Research, development and extension investment plan

Research, development and extension priorities for sustainable value gains through Tree Breeding & Genetic Improvement

2020

Adapted from ***Investment Plan – Sustainably maximise value gains through Tree Breeding & Genetic Improvement,*** **prepared for FWPA by Authors: Mr David Hudson & Dr Carl Ramage**

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Executive Summary

Since the first *Eucalyptus sp., Pinus radiata* and Southern Pine plantations were established in Australia, plantation tree breeders have constantly focused on selecting material that demonstrates superior performance to previous generations. As a result, the yields and quality generated from plantations and individual logs have continued to increase between generations, resulting in increased returns for millers, supply chain participants and investors.

For example, recent advances in genetic improvement within Tree Breeding Australia[1] (TBA) and the Radiata Pine Breeding Company (RPBC), has resulted in the adoption of modern breeding strategies (e.g. rolling front) and technologies such as 'early generation' genomics and phenomics which have generated data that has been converted into breeding values for use in genetic evaluation programs such as TREEPLAN®.

The use of TREEPLAN® has provided the plantation industry a 'world leading' integrated solution to managing data that generates breeding values for a range of economically prioritised traits within a breeding population. These economically prioritised traits improve the selection of 'elite' parent stock that generate improved plantation productivity and forest product quality, which more importantly generates incremental profit for industry stakeholders and investors. For example, the rate of genetic gain in Radiata pine as reflected in the average marginal improvement value ($) of the best 5% of genotypes identified within each annual analysis by TBA has demonstrated that the marginal profit ($NPV/Ha) for a vertically integrated industry stakeholder has increased from approximately $800/ha in 2002 to approximately $1550/ha in 2017[2]. Similarly, for shareholders investing in TBA during the same period, the investment in tree breeding and genetic gain when measured by the Internal Rate of Return (IRR), generated on average an IRR for Radiata pine of between 10-14% and for Blue gum between 17-28%[3]. The IRR achieved by TBA in the forestry industry is comparable with that of the grains industry which over the period 1977–78 to 2017–18, generated an average annual productivity growth of 1.0% and that of the dairy sector which generated an average annual productivity growth of 1.6%[4].

Despite the rate of genetic improvement achieved through the use of these advancements, the industry needs to continue to invest and support the adoption of 'next generation' breeding technologies as it faces a number of challenges in the near and long term. These challenges include the following:

- Vulnerability assessments indicate that climate change may have large consequences for sections of the industry in the future[5]. Nevertheless, climate change presents both a threat and an opportunity for the forest industry, and forward planning to minimise

[1] Tree Breeding Australia (formerly Southern Tree Breeding Company)
[2] Tree Breeding Australia (2017) Economic and genetic gain continue to improve over time for *P. radiata* (National TREEPLAN analysis for *P. radiata* completed 25 August 2017) www.stba.com.au
[3] T. McRae (2019) Tree Breeding Australia. Pers Comm.
[4] Boult C, and Chancellor W. (2019) ABARES Agricultural commodities: March quarter 2019. http://www.agriculture.gov.au/abares/research-topics/productivity/agricultural-productivity-estimates
[5] Battaglia, M., Bruce, J., Brack, C.L., Baker, T., 2009a. Climate change and Australia's plantation estate: analysis of vulnerability and preliminary investigation of adaptation options. CSIRO, Hobart, Australia,

the threats and take advantage of opportunities will help maintain the viability of the industry and the communities it supports, into the future. While there are threats to production in the current heartland of Australia's plantation estate, overall climate change response by society may increase demand for sustainable forest products and may spawn new product opportunities in forest carbon, biofuels and bioenergy[6].

- The projected long-term impact of climate change and demand on agriculture for food, feed, fibre and energy, together with urban expansion has the potential to force the future establishment of plantations in environments where the current plantation species will need to be adapted to cope with variable site conditions and a predicted increase in abiotic and biotic stresses.
- A key challenge is that there is a perception that investors within and external to the industry have a poor understanding of the value that tree breeding and genetic improvement generates both currently and into the future. As a consequence, this is impacting on the level of investment in the capability, capacity and infrastructure required to generate value that can be achieved through tree breeding and genetic improvement. This has become more critical due to the declining investment by the Federal, State and Territory governments in forest related capability, capacity and infrastructure.
- A challenge for the tree breeding and genetic improvement sector is the lack of a succession plan to train, engage and retain graduates, PhD's and Post Doc's within the sector. This is a growing concern with the ageing male dominated research population within the industry.
- The loss of federal and state government investment in research institutions such as CRC's and the CSIRO to maintain their capabilities in a range of plantation forest related research fields has had a significant negative impact on the research capability and capacity of the industry.

