Plantation Silviculture and Nutrition Research Investment Plan

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Prepared by University of Melbourne

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Author declaration of interest

The authors, Chris Weston and Luba Volkova have not 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.

Executive Summary

The Silviculture and Nutrition Investment Plan identifies Research, Development & Extension (RD&E) project themes and topics from consultation with industry and is intended to help guide FWPA research investment throughout 2025 to 2029.

Since 2020 the challenge of maintaining and increasing wood supply from plantations has intensified because the area of plantations has decreased, with a tendency of more productive sites to revert other land uses. This decline in plantation base together with losses to wildfire, and increasing climate variability, create supply constraints and are major issues driving the need for investment in silviculture and nutrition RD&E.

This plan seeks to enable increased wood production from the existing land base and to build confidence for plantation expansion onto new sites that present new challenges for managing for optimum productivity.

This report identifies that Australian plantation RD&E will benefit from a clear focus on sustainably increasing productivity through continuous improvement including realizing potential gains from emerging technologies. Through a future-oriented focus on research to enable gains in productivity, Australian plantation forestry has the best chance to advance and move ahead from business-as-usual activities.

Australian silviculture and nutrition research should acknowledge the gains made, for example, in New Zealand plantation research that has embraced clear targets of sustainably increasing productivity by improving the current tree crop and from maintaining and building site resources.

Key themes for this silviculture and nutrition RD&E investment plan are to maintain and increase commercial plantation productivity whilst also adapting to the potential impacts of climate change, and to identify and develop improved tools and strategies for the selection of land for plantation expansion.

A list of recommended research themes and topics are summarized in Table 1 in the body text of this report, and these are summarized here.

Three broad approaches are recommended for advancing silviculture and nutrition research, development and extension – field trials, modelling and simulation, and workshops. It is recommended that funding is directed to fewer and larger projects that bring industry personnel and researchers together in a strongly collaborative way. Projects should have clearly identified modes of reporting to ensure the effective communication of findings, and the creation of an accessible record of project aims, methods and results. Ideally each research-oriented project would yield one or more peer-reviewed publications that could stand in online databases, be searchable by everyone, and act as a persistent record of the research funded by the FWPA.

Approach #1: It is recommended that new field trials are established in operational plantation areas as a shared research resource among growers, and with the aim of addressing projects that are identified from Table 1 as high priority (to be determined, currently identified as actions 2, 13, 15, 18, 20 and 22). The planning and execution of the trials should encompass 3 or more regions (e.g. green triangle, SE Qld, NSW tablelands, Tas) to create range in results comparisons and to act as a catalyst for strengthening interactions and learning amongst industry personnel. Key aspects of this approach are the continued development of current industry researcher capacity and the demonstration of new technologies for capturing plantation responses to extreme weather and climate events. It is

recommended the new trials demonstrate new technologies such as remotely sensed canopy characteristics for nutrition diagnosis and tree health status, and soil moisture status monitoring for interpreting growth limitations.

Approach #2: Modelling and simulation comprising ongoing support for PROFERT and the further calibration and adoption of APSIM is recommended. Support for the continued development of PROFERT for pines, and for the more recent trials to develop PROFERT for hardwoods is recommended. Further investment in PROFERT for pines should address the need to improve phosphorus requirement diagnostics and the ability to set baseline site type according to 1st, 2nd, 3rd or 4th rotation sites, and for non-sandy soils.

The APSIM software framework will become an increasingly important tool to allow growers to forecast impacts of a rapidly changing climate on growth and then to adapt silviculture and nutrition to maximize growth and minimize losses to mortality. To improve APSIM for pine and eucalypt it is recommended to fund projects that address the interplay between water and nutrients as main factors limiting productivity.

Approach #3: Funding of a facilitated workshop focused on planning silviculture and nutrition interventions now to address climate extremes so that readiness and response plans are in place prior to extreme weather events. An industry workshop would allow the sharing and further development of ideas on how to prepare for climate change. The emphasis of the workshop should be on participant-driven development of response plans – with some facilitation to assist this process.

Table of contents

1. Background

The vision of the FWPA Grower Research Advisory Committee (GRAC) is to double the value of Australia's commercial forests by 2040, by fostering an innovation culture, applying world's best practices, collaborating, and investing into research and development. FWPA commissioned a suite of investment plans that provided technical reviews and business cases to guide industry investment in RD&E for the Australian forestry sector from 2019 to 2023, with an outlook to 2028 and beyond. These were developed in consultation with Australia's commercial forest growers to inform investment in RD&E activities. From the Investment Plans, the Priority Topics were identified as the key targets for investment.

