Mapping foliar nutrition in *Pinus radiata* from Hyperspectral satellite image data	1. Useful models for foliar nutrient concentrations can be calibrated on field data collected from a range of age classes for several nutrients, but that translation of models to stands less than 3 years of age is unreliable.	1. A number of factors limit the utility of Hyperion 2. It may be possible to approximate the results in this study using multi-spectral satellite imagery such as Landsat, and this may suffice in some circumstances until newer, more suitable satellite hyperspectral sensors become operational. 3. A number of hyperspectral satellite launches were due to be deployed after this project.

Report	Author Surnames	Title	Relevant Conclusions	Relevant Recommendations
PRC072-0708 2008	B. May, P. Smethurst, C. Carlyle, D. Mendham, J. Bruce & C. Baillie	Review of fertiliser use in Australian forestry	1. Rates of fertilisation with macro-nutrients in softwood plantations were almost double those for hardwood plantations on a per-unit-area fertilised basis. 2. Average estimated relative growth responses over 6 years to fertiliser application in hardwood plantations varied from 24% at establishment to 49% for mid-rotation stands. 3. In comparison responses in softwood plantations varied from 13% for young stands to 30% at establishment. 4. Responses were most profitable time when applied at mid-rotation. 5. Plantations were estimated to contribute c. 2% to total N_2O emissions from fertiliser use. 6. The overall contribution of fertiliser use in forest plantations to nutrient leaching across Australian catchments was estimated to be just 0.2% for N and 0.1% for P. 7. Nutrient inputs to streams were expected to be negligible provided best management practices were adhered to including retention of forest litter after harvest and stream-side buffer strips, direct application of fertiliser to waterways was prevented, and overuse of nitrogen fertiliser was avoided.	1. Improve prediction and modelling of fertiliser responses. 2. Assess nutrient requirements of mid-rotation and second rotation hardwood plantations. 3. Improve economic modelling of the effects of alternative fertiliser strategies. 4. Apply remote sensing for broadscale assessment of nutritional. 5. Requirements of individual stands across the plantation estate. 6. Quantify N2O emissions from fertiliser application in plantation forest for greenhouse gas accounting. 7. Improve estimates of losses of fertiliser through leaching and runoff across a broader range of soils climates and stand ages to improve understanding of the effect of plantations compared with other land-uses on water quality.

Appendix 2: Stakeholders consulted, industry workshop details

FWPA Nutrition Investment Plan

Notes from Workshop, Canberra 6th September 2018, 8:30 am to 1:00 pm

Participants

In-Person: John McGrath, Jodie Mason, Braden Jenkin, Phil Smethurst, Andrew Moore, John Turner, Phil Green, Mike Sutton, Jim Wilson, Ian Dumbrell, Allie Muneri, Tony O'Hara, Stephen Elms, Barrie May, Tim Smith

Telephone: Ian Last, Daniel Mendham, Gary Pearson

Apologies: Ben Bradshaw

Some Introductory Comments

Unsophisticated approach to nutrition - generic prescriptions despite different species and soil types

Silvicultural systems have succumbed to financial pressures (lack of "knowledge drives value")

If fert program is delivered, how do you know you have achieved the response? Need monitoring program.

Throughout the workshop, no disagreements emerged with the material presented as slides or handouts. However, some points were added or embellished.

Water use efficiency - importance of interaction of nutrition and genetics

We need to cope with site variability (soil, rainfall), implying the need for fine-scale information systems and management responses.

Tech transfer deserves a focus for reducing the research-to-practice discount of about 20%.

Yield Gaps

Debated the discount for maximum achievable operational yield (20% suggested), some thought this was too large a discount. However, there was an understanding that translating from R&D to operations had an even higher discount (suggested 40-60%).

Definition as to what we should be aiming for was rated highly. This is critical in identifying what proportion of the doubling in value by 2040 can be achieved through improved management and how much needs to come from additional plantations.

Need to understand the interaction with pests and diseases, improved nutrient status can increase vulnerability to pests and diseases.

Partitioning the components of the potential increase in yield – Check out the New Forests report that does this also O'Hehir and Nambiar.