PTM Solutions has identified two key fields of tree breeding and genetic improvement research which require near, and long-term investment by industry stakeholders:

1. Within the context of adaptation for climate change, enhance the production and value of future products generated from *Pinus radiata,* Southern Pines and *Eucalyptus sp.* estates to supply chain stakeholders through improvements in yields, quality, increased tolerance to abiotic and biotic stress and enhanced silviculture practices.
2. Generate new high value product opportunities, such as the growing of 'elite' individual trees and plantations for the bio-economy which have been selected using 'next generation' modern breeding technologies such as genomics, phenomics, bioinformatics and genetic markers applied within an economic value based genome wide selection breeding program.

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[6] Pinkard, L. Jody Bruce, J. Battaglia, M. Matthews, S. and Drew, D. (2014) Adaptation strategies to manage risk in Australia's plantations. FWPA Project No: PNC228-1011

Within these two fields of tree breeding and genetic improvement research, PTM Solutions has identified **six investment opportunities** which have the potential to **generate an incremental $80.0m per harvest in Net Present Value** (NPV)[7] across the plantation estate of *Eucalypt sp*. and *Pinus radiata*[8] with flow on benefits and gains for Southern Pines.

The six prioritised investment opportunities are:

1. Development and application of genomic tools to accelerate the generation of genetically improved plantations with improved plantation productivity and forest product quality.
2. Enhance public and private sector investment in the capability and capacity required to support the adoption and use of modern breeding technologies across the plantation industry value chain for improvement in productivity and profitability.
3. Breeding Plantation *Pinus sp.* and *Eucalypt sp*. for Climate Change.
4. Maintaining Genetic Diversity within Australia's *Pinus sp*. plantations.
5. Building an Australian plantation industry platform for the future bio-economy.
6. Plantation Tree Breeding and Genetic Improvement for Enhanced Value Capture.

Opportunities (1-5) are directly related to advancement of genetic improvement within the plantation forest industry. For each of these opportunities a comprehensive review of current resources indicated that within the public and private sectors within Australia and New Zealand, the research capability, capacity, infrastructure and technological advancements already exist within the industry to deliver on each of the opportunities.

Based on discussions with industry stakeholders, research service providers and the experience of the authors, the projected **FWPA investment** to support these six opportunities during the 2019–2024 timeframe is **approximately $14.3m** which would generate a projected **return to the plantation industry of $5.60 per $1.00 invested**. This compares very favourably with investments by other Rural and Development Corporations (RDC's) such as the Australian Wool Innovation where the average return to woolgrowers was estimated at $2.90. The Grains Research and Development Corporation returned an average of $6.00; the Meat and Livestock Australia returned $6.20, while the Cotton Research and Development Corporation was $8.29[9].

A key finding from this program is that delivery of this return on investment will require an increased level of collaboration between stakeholders within Australia (e.g. Tree Breeding Australia, Radiata Pine Breeding Company, HQ Plantations, Gondwana Genomics, AgriBio) and secondly, with their counter parts in New Zealand (e.g. SCION).

[7] Discount Rate = 8.0%

[8] Based on annual replanting and harvest of 23,333 ha of *Pinus radiata* and 8,750 ha of *Eucalyptus globulus*.

[9] Marshall, A (2017) It doesn't add up – RDC figures can't calculate real returns. www.farmonline.com.au/story/5120078/more-to-rdc-results-than-figures-can-tell

The opportunities identified for investment **Opportunity One,** relating to the development and application of genomic tools within the Radiata pine plantation industry, has the potential to deliver the majority of the **projected incremental NPV ($52.00m @ 12.3 % IRR @ 6% Discount Rate).**

Opportunity One focuses on the collaborative development by TBA and RPBC of a low-cost high-throughput Single Nucleotide Polymorphism (SNP) assay for genotypic characterisation of Radiata pine (V2 SNP). The delivery of the V2 SNP assay will enable each breeding program to implement a genome wide selection program that will more accurately generate selections of 'elite' genetically advanced parental stock for seed orchard increase and deployment and at the same time accelerate the breeding cycle, thus reducing the time frame for the delivery of trees with improved plantation productivity and forest product quality.

Therefore, it is recommended that as a tree breeding and genetic improvement priority for the 2019–2024 timeframe, industry **investment of $3.60m** be directed towards **Opportunity One**.

With regard to **Opportunity Two,** which is related to addressing key barriers that exist to the advancement of tree breeding and genetic improvement within the plantation forestry industry, it is recommended that an industry stakeholder **investment of $3.63m** for the 2019–2024 timeframe be a further priority. Without addressing these barriers the production and economic impact benefits of all other Opportunities (1 and 3 to 6) will be either delayed or in some cases may not be delivered.

It is recommended that the investment in the Opportunities (3-6) remain a secondary priority until such time as investment in tree breeding research is increased and/or the deliverables from Opportunity One have been made available for adoption and implementation by TBA and RPBC.