FWPA's Nutrition Investment Plan and Plantation Silviculture Investment Plan, both published in 2020, identify opportunities for progressing the GRAC Vision through investments in RD&E that achieve value gains through management of plantation silviculture and nutrition.

A key part of this review is to bring these two documents into one single investment plan (Plantation Silviculture & Nutrition).

The task of this report is to provide a new 5-year Investment Plan based on broad industry consultation, a review of current developments within Australia and around the globe, and via input from an Expert Review Group.

2. Outline of approach and methods used to compile this review

The Investment Plan identifies issues relevant to FWPA plantation forest growers nationally and prioritizes project themes for potential funding in the next five years. The scope of the review includes past and current research programs under the stewardship of GRAC, and current research programs at a national and global scale with relevance to the Australian context for plantation silviculture and nutrition.

A range of stakeholders, including GRAC members, were contacted for comments on investment needs and this information was combined with a review of current and recent past research to identify key themes for future investment. This approach involved review of current and past silviculture and nutrition research in Australia and elsewhere that is relevant to forest growers. The literature sources and reports (grey literature) and stakeholder responses constitute broad industry consultation, and they are discussed below with summary tables included as appendices. About 20 industry people had an input via either group discussion (GRAC 19/3/24, 18/12/24), expert working group (22/5/24; 16/9/24) or one-on-one discussion.

Therefore, the steps in developing this investment plan were:

- Initial engagement with FWPA to compile a key contact list of stakeholders to engage with to understand the main silviculture and nutrition-related issues for grower members
- One-on-one conversations with grower members, key industry and research personnel
- Aggregation of silviculture and nutrition-related projects from existing investment plans and capturing of additional themes and topics
- A high-level review of current and recent research programs and available reports
- Consolidation of research themes and topics based on engagement feedback
- Preparation of a draft investment plan for review
- Review of the draft Investment plan and ranking of projects by a selection of stakeholders
- Presentation of the investment plan to GRAC, and
- Finalization of the investment plan based on feedback from FWPA/GRAC.

This investment plan does not try to present research topics in their final form but rather gives an indication of the priority areas to be explored and scoped further into mature research proposals fit for submission to FWPA for evaluation.

3. What has been achieved and what to update from the most recent plans?

This section identifies the written outputs from the most recent FWPA silviculture and nutrition plans (2020-2024), funded projects from the NIFPI (National Institute for Forest Products Innovation), and provides a snapshot of relevant published literature (accessed via Web of Science database). Bringing the outputs of these three sources together provides one version of what has been achieved since the publication of the 2020 investment plans. These outputs address a subset of priorities identified, as well as topics not identified in previous investment plans.

FWPA Research Reports 2020-2024

A search of the FWPA Research Report online database for 2020 to 2024 turned up 8 reports dealing with plantation silviculture and nutrition (Table A3). Two reports released in 2024 support nutrient management of plantations. Hardwood plantations are dealt with in PNC478-1819, with a focus on optimizing nutrient management, while VNC476-1819 describes a tool to predict fertilizer response in softwood plantations in Western Australia; the soon to be published PNC477-1819 provides a similar analysis for southeast Australia. Together these reports provide a ProFert tool for much of the softwood estate across Australia.

A further 2024 report VNC516-1920 presents a yield gap analysis for optimizing productivity of *Eucalyptus globulus* plantations in southern Australia; the report considers nutrition as well as stocking, site, climate and land use history as driving variables for productivity. These reports build on VNC422-1617 released in 2022 that discusses optimizing blue gum productivity through improved fertilizer regimes. VNC402-1617 (2022) examined plantation density and nutrition responses in a climate context and discusses silvicultural systems to optimize value from northern Australian mahogany plantations.

The other 4 reports cover separate topics with PRC522-2021 (2022) reviewing current knowledge of mechanical and robotic tree pruning equipment, VNC519-1920 (2022) the next generation resource assessment and forecasting for Australian plantation forestry, and VNC520-1920 (2023) the operational application of point cloud data in forest inventory.

These FWPA reports demonstrate ongoing achievements in providing tools for the plantation industry to support plantation nutrition decisions for both pines and hardwoods. The reports also provide guidance on gaps in research knowledge for the continued improvement of silviculture and nutrient management to optimize growth.