Forest & Wood Products Australia

Need to quantify the magnitude of the Yield gap, assessing this through either direct measurement or modelling. The latter will be useful/critical as it's unlikely we will have sufficient data to do this empirically.

Understand the site-specificity of the yield gap, e.g. radiata planted between 600 and 2000 mm, plus soil variability makes it a difficult task. Understand variation both between and within regions. Site stratification will assist in stratifying the estate.

Likely that a useful assessment will be done at a compartment level.

Need to understand that it's not only a productivity issue (volume) but also a value issue, and wood quality needs serious consideration as there is no point in increasing volume and compromising value by reducing wood quality (density and importantly stiffness).

The index used would benefit from being translatable into value. Local conversions from volume to value could be used.

Understand the age progression, e.g. seedling to canopy closure, to mid rotation, to late rotation. A small juvenile core is advantageous as most of the log is then high-quality material.

Volume was generally thought to be the most useful metric for yield estimation.

However, it was thought that the response measured as value may be higher (much) than simply the volume gain, though this does depend on having higher prices for higher value material which doesn't always happen.

Recognition that value has to be recognised and paid for by the processing industry, need steps in the pricing structure that recognises the increased value. Need to include processors in the conversation about delivering value.

How to identify/quantify the yield gap and partition the nutritional component is critical:
Suggested LAI relative to optimal LAI

A range of other factors influence productivity and hance influence the responsiveness to fertilizer, such as:

- Role if soil organic matter
- soil health,
- N fixing systems
- Weed competition
- Nutrient interactions, look at the whole suite of nutrients that may be responsive and that may have deficiencies induced by heavy fertilizer programs. K of particular interest to HVP
- Do slow-release fertilizers have a role, not much general used, but Tas hardwood plantation growers (FORICO) are convinced of this.
- 1R/2R productivity and responsiveness.

Slash management was seen by many as a key issue in both maintaining and enhancing productivity, though there was a need for a cost benefit analysis for slash retention as there are both costs and benefits in retention. Costs: higher planting costs, OHS issues with hard terrain. Benefits: nutrient retention, mulching effect. Practical slash management options exist for pines, but they remain a high priority for hardwood slash technology development.

Should try to keep fine material on site, where the nutrients are. Not sure we have all the answers yet about the nutrient value of retaining slash. When factoring in slash value, cut to length may be better option than whole tree chipping.

Some research already (?) on relative importance of different parts of the tree. Reintroduction of slash burning in recent years – communication challenge. Harvesting system - still not determined which is best. Interest from biomass perspective, but not clear on value of how slash is managed.

NSW – chopper rolling better productivity, but significant cost in establishment costs and OHS hazards. Qld also – plant survival is not as good as should be if slash is retained. Quantify opportunity cost data of burning.

Measuring yield potential, identifying responsive sites, and tools:

LAI assessment, hyperspectral signals – but these might not yet be operational. Sth USA have good relationships with LAI and nutrient status.

Sentinel – multispectral good resolution – calibrate with additional info e.g. harvester head data.

UniSA technology from defence has direct application to forestry.

Agreement with the presentation/assessment of the status of the tools (see ppt slide that summarised this)

Monitoring was not mentioned extensively; however, it was suggested that this is a key part of any business case, i.e. need to know what the operational not just the research level responses are. There may be a role for using Psp to monitor this.

We need enhance Australian Soil and Landscape Grid data to cope with forestry, e.g. increased depth. National soils databases only looks at 2m depth of soils, and pixel size can be large – room for improvement in quality of soils information. Australian soils and landscape grid is 90m resolution. What is the appropriate scale to aggregate the available information? Other types of data can add to understanding, e.g. remotely sensed.

Age-season specificity critical foliar nutrient concentrations in pine. May need multi-stage sampling. More work needed on foliar analysis.

Root architecture of open rooted seedlings vs container stock – implications. Open rooted often best at 10 years, which appears related to root architecture. Containerisation leads to smaller and smaller roots, which is a big issue. Nutrient loading is being tested. There are also slow-release fertiliser questions, weeds and over-spraying. Can nutritional management help? What about microbial activity and inoculants?