Detailed background, investment theme and economic impact analysis for each recommendation is provided in **Section 3.0** - **Industry driven opportunities for FWPA investment in tree breeding and genetic improvement research for plantation Eucalyptus sp. and Pinus sp. (2019 – 2024 & beyond).**

Details of the prioritised investment opportunities in tree breeding and genetic evaluation for the Australian *Eucalyptus sp. Pinus radiata and* Southern Pine plantation industries together with the time frame for investment are summarised below.

FWPA investment opportunities in tree breeding and genetic evaluation for the Australian *Eucalyptus sp.* and *Pinus radiata* plantation industry (2019 – 2024 & Beyond).

Priority	Investment Description	Proposed Investment	FWPA Investment 2019 - 2024	Economic Impact
One	***Development and Application of Genomic Tools to Accelerate the generation of genetically improved forests with improved plantation productivity and forest product quality***	*It is proposed that FWPA support the establishment of a 'big picture' collaborative project between TBA, RPBC and HQP that would build on research already undertaken by Australian and New Zealand researchers. The proposed research projects would focus on the development of genomic resources and tools that will have wide and ongoing applications across forest improvement. The streams of collaboration include:*		**$51,936,458 per Harvest (Pinus radiata)**
		1. Build complete and annotated reference genomes for Pinus radiata, Slash x Caribbean pine hybrid, Eucalyptus globulus and Eucalyptus nitens. *The reference genomes of these four important forest species serve as the foundation for building all other genomic tools that will enable advanced forest tree breeding as well as tackling a number of existing challenges (e.g. impacts of climate change). The reference genomes will facilitate the development of genetic, QTL and association maps, alignment of SNPs for development of genotyping assays and elucidating the genetic basis of complex traits.* *This collaboration would leverage existing genomic resources such as the reference genome of E. globulus and the draft Pinus genome developed by SCION as well as an incomplete draft for E. nitens (AgriBio). In each case, concerted sequencing and bioinformatics are required and could be achieved through a focused TBA and RPBC collaboration.*	**$1,750,000**	
		2. Development and deployment of a radiata pine SNP V2.0 Chip for genotyping and a slash x Caribbean pine hybrid SNP Chip *It is understood that a first-generation Radiata pine SNP Chip has been developed by SCION and being validated for implementation in a genomic selection program, but requires further development towards a practical, low cost, high-throughput genotyping resource.*	**$1,750,000**	

Priority	Investment Description	Proposed Investment	FWPA Investment 2019 - 2024	Economic Impact
		SNP detection can be achieved through whole genome sequencing of germplasm from both Australia and New Zealand breeding programs (including the important founder lines) and aligning them to the reference genome. *SNPs from genetic regions can also be added from RNASeq analysis of samples from various tissue types and stages of development. Once aligned to the reference genome, the SNPs can be filtered, selected and arranged into an array for validation. A subset of highly informative SNPs can then be arrayed providing a practical, low cost, high-throughput genotyping resource for radiata pine.* *SNP chips for the parent species of the slash x Caribbean pine hybrid are being developed by a consortium led by North Carolina State University and the University of Pretoria. Key ancestors and hybrid progeny from Australian populations can be genotyped using an initial 440K chip to help select the most relevant SNPs for a 50K chip being designed for use in 6 tropical pine species (including Caribbean pine) and related hybrids. This chip could provide a very low-cost interim genotyping platform for the slash x Caribbean pine hybrid as soon as late 2019. During the 2019-2024 timeframe, it is expected that the most informative SNPs from the parental chips could be combined with additional SNPs discovered through sequencing and alignment with the hybrid reference genome, to create a slash x Caribbean pine hybrid SNP array.*		
		3. Convert genomic tools for pedigree reconstruction *Many softwood and hardwood breeding programs are based on an open-pollinated (OP) breeding population. Therefore, when determining breeding values it is expected that there will be some inaccuracy due to unknown paternal contribution. Precisely recorded pedigrees and known ancestors of the breeding population individuals are prerequisites for accurate genetic evaluation and consequently, efficient breeding program management and boosted genetic gain in forest tree species.*	**$100,000**	

Priority	Investment Description	Proposed Investment	FWPA Investment 2019 - 2024	Economic Impact
		Molecular marker data are widely used to reconstruct pedigrees of Eucalyptus breeding populations in which behaviour data are difficult to obtain. It is understood that those genomic resources and tools that are available to reconstruct pedigrees from mixed populations of Eucalyptus plantations could be easily adapted to radiata pine. *It is proposed that FWPA support research that would facilitate the conversion of genomic tools used for pedigree reconstitution of open pollinated Eucalyptus breeding material to be applicable for radiata pine and Southern Pine breeding programs.*		