NIFPI Projects Funded in Rounds 1, 2 and 3

Research commissioned by the NIFPI centres over the last few years is listed in Table A4, showing a diverse range of topics that relate directly to plantation silviculture and nutrition. Many of these projects address topics that have been suggested by the GRAC in first half 2024 meetings as part of the current review. There is clearly an opportunity to build on the NIFPI project topics with FWPA funding for the benefit of the plantation tree growing community.

Web of Science database 2020-2024

A search of the Web of Science (WoS) for publications with keywords “plantation silviculture” and “plantation nutrition” for the years 2019 to 2024 turned up 176 publications. Ten of these publications originated in Australia and addressed Australian plantation silviculture and nutrition topics. Two of the ten Australian publications addressed boron deficiency and nutritional management in pines, four dealt with branch development, size and orientation, one summarized silvicultural practice – site

preparation, nutrient addition, planting density and weed control, two concerned stem borer and bark stripping in *Pinus radiata* and one publication dealt with nutrient limitations of African mahogany in savanna soils.

More broadly within the WoS 2020-2024 publications were 8 review articles including several that summarized nutritional aspects of Ca, Mg and B (already mentioned) that are of direct interest to Australian plantation growers for review and implementation of findings. One paper reviewed the application of remote sensing to diagnosis of nutritional deficiencies in forests (see Watt *et al.* 2019); all 8 review articles are listed in Appendix 3 Table A5.

New Zealand work on precision silviculture

During the review of this document comments received pointed to the need to highlight precision silviculture research in New Zealand and especially the "Accelerator Trials" that have been in place for about 8 years. These trials, established with industry support over 6 sites, aimed to support the target of sustainably increasing productivity of *Pinus radiata* on sites with growth limitations. These accelerator trials have demonstrated the potential for treatments to improve both the current tree crop and, according to the results, to the site, and to test pathways to productivity gain through thinning and mid-rotation management strategies. These trials should be considered as an example of what can be achieved through collaboration among industry and researcher groups, and by embracing multiple sites, each with a big enough trial area to allow for several treatments that are well replicated.

4. What has changed in the external environment?

Comments from industry consultation as part of this review give some guidance on changes in the external environment that in turn influence the setting of research priorities. These comments on changes in the external environment are number listed here:

Biophysical issues

1. The availability of land suitable for plantations is becoming increasingly limited due to the use of land for the highest and best use. This has translated to a declining plantation area, particularly for hardwoods, and a static area of softwood plantations. This means that the productivity of the available plantation base needs to be optimized, and silvicultural systems need to be developed for areas previously not considered for plantations, that may encompass poorer growing conditions (lower rainfall, harsher soils). For example, blue gum plantings in Victoria are now declining, especially in areas on better sites representing the top end of the productivity range. This trend to decreasing plantation area runs counter to the "Plantations 2020 Vision" of increasing plantation area.
2. There is increasing scrutiny of plantation water use, with an emphasis on the efficient use of scarce water resources. Water use needs to be a focus for plantation managers. Optimizing water use will generally result in optimized productivity on an area basis.
3. The impact of climate change and climate variability is even more apparent now than five years ago. This presents both challenges and opportunities for plantations. There is a challenge adapting plantation silviculture to climate change (response to drought), including the selection of new locations for plantations and the relocation of existing plantations to accommodate changed climate conditions. On the opportunity side there is the role of plantation silviculture in mitigating climate effects through the efficient sequestration of carbon.
4. Currently there is a shortage of structural timber in Australia; this opens the opportunity for silviculture to redirect current hardwood for pulp plantations to structural products.
5. Large areas of plantations were fire-damaged in NSW in 2020 and more generally there are ongoing plantation losses in many areas.

6. Evidence for decline of plantation productivity that is partly countered by increases from breeding/genetic gains (no evidence supplied for the statement).

Industry structural issues

7. The increasing role of contractors in completing plantation management tasks suggests the need to include them in training courses targeted at growers, i.e. to treat the contractors as part of the grower cohort for training purposes.
8. The need for collaboration among companies is ever more apparent. For example, because genetics are improving, the silviculture needs to continue to adapt – this requires productivity monitoring and tracking change, and long-term growth and yield data. In forming a collaborative effort, landscape level data does not need to be shared, just the research data.
9. Difficult to find field workers for manual tasks leading to labor shortages. These labor shortages point to the need for more automation of tasks such as planting, pruning and inventory.
10. New graduates with a Bachelor Forest Science qualification are scarce so companies are employing Forest graduates from overseas or from more general Environment Science graduates. This carries an extra impost for the employing company to develop the skills of the graduate on the job.
11. The trend for forest professionals to shift jobs more regularly on a “career ladder” continues so that development of corporate knowledge is more fragmented and concentrated in fewer individuals. This trend eventually feeds into the loss of awareness within an organization of what research has already been done, unless rigid and transparent reporting, publication, archiving and retrieval systems are put in place, and maintained through the workplace culture.