N&P important almost everywhere. Other macro and micronutrients are also important on many sites, e.g. later age Ca may give better returns for larger rotations. Think about variability of estate – stratification.

Wood quality and piece size and uniformity are important too.

Tas and NSW don't use any of the existing tools. What is industry best practice? We need a SOP developed by best minds and best research for defining best responsive sites and how to get there.

PROFERT is designed to do just that. Is there a need to share information about using PROFERT?

Calibration needs to be to a meaningful level to be useful. Need fundamental relationships from trials. ProFert is the only tool.

Current proposed hardwood project will address this need.

K response is the weakest part of the tools for softwood currently

Sensitivity to decline should be built into tools (softwoods). No single factor responsible - can't necessarily say it's nutritional. Movement of Ca offsite is a factor in reducing wood quality. Classify sites for sensitivity to decline.

Some don't use predictive tools but are interested to learn more about them. Look at historical fertiliser treatments and soil types. P at establishment is used, but we are now using less than in the past. Some say there is no convincing evidence yet for mid rotation fertilisation.

Slow-release fertiliser –only use control release fert now in Tas. NSW uses some SRF for southern pines for better economics – results are comparable, but based on observations not trial work. Confounded by silvicultural and harvesting regime (thinning). Need to incorporate thinning or basla area control in experiments to filter out confounding factors.

What should be done with current soil maps and other databases - for better nutrition?

The concept of "canary" species was mentioned - is it easier to sample and indicate nutrient deficiencies?

There is no silver bullet for knowing what optimum nutrition is, i.e. need steady research to build on the past and cope with newly emerging deficiency conditions.

International experience

General interest in how the international experience related to the Australian situation.

However, there was a strong realisation that it was only valid to compare the Australian situation with 'reasonably comparable' situations. We should also try to learn from the Mediterranean, South Africa and NZ experiences, as well as those we have already presented Brazil and SE USA. Look at Spain and Portugal particularly in relation to nutrition of coppice vs seedlings. Do nutritional prediction systems hold for coppice – limited data suggests they perform similarly. Australian research would be useful.

Company amalgamation is an issue with cooperatives as membership shrinks. USA has addressed this by expanding geographically. How are these co-ops funded? There appears to be little government money involved, i.e. direct industry funding, e.g. levy, but this needs to be checked.

Note that a lot of the discussion on this issue was embedded in both the yield gap and delivery components.

Delivery

Key focus on knowledge transfer with the cross fertilization of ideas from visiting scientists

Knowledge transfer to the level where change happens, this needs both senior managers and operational managers to be informed via workshops seminars and direct contact with R&D people. Manager-level workshops. Field-based workshops.

There is a lag in implementation and if this can be overcome then there is a significant gain to be made with minimal additional work.

Need to identify the areas that previous R&D hasn't covered (Gap analysis)

Internal company processes are important in getting traction for R&D, there has been an erosion of silvicultural practices in some companies and that means, that to optimise production, these practises need to be revised before moving forward.

Key issue for managers is to identify and reduce the barriers to knowledge implementation.

Tools need to be usable at a grower level, outcomes must be applied.

Regional delivery hubs/mechanisms seen as a strong approach though there was some discussion as to how the emerging NIFPI hubs will work.

Need regional hubs of expertise, value of having people who understand the regional differences. Potential to do this through NIFPIs

Longer term projects, currently are too short, need ongoing funding

Coordination of effort was highlighted

Need to have sustainability of both the R&D effort and the extension effort

Mentoring within whatever integrated R&D/Industry program develops for both for research scientists and practitioners is critical. Mentors and FWPA need to review and prioritises options and jointly oversee the distribution of funds.

Can we work cooperatively - disconnect between NIFPI and FWPA? Regarding extension – how can we address this? How do we link to universities to create the link for capacity building? Problem with universities is that PhD projects are often only for 3 years, academically focused, and then there are no employment opportunities afterwards. Syd Uni has several PhD opportunities but no one taking them up.

Include mentoring of youngish people within companies in research proposals.