Priority	Investment Description	Proposed Investment	FWPA Investment 2019 - 2024	Economic Impact
Two	***Enhance public and private sector investment in the capability and capacity required to support the adoption and use of modern breeding technologies across the plantation industry value chain for improvement in productivity and profitability.***	*In the absence of a current lead state government agency for the plantation forestry research within the National R, D & E Strategy it is proposed that FWPA engage with a government agency such as the Department of Jobs, Precincts and Regions, Agriculture Victoria for the purpose of nominating the state as the lead agency for coordinating Federal, State and Territory government investment into capacity and capability that supports the plantation industry in Australia.*		**Refer Priorities 1, 3-5**
		It is proposed that FWPA coordinate a communication strategy aimed at promoting to value chain participants (e.g. Seed nursery and Estate Managers, Commercial Growers, Millers etc.) along with government agencies and the investment community as to the long term economic value (e.g. ROI) of investing in tree breeding and genetic improvement breeding programs.	**$125,000**	
		It is proposed that FWPA support the engagement of a suitably qualified and experienced person to assist industry participants in their adoption and deployment of modern breeding opportunities such as the use of advanced phenomics technologies, integration of adaptation deployment strategies based on genomic selection of traits for climate change, together with the integration of 'value added traits' from genomic selection for next generation wood based products for the bio-economy.	**$750,000**	
		On behalf of the plantation industry it is proposed that FWPA establish fully funded post graduate (2) and post - doc (2) positions within Australian public sector research institutions with a focus on undertaking research in fields that are associated or aligned with tree breeding and genetic improvement for the plantation industry.	**$1,500,000**	
		To ensure that the national cooperative tree improvement programs continues to deliver the accelerated generation and delivery of improved plantation productivity and forest product quality it is recommended that FWPA co-contribute together with TBA, local, state and Federal government agencies to the replacement of the current field based infrastructure (e.g. buildings, laboratories, staff facilities) at Mt. Gambier.	**$500,000**	

Priority	Investment Description	Proposed Investment	FWPA Investment 2019 - 2024	Economic Impact
		TBA, RPBC and HQP further evaluate opportunities to collaborate in the field of tree breeding and genetic improvement with an initial opportunity being co-investment to the generation of SNP assay V2 for Radiata Pine.	**Refer Priority One**	
		To address industry wide issues related to declining capability within the sector and to facilitate closer research collaborations between Australia and New Zealand it is proposed that FWPA contribute funding to support the activities of Tree Breeding Australia's Technical Advisory Committee. The Technical Advisory Committee is made up of industry representatives, technicians, breeders and research scientists from the public and private sectors in Australia and New Zealand.	**$750,000**	

Priority	Investment Description	Proposed Investment	FWPA Investment 2019 - 2024	Economic Impact
Three	***Breeding Plantation Pinus sp. and Eucalypt sp. for Climate Change***	*It is proposed that FWPA support the establishment of a 'big picture' collaborative project between TBA, RPBC and HQP which would build on research already undertaken by Australian and New Zealand researchers. The proposed research project would include the following streams of research:*		**Increase MAI +10%** **$20,813,333 per Harvest (Pinus radiata)** **$12,040,000 per Harvest (*Eucalyptus globulus*)**
		1. *Characterising diversity within ecologically and economically important softwoods and hardwoods – having a lens on the national breeding program and natural provenance genetic resources – Such a program would utilise and compliment the genomic tools developed through Opportunity 1. This program would specifically identify important germplasm that would assist in the breeding of elite material suited to climate variability including new and untested plantation sites.*	**$2,000,000**	
		2. *Assist with the genomic assessment (genotyping) of existing populations that have extensive phenotypic data (including site and environmental characterisation). Where applicable, integrate processing information to add to the phenotypic dataset. Target genomic assessment of 100,000 trees. Collectively this information can be used to establish genetic breeding values for key productivity and quality traits as well as 'future traits' such as for abiotic and biotic stress.*	**$1,500,000**	
		3. *It is proposed that part of the research be focused on identifying and characterising non-key traits such as internal checking (INC), external resin bleeding (ERB) and number of heartwood rings (NHR). The genotypic information along with the identification of genetic markers can then be translated into the development of a breeding values which can be incorporated into the Pinus radiata and* Southern Pine *genome wide selection programs.*	**$1,000,000**	