5. The 2025-2029 Silviculture and Nutrition Investment Plan

The recommendations of this silviculture and nutrition investment plan are set out in Table 1 immediately below. Proposed research themes and topics are grouped under categories starting with site selection and finishing with linkages between silviculture and products. Research actions are listed for comment and priority ranking; to date GRAC has reviewed this table to identify omissions and has provided feedback on the suggested priority ranking to each “Action”. The table identifies 13 possible actions, with priority high, medium and low suggested. These recommendations arise from the summary of points coming through from the initial round of discussions with GRAC, the expert working group, and individuals – as presented in table format in Appendix 4 (Table A6).

Table 1: Research theme/topic – summary

Categories	Theme	Background and rationale	Proposed research theme/topic	Priority ranking	Comments
1.Site selection for plantation estate expansion.	Site selection for new plantations in non-traditional plantation areas that are likely to have soil limitations.	Research is required to support the expansion of plantations onto sites not previously planted.	1. How to model potential growth rates on new site types requires a better understanding of soil type and nutrition.	High.	Addressing this topic will assist the industry to expand the plantation base and the amount of wood grown annually.
2.Silviculture for climate resilience.	Learning how to vary silviculture under climate change – drying environment, weather extremes, long periods of no rainfall.	Investors want to know how the trees are coping with the changing climate; element of judging risk for investors.	2. Initial stocking trials and thinning age.	High.	Ensure wide range of growing environments and climatic scenarios with emphasis on improving growth model parameters.
			3. Post-thinning fertilizer strategy.	Medium.	May recommend no fertilizer to reduce risk of droughting remaining trees post thinning.
			4. Predetermine strategies to respond to extreme weather events such as hail damage, strong winds and windthrow.	High.	This applies to all plantation areas and suggest this action is addressed with a facilitated workshop where participants share knowledge and develop plans during the workshop.
			5. Further develop APSIM parameters for softwoods and hardwoods to create a tool to predict long term climate change responses, and to help to identify water and nutrient limitations.	High.	A simplified interface for developed APSIM modules would be desirable – to empower commercial growers in testing the effect of climate change scenarios on their own crops.
3. Plantation nutrition – plant and soil nutrient diagnosis technologies.	Development of spectral imagery for foliage nutrient status to scale from sampling small area to whole estate.	New technologies could ultimately replace more expensive current foliage chemical analyses.	6. Test multi-spectral and hyper-spectral imagery for assessing foliar nutrient status (promising for N, more difficult for P).	High.	Need to link imagery to ground data/causality i.e. to soil moisture data and/or physiological status of the trees. Are there imagery techniques to measure the seasonal progression of water stress?
		Profert has been a good tool, is heading in the right direction and should be further invested in and developed.	7. Improve Profert to better integrate with business datasets	High	Requires specialist input to improving the Profert software

Categories	Theme	Background and rationale	Proposed research theme/topic	Priority ranking	Comments
		Expertise in soil diagnostic testing is hard to access. Some companies have good growth and nutrition data that could be worked on to get a better idea of limitations.	8. Later age fertilizing needs attention in hardwoods, especially as rotation age increases from 15 years to 20 or 25 years.	High.	Recommend addressing this action in a new set of operational research trials suggested under this plan.
			9. Investigate value of nutrient addition in 8- to 12-year-old hardwood plantations on sandy soils	Medium.	Recommend addressing this action in a new set of operational research trials suggested under this plan
			10. Develop common nutrient trials across companies that can be followed over a rotation (overcome problem of "short-termism")	High.	Recommend addressing this action in a new set of operational research trials suggested under this plan
4.Plantation operations automation technologies.	Research and development for automation of planting, application of herbicides and fertilizers.	Driven by difficulty in sourcing labor for manual planting, and to reduce or eliminate significant safety risks with manual planting.	11. Research to support the wider application and improvement of mechanical planting.	High	Planting automation trials need to be brought into this plan.
			12. Test and develop more efficient application of herbicides and fertilizer.	Low	Evidence from improvements in agri-chemical application technologies.
5.Knowledge and capacity building.	The sharing of learning and collating existing information among growers, coordinate industry-wide approach to current issues.	The recording and handing down of research trials knowledge and the learning from what has already been done. Keeping data alive.	13. Handling of residues and need to stop burning. What are the impacts of residue removal for silviculture and nutrition?	High priority for desktop review and results integration with APSIM. Low priority for new trials establishment.	This is an important topic and there is a good evidence base to support residue retention and non-burning management of residues. The value in supporting this action would be more in demonstrating what we already know.
			11. Tailoring and application of new herbicides to weed spectrum	Low.	
			12. Browsing control without shooting	Medium.	Previous work done to address this action could be better disseminated.
6. Silviculture for new products and new technologies for existing	Supply chain from growing the trees to products – need to link	There has been a lot of work done to address this ac-	13. Optimize hardwood silviculture to produce solid wood	High.	Opportunity to address this action in a new set of