Key messages/Summary:

- Yield gap approach
- Endorsement of the approach by industry
- Identify/quantify the yield targets and decide on the practical target (80% of biological yield)
- Interaction between fertilizer responsiveness and other silvicultural activities
- Impact of soils, topography, aspect on yield potential
- What level do we assess the yield at (suggest compartment level, though this is contrary to the precision silvicultural approach)
- Volume (productivity) and value are both important.
- Impact of fert on WUE
- Conservation of harvest residues
- Use of emerging technologies to map yield and responses
- Manage for overall soil health

International experience

- Provides a context for the Australian work
- Look at similar regions for bot checking the reality of yield expectations and the systems and techniques to improve yield
- Gain this knowledge through both published literature and coincidental contact, setting up long term relationships can be beneficial
- Resourcing: is there a quantum/scale of investment and activity that makes it all work?

Delivery

- Delivery has declined as economic constraints have been applied by new owners

- Identify and deal with the barriers to the implementation of R&D
- Assessment of the responses, monitoring the effectiveness of fertilizer programs is a key issue
- Need to communicate the knowledge at a range of delivery levels
  eg IFA conferences
  Managers
  Field managers
- Operationally relevant techniques (simple, robust reliable)

4. Issues identified by Industry (2)
Summary of Interviews by Barrie May 2017-2018

Topic	Sub Topic or Closely-Related Topics
Slash Management	• Slash management effects on nutrition including fertiliser responses
	• Slash management practical options
Stand Condition	• Remote and aerial sensing for LAI, inventory and forest health
Fertiliser Response Prediction Tools	• Stratification of the forest estate for fertiliser response, e.g. soil type, site quality, nutrient and water stress, and LAI. • Indicators of responsive sites and magnitude and timing of response • Economic evaluation tools • Integrated data collection and processing • Extrapolation of experimental results to broad estates • Local data to populate PROFERT, FPOS etc. • Interaction of water availability on fertiliser responses
Fertiliser Experiments	• Complete analysis of earlier experiments
	• New fertilizer experiments at various ages (establishment to later rotation) • Fertiliser and weed control placement • Follow-up fertilisation in relation to use of slow-release fertilisers at planting
More Use of Permanent Plots	• Current condition of estate
	• Data for tool development or testing

4. Issues identified by Industry (3)
Summary of CRC-SPF Eucalypt Interviews by Greg Holz 2002

- Nutritional management is a dynamic, continuous and iterative process of improvement
- Companies, and operational staff within companies, need to own the research results as much as the researchers – teamwork managers-researchers; research culture as routine business
- Researchers tend towards long-term, strategic research vs companies towards short-term, tactical – balance needed
- Tactical aspects need to be relevant to industry, e.g. fertiliser questions:

  i) will the crop respond to fertilizer?
  ii) magnitude of the response?
  iii) economics of the response?
  iv) which nutrient to apply?
  v) which form of that nutrient (type of fertilizer)?
  vi) how much fertilizer?
  vii) when to apply (season, stage of crop)?
  viii) how often to apply?
  ix) how to apply?
  x) where to apply?

- High weighting of geography - local anecdotes vs distant research
- Discount 20-40% research transfer to operations
- Long-term data needed
- Better tools needed to diagnose deficiencies and predict responses to fertiliser

Appendix 3: Method 2 Productivity Calculations

The benefits from optimising nutrient management are delivered by avoiding losses of nutrients through poor plantation management, by reducing the costs of fertilizer programs through the accurate targeting of plantations that will respond to fertilizer applications and by increasing the productivity of plantations that are responsive to fertilizer. The calculations below take into account all of these issues.

(a) - Direct estimate of softwood fertilizer responses: Optimum response

Parameter	Value	Comment
Current MAI	16 m^3 ha^{-1} $year^{-1}$	Pers Comm Braden Jenkins based on ABARE data
Predicted response to optimum fertilizer	30%	Trial response range 20-100%; weighted estimate of 30%. Discounted relative to trial responses as some operational programs already exist
Discount factor from research to operations	0.6	Internationally estimated at 20%, Australian industry suggests 40%, hence the factor of 0.6
Uptake proportion	0.7	Authors estimate of uptake
Discounted response	13%	30% x 0.6 x 0.7 (Response x R/O x Uptake proportion)
MAI with fertilizer implemented	18.1 m^3 ha^{-1} $year^{-1}$	16 x 1.13
Total plantation area	1,000,000 ha	ABARE (value rounded)
Area responsive to fertilizer	500,000 ha	Discounted for previous farmland and water limited sites, authors estimate
Total response	1,050,000 m^3 $year^{-1}$	(500,000 ha x 2.1 m^3 ha^{-1} $year^{-1}$)
Over a 30-year rotation	31,500,000 m^3	