Priority	Investment Description	Proposed Investment	FWPA Investment 2019 - 2024	Economic Impact
Four	***Maintaining Genetic Diversity within Australia's Pinus sp. plantations***	*Tree Breeding Australia (TBA) and Radiata Pine Breeding Company (RPBC) in collaboration with Plant Health Australia (PHA) establish an 'off-shore' research program in the US (i.e. California), Chile and South Africa for the purpose of evaluating the current level of susceptibility / tolerance / resistance of Australian Pinus sp. germplasm when exposed to major plantation diseases (e.g. Pitch Canker) and pests that do not currently exist within Australia's Pinus sp. plantations.*	**$1,000,000**	**Between $0.3 million per harvest (0.04% of GVP)** **and** **$12.4 million per harvest (1.6% of GVP)**
		As a precursor to introducing and evaluating genetically diverse germplasm from international sources, it is recommended that FWPA actively engage with Biosecurity Australia and the Ministry of Primary Industry (NZ) to undertake a review of current quarantine restrictions with the objective of creating more amenable regulations and processes that will facilitate import/ export of genetic material.	**$200,000**	
		To support the review of current quarantine restrictions it is recommended that FWPA invest in establishing research that aims at identifying and evaluating methods and processes for germplasm exchange/transfer that meets current and future biosecurity requirements of exporting/importing countries. The scope of the research will need to evaluate techniques such as tissue culture together with the protocols and methodology for identification of DNA and RNA based pathogens and pests. Additional evaluation will need to be undertaken of the current and future capacity and capability of quarantine procedures and facilities.	**$350,000**	
		Engage with international tree breeders and organisations to facilitate germplasm exchange from international breeding programs that will allow joint evaluation across a range of environments.		

Priority	Investment Description	Proposed Investment	FWPA Investment 2019 - 2024	Economic Impact
Five	***Building an Australian plantation industry platform for the future bio-economy***	*It is proposed that FWPA invest in research that:* 1. *Identifies the bio-economy generated products that will be generated from a plantation forestry-based bio-economy.* 2. *Identifies the current status of Australian and international research and investment in forestry related tree breeding for the bio-economy; and* 3. *Quantifies the economic opportunity (e.g. ROI) and investment required for the Australian plantation forestry industry to commit tree breeding and genetic resources to building a germplasm platform with traits that will be required to deliver products into the bio-economy.*	**$150,000**	**To be developed by project**
		Following the completion of the initial market evaluation and providing it delivers a positive recommendation to proceed and establish a Pinus sp. based tree breeding program in Australia, it is proposed that FWPA initiate discussions with Tree Breeding Australia, RPBC, HQP and SCION for the purpose of establishing a collaboration that would create and support a national Pinus sp. tree breeding program in Australia for the bio-economy.		

Priority	Investment Description	Proposed Investment	FWPA Investment 2019 - 2024	Economic Impact
Six	***Plantation Tree Breeding and Genetic Improvement for Enhanced Value Capture***	*To enable the collection of miller data sets it is proposed that FWPA facilitate access on behalf of the industry and that the data be available confidentially to researchers engaged in tree breeding and genetic improvement activities and research. This would enable the integration of the datasets into models for forecasting the best performance of genetic material in relation to preferred end product quality traits (identifying 'elite' material) in hardwoods and/or softwoods, especially related to high value quality components of the log. The aim being to increase the volume of high value quality wood harvested from each saw log resulting in incremental value per log which can captured by the miller.*	**$500,000**	**$13,309,758 per harvest (+10% MoE)** **$3,347,300 per harvest (-10% BRS)**
		In addition to current quality related traits it is proposed that research be initiated to identify and characterise 'new product' traits including improved stability, durability, appearance and wood fibre traits. The genotypic information along with the identification of genetic markers can then be translated into the development of a breeding values which can be incorporated into the TBA and RPBC Pinus radiata genome wide selection programs.	**$1,000,000**	

1.0 Introduction

1.1 Objectives

The primary objective of this study was the development of an Investment Plan that establishes a blueprint for R,D & E for the Australian plantation sector from 2019 to 2024, with an outlook to 2028 and beyond to 2040. The Investment Plan focuses on R,D & E activities that will maximise value gains through **tree breeding and genetic improvement** and attempts to quantify costs of implementing at least the first five years (2019 to 2024) of the Investment Plan.

The Terms of Reference for this engagement and where in the report each has been addressed are presented in **Table 1**.

Table 1. Terms of Reference

Terms of Reference	Reference Document	Pages
1. Identify and report on the deployment of relevant previous and current FWPA and other sponsored R, D & E activities relating to tree breeding and genetic improvement.	Appendix 3	18 - 59
2. Identify and report on breeding strategies, including the adoption of new breeding technologies related to genetic improvement that are being applied in various international plantation tree breeding programs.	Appendix 4	60 - 71
3. Identify and report on emerging new breeding technologies and strategies that are currently being introduced into breeding programs within a range of species that have the potential to be applied in plantation tree breeding strategies.	Project Report Section 2: Background Section 3: Opportunities for investment	 25 – 32 33 - 75
4. Identify and report on FWPA levy payers and other stakeholders' priorities for R,D & E investment in genetic improvement in plantation tree breeding	Appendix 3	18 - 59
5. Identify and report on Australian and international public and private sector capability and capacity in the application of technologies and strategies for genetic improvement in plantation tree breeding.	Appendix 4	60 - 71

1.2 Methodology

The following provides details of the project methodology. Development of *The Plan* included five steps, considering information in the literature, the running of workshops with industry participants for softwoods and hardwoods, undertaking interviews with key stakeholders, conducting a survey of the plantation industry and economic impact modelling of the proposed recommendations.