Categories	Theme	Background and rationale	Proposed research theme/topic	Priority ranking	Comments
and future markets.		tion and this research could be better disseminated. E.g. the "Hardwood plantations for sawlogs" program.	products; establishment spacing, timing and weight of thinning and pruning, also impacts of these on wood density.		operational research trials suggested under this plan.

Further scoping for each project theme or topic will be required before seeking any research funding provision to ensure sufficient detail is captured, deliverables are clearly defined, impacts assessed, and any complimentary work being undertaken either recently or concurrently can be adequately considered.

The overwhelming impression from review of previous silviculture and nutrition investment plans is that the quantum of research suggested exceeds the available resources. Hence the priority-setting process based on broad industry consultation. For example, the previous nutrition investment plan identified four high priority investment opportunities and commented: *'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 (high priority). 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.'*

There is also a tension in the formulation of research projects and the extent to which they are carried through to development or industry-ready application. This may not be possible for all funded projects; for example, discovery-oriented research is usually focused on peer-reviewed publication as an output while more applied research is usually focused on more industry-ready outputs. Therefore, FWPA-commissioned research and development projects should have previously negotiated and agreed outputs so that all actors in the research and development chain clearly understand the endpoint of the research. In this context the scan of the peer-reviewed plantation silviculture and plantation nutrition literature published since 2020 provided in this report, whilst not exhaustive, indicates that peer-reviewed and published Australian studies are few – especially relative to publications contributed from other plantation-growing countries. This is a weakness in the way current funding is deployed for plantation silviculture and nutrition research.

Appendix 1 – Record of consultation

Name	Organisation	Interviewed
John Tredinnick	Forest Products Commission WA	13 May 2024
John Turner	ForSci Pty Ltd	12 April 2024
Jim O'Hehir	UniSA STEM	12 April 2024
John McGrath	McGrath Forestry Services	12 April 2024
Andrew Jacobs	Forico	15 May 2024
Duncan Watt	Forestry Corporation of NSW	22 May 2024
Suzette Weeding	Sustainable Timbers Tasmania	31 May 2024
Ben Bradshaw	Australian Bluegum Plantations	30 May 2024
John Senior	HQPlantations	GRAC 19 March 2024; Expert Working Group 27 May 2024
Tarryn Turnbull	HVP Plantations	9 October 2024 and Expert Working Group 27 May 2024
Daniel Mendham	CSIRO	Expert Working Group meeting 27 May 2024

Appendix 2 – Summary of Investment Plan Priorities from 2020

This section restates the summary of the 2020 silviculture and the 2020 nutrition investment plans. These plans differ in the style of writing and that is evident from the summaries reproduced here. The 2020 silviculture investment plan research needs have been grouped by the following themes – establishment, productivity and wood quality; noting that biotic stressor and the fire research needs theme have been omitted as they are covered in other FWPA investment plans.

Silviculture Investment Plan

This list of "research needs" is reproduced from the 2020 Silviculture Investment Plan and is a subset of the text presented in Appendix 4 of that plan – titled "The identified research needs, issues and opportunities". Table 7 from the same plan (not reproduced here) presents "A summary of the logical research themes relevant to identified needs", the table lists seven high (versus medium or low) priority "topics" from a list 16 topics. For each of the identified topics a research method, timeframe, benefit, and implementation budget are listed.

Establishment theme:

Research need 14: There is a need to better understand the options to kill coppice and the rootstock of a regenerated stool to allow a change in crop. There are mechanical and chemical options available, and options at different operational stages (e.g. at harvest, soon after harvest or after coppice regeneration). Regarding the chemical options, forest managers face the issue of off label use and certification. The individual treatments require costing as well as consideration of the impact of the cost and the efficacy of the subsequent operations.