(b) - Direct estimate of softwood fertilizer responses: Likely operational implementation

Parameter	Value	Comment
Current MAI	16 m^3 ha^{-1} $year^{-1}$	Pers Comm Braden Jenkins based on ABARE data
Predicted response to operational fertilizer	15%	Range 20-100%; weighted estimate of 15%. Discounted relative to trial responses as some operational programs already exist and operational applications will be lower than optimum
Discount from research to operations	0.6	Internationally estimated at 20%, Australian industry suggests 40% hence the factor of 0.6
Uptake proportion	0.7	Authors estimate of uptake
Discounted response	6.3%	(15% x 0.6 x 0.7 (MAI x Response x R/O% x Uptake %)
MAI with fertilizer implemented	17.0 m^3 ha^{-1} $year^{-1}$	16 x 1.063
Total plantation area	1,000,000 ha	ABARE (value rounded)
Area responsive to fertilizer	500,000 ha	Discounted for previous farmland and water limited sites
Total response	500,000 m^3 $year^{-1}$	(500,000 ha x 1.0 m^3 ha^{-1} $year^{-1}$
Over a 30 year rotation	15,000,000 m^3	

(c) - Direct estimate of hardwood fertilizer responses: Optimum response

Parameter	Value	Comment
Current MAI	13 m^3 ha^{-1} $year^{-1}$	Pers Comm Braden Jenkins based on ABARE data
Predicted response to optimum fertilizer	30%	Range 20-100%; weighted estimate of 30% Discounted relative to trial responses as some operational programs already exist
Discount factor from research to operations	0.6	Internationally estimated at 20%, Australian industry suggests 40% hence the factor of 0.6
Uptake proportion	0.7	Authors estimate of uptake
Discounted response	13%	30% x 0.6 x 0.7 (Response x R/O x Uptake proportion)
MAI with fertilizer implemented	14.7 m^3 ha^{-1} $year^{-1}$	13 x 1.13
Total plantation area	1,000,000 ha	ABARE (value rounded)
Area responsive to fertilizer	400,000 ha	Discounted for previous farmland and water limited sites, authors estimate
Total response	680,000 m^3 $year^{-1}$	(400,000 ha x 1.7 m^3 ha^{-1} $year^{-1}$)
Over a 10 year rotation	6,800,000 m^3	
Over 3 10 year rotations	20,400,000 m^3	Assuming no yield decline between rotations (likely incorrect)

(d) - Direct estimate of hardwood fertilizer responses: Likely operational implementation

Parameter	Value	Comment
Current MAI	13 m^3 ha^{-1} $year^{-1}$	Pers. comm. B. Jenkins based on ABARE data
Predicted response to optimum fertilizer	15%	Range 20-100%; weighted estimate of 15%, Discounted relative to trial responses as some operational programs already exist and operational applications will be lower than optimum
Discount factor from research to operations	0.6	Internationally estimated at 20%, Australian industry suggests 40% hence the factor of 0.6
Uptake proportion	0.7	Consultants estimate of uptake
Discounted response	6.3%	15% x 0.6 x 0.7 (Response x R/O x Uptake proportion)
MAI with fertilizer implemented	13.8 m^3 ha^{-1} $year^{-1}$	13 x 1.063
Total plantation area	1,000,000 ha	ABARE (value rounded)
Area responsive to fertilizer	400,000 ha	Discounted for previous farmland and water limited sites, authors estimate
Total response	320,000 m^3 $year^{-1}$	(400,000 ha x 0.8 m^3 ha^{-1} $year^{-1}$)
Over a 10 year rotation	3,200,000 m^3	
Over 3 10-year rotations	9,600,000 m^3	Assuming no yield decline between rotations (likely incorrect)