1.2.1 Part One: Desktop Literature Review

The initial phase of the project encompassed a comprehensive review of literature relating to tree breeding and genetic improvement in Australia and globally based on access to the following sources:

- Publications provided by FWPA including research plans and research reports associated with investment in breeding and genetic improvement
- Publications provided by members of the Technical Panel including research plans and research reports associated with investment in breeding and genetic improvement
- Publications provided by industry personnel interviewed
- Publications obtained from 'on-line' research of international literature, including conference reports, research reports etc. associated with investment in breeding and genetic improvement.

A bibliography of publications referenced is presented in **Appendix One.**

The review of tree breeding and genetic improvement within Australia is presented in **Appendix Three.**

The review of tree breeding and genetic improvement within a global context and based regional perspectives is presented in **Appendix Four.**

1.2.2 Part Two: Hardwood and Softwood Industry Workshops

To ensure input from across the industry sector was obtained an initial workshop was planned to be held with representatives from the GRAC executive members (3) nominated for oversight of the project and members of the Technical Panel (17). Following further consultation, with the Project Sponsor it was decided to split the workshop and hold two workshops with one being focused on representation from the softwood sector and the second with representation from the hardwood sector.

The objectives of the respective workshops were as follows:

- Gain an insight into the current forest industry objectives related to tree breeding and genetic improvement within Australia/New Zealand
- Are there collective objectives for all participants or are these on an individual company basis?

- Confirm the current status of forest industry R, D & E in relation to achieving these objectives
- Identify and confirm current capability and capacity for science and innovation within the forest industry:
    - Is there duplication?
    - Are there gaps?
    - If so what are these?
- Review and discuss the forest industry experience and perspective in adopting innovative breeding technologies and strategies:
    - What has worked well over the last 10 – 15 years?
    - What have been the learnings?
    - What are the implications for future tree breeding strategies?
- Provide a forum to discuss challenges and opportunities in developing future breeding objectives and strategies related to genetic improvement in tree breeding
- Identify issues/barriers limiting breeding/innovation opportunities and explore strategies to address those issues
- Identify gaps in existing strategies and activities. What is required to address these gaps?

Based on a database constructed by FWPA, invitations were extended to participants in the plantation industry to attend one or both of the workshops which were held on Monday 4th March 2019 (Hardwood) and Tuesday 5th March 2019 (Softwood).

The composition of the respective workshops based on the role of the participants within the hardwood and softwood industries is presented in **Table 2**.

Of the participants attending the Hardwood workshop, 11 participants also attended the Softwood workshop. Two participants in the Hardwood workshop from Western Australia attended via conference call.

The agenda for the respective workshops is presented in **Appendix Five.**

Table 2: Workshop Participant Composition

Participant Background	Hardwood	Softwood
Steering committee	1	3
Tree breeder/geneticist	7	8
Grower	6	5
Researcher	3	3
Commercial seed producer	1	1
Total	**18**	**20**

The initial component of the workshops involved participants undertaking a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of the respective hardwood and softwood tree breeding and genetic improvement segment of the plantation industry.

The responses for each SWOT were allocated to those that directly related to the plantation industries i) capability and capacity in tree breeding and genetic improvement and ii) those that were indirectly related tree breeding and genetic improvement in that they were more related to broader industry related comment.

1.2.3 Part Three: Hardwood and Softwood Industry Interviews

As part of gaining an insight into the current status of tree breeding and genetic improvement with the plantation industry, the authors have undertaken a range of interviews with key personnel within the industry. The scope of industry representatives interviewed includes representation from the following:

- Individual members of the Technical Panel engaged in plantation tree breeding and genetic improvement with a focus on identifying strategies and technologies applied in their R,D & E activities
- Key Australian and international researchers engaged in plantation tree breeding and genetic improvement with a focus on identifying strategies and technologies applied in their R,D & E activities
- Key Australian and international researchers engaged in modern plant breeding and genetic improvement with a focus on identifying strategies and technologies applied in their R,D & E activities associated with various crops.

Interviews have been undertaken with representatives from the public and private sectors in Australia and New Zealand, together with representative from international breeding programs in the USA, South Africa, Scandinavia and South America.

Information collected from specific personal interviews remains confidential and has been collated and reviewed with relevant aspects being incorporated into the final report.