Research need 15: There is a need to review the current inputs and operations in hardwood and softwood nurseries to understand the impact of loss of access to a range of chemicals and practices. Other linked operations need to also be considered. The outcome of the different nursery strategies on growth and performance in the field needs to be reviewed: does a cost-effective planting stock maximise the value recovered from the area of land planted?

Research need 16: There is a general research need to consider plantation establishment.

Research need 17: There is a need to revisit the current cultivation strategies and options to better determine the fit for purpose options available matching plantation outcomes to the site requirements. This should be considered within the context of the whole silvicultural package including weed control issues and sustainability related issues. This should be linked to the attributes of first rotation forestry sites and the treatment of harvest residues on subsequent rotation sites.

Research need 18: There is a research need to catalogue, document and rate the significance of the current spectrum of weeds associated with plantation forestry at the four identified stages (e.g. pre-plant, post-plant, pre-clear-felling and ad hoc). This should then include a rating of the status of control options and any risks to those options. Where a weed species is of significance and the effective control options are at risk, these species should be identified for further research. For example, blackberry is a weed species of specific interest at present.

Research need 19: There is a need for research into weed control in plantations with a specific focus on alternative regimes driven and demanded by voluntary third-party certification requirements and environmental constraints (including adjacent planted crops). This would include the use of combined cultivation and chemical methods with both manual and mechanical application. This is for both hardwood and softwood plantations.

Research need 20: There is a need for research into alternative chemicals (molecules) for use in the various tree crops recognising fundamental difference in the tree species between softwoods and

hardwoods and the climatic zones which in turn will dictate the spectrum of weeds involved. This need is of some urgency given the current focus on glyphosate and the utility of this molecule to plantation establishment and management.

Research need 21: There is a need to consider the options and technology available to reduce reliance on manual planting during the establishment of a plantation. This research should focus on second and subsequent rotation sites and be linked to consideration of the treatment of the harvest residues on that site.

Research need 22: There is a need to document the drivers of poor initial survival of planted trees and the interventions possible to improve the rate of survival. This will link with the question management (e.g. weed control) and damage agents (e.g. browsing animals). For each current and potential intervention there is a need to understand the degree of exposure to forced reduction in use or loss of the intervention option due to voluntary third-party certification or changes in the regulatory environment.

Productivity theme:

Research need 2: Research is required to benchmark the current productivity of the Australian plantation estate at the macro scale (nationally) and within the plantation zones as defined by the National Plantation Inventory.

Research need 3: A next step is to determine the drivers of productivity (both positive and negative) and to assess any exposure to change (e.g. access to herbicides or fertiliser use). A review is required of the current state of factors that may offer increased productivity (e.g. a focus on the rhizosphere).

Research need 4: There is a need to quantify and understand the gap between research and operational outcomes for the silviculture applied to determine the underlying cause of this gap and therefore the ability to realise the full potential of a plantation site and the management applied.

Research need 6: There is a need to research on a holistic basis, the overall management of a site to maintain site productivity. The elements include the management of harvest residues, the application of nutrients, the use of biotic tools such as leguminous plants, and fungi and mycorrhiza in the rhizosphere. Management and enhancement of available water should be considered in parallel to nutrition.

Research need 7: There is a need to revisit land capability and suitability for softwood and hardwood plantations in the current and potential zones for plantation development. From the current plantation zone perspective, the issue of climate change, site management and changes in social licence as it impacts on possible (the maximum) and realised site productivity potentials needs to be understood. For the new zones, there is a need to extrapolate the current experience base to these areas to generate a realistic and defendable estimate of site productivity. In both cases, there is a need to better understand site and species (particularly new species) matching.

Research need 8: There is a need to include the impact of stocking rates at initial establishment and subsequent management of the stocking levels of a plantation as a variable in many Research themes e.g. site type, genetics and initial stocking rates; thinning and fertiliser application.

Research need 12: There is a need to better understand the impacts of the different harvest reside management strategies and the impact on site productivity, the cost of the operation and the risks posed. Any analysis should consider the cost impacts to the overall rotations (the one harvested and the subsequent rotations) and not just the costs of the single operation.

Research need 13: There is a need to revisit the management of postharvest residues in softwood plantations and to consider the application of advances in technology. This should consider the impacts on site productivity, particularly where possible the impacts between rotations.

Research need 23: There is a need to better understand the options of the whole of rotation management of stocking rates from initial planting through to final clear-felling.