To enhance the personal interviews undertaken with input from a broad cross section of the plantation industry the authors have:

- Initiated an industry survey which was constructed and distributed for completion by participants attending the hardwood and softwood workshops, together with 3rd parties from across the industry (domestic and international)
- Attended the recent Eucalyptus Breeding Conference held in Hobart (18th – 21st February 2019) which provided a unique opportunity to gather information related to plantation tree breeding and to meet key industry personnel attending the conference.

A list of industry participants and stakeholders consulted with is presented in **Appendix Six.**

1.2.4 Part Four: Plantation Industry Survey

Given the breadth and depth of organisations and individuals engaged in tree breeding and genetic improvement within the plantation industry in Australia and New Zealand the authors initiated an on-line survey for participants representing the industry attending the workshops and additional nominated industry representatives to complete.

The survey's objectives were to:

- Establish the current capability, capacity and resources that different organisations were committing to plantation tree breeding and genetic improvement
- Gain an insight into what are the current areas of focus (i.e. breeding objectives)
- What opportunities exist for FWPA for future investment opportunities in tree breeding and genetic improvement?

The questions that were incorporated into the survey are presented in **Appendix Seven**.

In total, 46 invitations to participate in the survey were sent to individuals within the private and public sectors of the plantation industry in Australia and New Zealand. From the invitations sent out 34 responses were received providing a completion rate of 73.9%.

In terms of the role of the individuals to the survey these included:

- Science/Research Leaders/Directors
- Professors of Forestry Genetics
- Research Scientists
- Estate/ Asset / Silviculture Managers
- Tree Breeders / Geneticists
- CEO's / General Managers / Directors
- Chief Technical Officers
- Forest Management Services Managers.

Private sector companies were the major respondents (39%) to the survey followed by an even spread amongst the remainder of the industry (**Figure 1**).

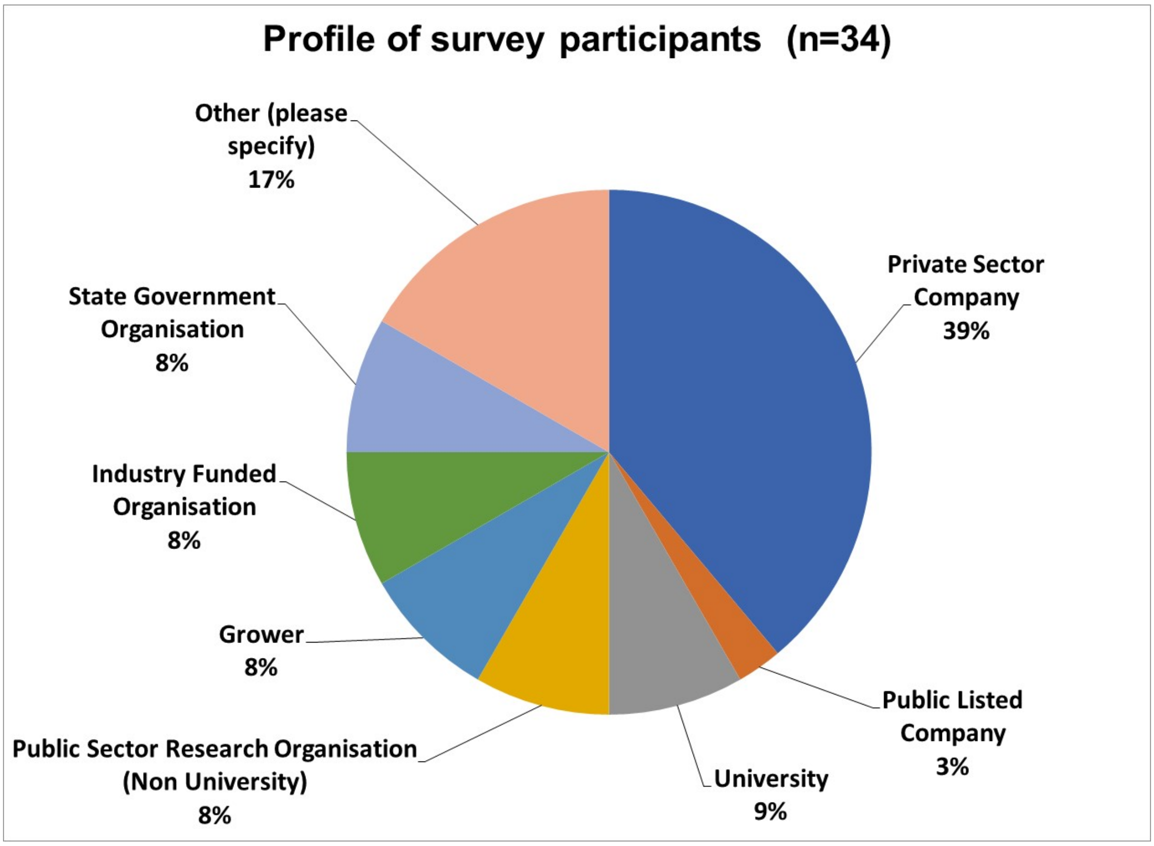

Figure 1: Organisations responding to the tree breeding and genetic improvement survey

Respondents were asked to nominate what aspects of the plantation industry supply chain they were engaged in, given that some organisations may be solely focused on one element whereas other maybe fully integrated across the supply chain (**Figure 2**).