Research need 24: With a focus on hardwood plantations, there is a need to better understand the options and outcomes of thinning, including the use of non-commercial thinning as a tool. The outcomes of the thinnings are defined by the resulting log piece size and the potential markets for the logs.

Research need 26: There is a need to document all the stressors (current and on the horizon) of trees in plantations in different areas and under different management. This should form the basis of documenting the appropriate responses to anticipated or current stress events.

Research need 27: There is a need for specific research and refinement of plantation monitoring tools and techniques to anticipate and correct impending issues or to identify actual stress events as a trigger to an intervention.

Research need 35: There is a need to better define the relationship between the condition of a plantation as impacted by management interventions and driven by site factors (e.g. current period climate) and tree stress.

Wood quality theme:

Research need 1: There is a need to better understand the impacts of silviculture on the wood properties within a tree as these relate to the utility of logs to a processor. This will include the attributes of the site, the species grown, the management of the stands and the individual trees. While this may be more critical for softwoods, there is also a need to better understand these relationships for hardwoods when considering alternative products and markets to the current woodchip trade.

Research need 5: The impact of productivity on wood quality and therefore potential products as a driver of value needs to be better understood. This requires development of a linkage between log wood properties and the price paid.

Nutrition Investment Plan

The priorities identified through the previous "Nutrition" review and consultation process are summarized below (this is a copy directly from the executive summary pages 4-5 of that review). These investment opportunities mostly fit under the establishment (investment opportunity 7) and productivity (investment opportunities 1, 4, 5, 6, 8, 9) themes identified to group the silviculture plan research needs.

Table A1. The priorities identified through the 2020 nutrition investment plan review

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 fertilization

		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 nutrients for 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 exists 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 nutrition management actions based on available soil and climate databases and potentially using knowledge of different genotypes.

Appendix 3

This appendix summarizes projects funded by FWPA (Table A3), NIFPI (Table A4) and lists Australia–relevant research outputs published and available on the Web of Science (Table A5). These tables are provided as a snapshot of recent plantation silviculture and nutrition research.

Table A3. Listing of projects funded by FWPA 2020 to 2024.

Report and Date	FWPA Research Reports January 2020 to September 2024
PNC478-1819 February 2024	Optimizing Nutrition Management of Hardwood Plantations for Sustainable Productivity & Profitability
VNC476-1819 March 2024	A Tool to Predict Fertilizer Response & Profitability in Softwood Plantations Across Australia. Component 1: Southwest WA.
VNC519-1920 December 2022	Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry
VNC422-1617 December 2022	Optimizing Blue Gum Plantation Productivity Through Improved Fertilizer Regimes
PRC522-2021 March 2022	A Review of Current Mechanical & Robotic Tree Pruning Equipment
VNC402-1617 November 2022	Silvicultural Systems to Optimize Value from Northern Australian Mahogany Plantations
VNC520-1920 August 2023	Operational Immersive Visualization & Measurement of Dense Point Cloud Data in Forest Inventory
VNC516-1920 February 2024	Optimizing Productivity of Hardwood Plantations: Yield Gap Analysis for *Eucalyptus globulus* Plantations in Southern Australia
September 2023	Forests, Plantations, Wood Products & Australia's Carbon Balance

Table A4. Listing of projects funded by NIFPI. Further information on these projects could not be found using web resources.

Project Code	NIFPI Research Outcomes Rounds 1 – 3, for Centre's in Tasmania (NT), Victoria (NV) and South Australia (NS)
NV059	Harnessing the power of airborne high spatial resolution hyperspectral imagery for the softwood plantation industry
NV068	Understanding Soil Resources for Radiata Pine Plantation productivity
NV070	Innovative nursery management solutions to sustainably manage root disease, improve nursery utilization, and enhance resilience and productivity of planted pines
NS020	Solutions for the optimal use of dense, remotely acquired data by forest growers (Jointly with Launceston Centre Project NT001)
NS024	Optimizing the management of plantation, water and environmental assets
NS088	Enhancing softwood and hardwood plantations site productivity and subsequent operational efficiency by use of an innovative clean-row establishment 'system'

NS089	Evaluation of remote sensing approaches for plantation health surveillance
NS091	Plantation water use estimation and measurement for plantation forests
NS096	Developing more productive plantation trees better adapted to changing environments
NT001	Solutions for the optimal use of dense, remotely acquired data by forest growers (Jointly with Mount Gambier Centre Project NS020)
NT004	Optimizing machinery configurations for profitable harvesting operations of small-scale plantations
NT018	A forest resource characterization of Tasmania – Stage 1 of 2. Feasibility

Table A5. Recent 2020-2024 Web of Science listed reviews of topics directly relevant for Australian plantation silviculture and nutrition.

Cornut, I., G. Le Maire, J. P. Laclau, J. Guillemot, L. Mareschal, Y. Nouvellon and N. Delpierre (2021). "Potassium limitation of wood productivity: A review of elementary processes and ways forward to modelling illustrated by *Eucalyptus* plantations." Forest Ecology and Management **494**.

de Sao José, J. F. B., B. du Toit, C. G. Volpiano, B. B. Lisboa, T. Tiecher, C. Bayer, A. Beneduzi and L. K. Vargas (2024). "Soil nutrient dynamics, harvest residue management and soil organic matter conservation for the sustainability of black wattle production systems in subtropical soils: a review." New Forests **55**(4): 581-608.

Hauer-Jákli, M. and M. Tränkner (2019). "Critical Leaf Magnesium Thresholds and the Impact of Magnesium on Plant Growth and Photo-Oxidative Defense: A Systematic Review and Meta-Analysis From 70 Years of Research." Frontiers in Plant Science **10**.

Leslie, A. D., M. Mencuccini, M. P. Perks and E. R. Wilson (2020). "A review of the suitability of eucalypts for short rotation forestry for energy in the UK." New Forests **51**(1): 1-19.

Mason, E. G. (2023). "Impacts of tending on attributes of radiata pine trees and stands in New Zealand - a review." New Zealand Journal of Forestry Science **53**.

Rocha, J. H. T., B. du Toit and J. L. D. Gonçalves (2019). "Ca and Mg nutrition and its application in Eucalyptus and Pinus plantations." Forest Ecology and Management **442**: 63-78.

Turner, J., J. Knott, P. Green and S. Turner (2021). "Boron nutritional management in Australian forest plantations." Trees Forests and People **5**.

Valadares, R. V., M. D. Costa, J. C. L. Neves, J. Netto, I. R. da Silva, E. Moro, M. R. Alves and L. A. Fernandes (2020). "Rhizosphere microbiological processes and eucalypt nutrition: Synthesis and conceptualization." Science of the Total Environment **746**.

Watt, M. S., G. D. Pearse, J. P. Dash, N. Melia and E. M. C. Leonardo (2019). "Application of remote sensing technologies to identify impacts of nutritional deficiencies on forests." Isprs Journal of Photogrammetry and Remote Sensing **149**: 226-241.

Appendix 4 Key findings from the initial consultation stages

Table A6. Summary of insights from the initial consultation.

#	Key Point	R, D & E indicated
1	Learning how to manage silviculture in a drying environment. Applies especially to Pine plantations in WA. Evidenced by some plantation losses to drought (mid-west and mid slope areas of Blackwood valley in WA). Enabling potential investors to evaluate risks in a changing climate is part of the issue.	Initial stocking trials, identify sites/areas within compartments with shallow soils, thinning age, post thinning fertilizer strategy that may recommend no fertilizer to reduce risk of droughting remaining trees.
2	Recognizing the need for site specific management and then applying it – given the range of sites (600-2000 mm rainfall, summer or winter or uniform rainfall, soil textures from sands to clays, 1st, 2nd, 3rd or 4th rotation). Need to match treatments to sites. This may involve a better "definition" of site to make advances.	Comment made as trend to Green Triangle/Sandy soils – dominated documentation (Profert). Industry overall appears to strongly support the continued development of the APSIM and Profert models, although the support is not 100%.
3	Development of remote (satellite/UAV) spectral imagery and/or sensors for soil moisture monitoring, survival counts/health and nutrition, identify stress in the stand, go from sampling small area to whole estate. Need to link imagery to ground data/causality i.e. to soil moisture data and/or physiological status of the trees.	Challenge is to make benefits of drone imagery/analysis more readily available to the staff who need it for decision making. This point also encompasses how to deliver new technologies.
4	Strategies to cope with increasing occurrence of extreme weather events – e.g. hail damage and *Diplodia* outbreaks, windthrow events and response, and long periods without rainfall (point 1).	Address with an industry workshop.
5	The recording and handing down of research trials knowledge and the learning from what has already been done. Keeping data alive. This could also be interpreted as a cultural issue within organizations – and one that each organization needs to consider, rather than making it a priority for FWPA to address.	Address by encouraging collaboration between industry groups in setting up operational trials recommended in this plan.