Of the 34 respondents indicating the elements of the industry they are involved in, 13 nominated they were engaged in only one aspect of the industry, of these 9 were focused on R,D & E with the balance being engaged in commercial production as growers.

A further 10 respondents indicated they were involved in two aspects of the industry and a further 12 were engaged in three of more aspects of the industry.

Only one respondent was fully engaged in the industry from R,D & E through to processing. Four respondents were engaged in R,D & E, grower, estate management and operating a seed nursery. Five respondents indicated they provided support services to the industry.

Of the 34 respondents, 25 (73.5%) nominated that they were engaged in R,D & E with a further 13 being engaged as a grower and 12 nominating they were engaged in estate management.

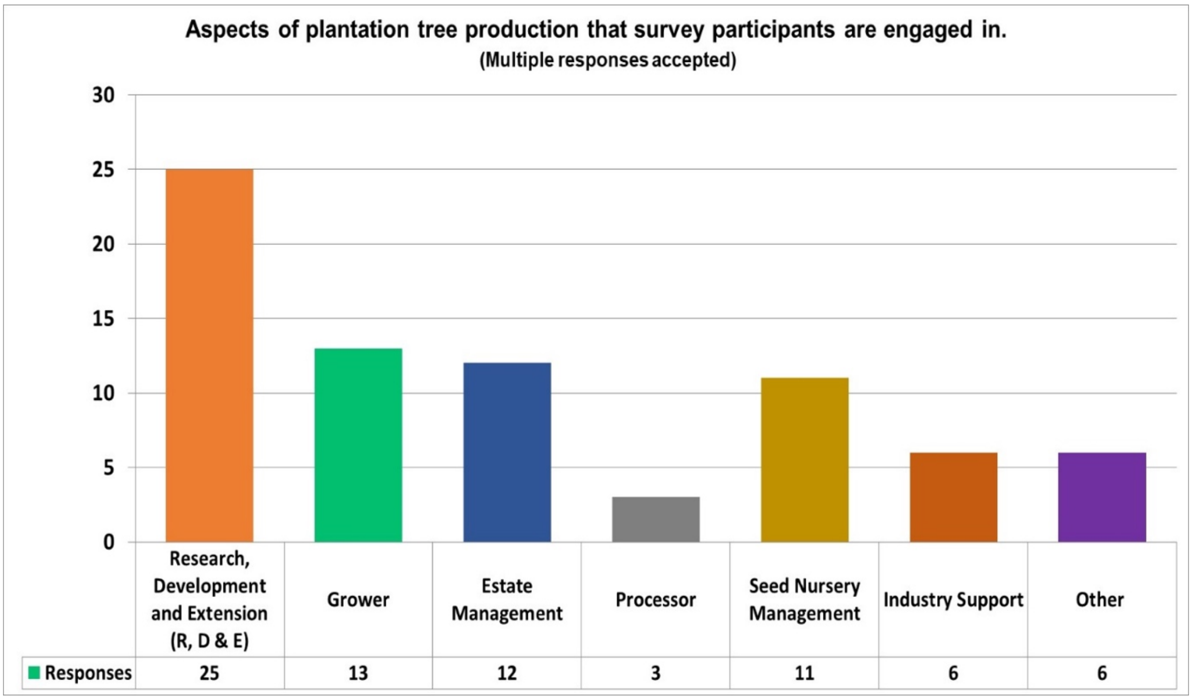

Figure 2: Aspects of plantation tree production that survey participants are engaged in.

The full results of the survey are presented in the following **Section 2 Background: The current status of tree breeding and genetic improvement research in Australia**.

A literature review of ‘Tree Breeding and Genetic Improvement - global context and regional perspectives’ countries is presented in **Appendix Three.**

1.2.5 Economic Impact Modelling and Analysis

In order to verify the economic impact/contribution of the report's recommended and prioritized opportunities to FWPA and the plantation forest industry, the authors engaged Tree Breeding Australia and SCION to independently evaluate a range of scenarios that would generate economic deliverables (e.g. NPV’s and IRR’s) related to the projected incremental forest production and wood quality that would be delivered from the nominated opportunities.

In order to demonstrate and establish the economic impact of the opportunities that the authors are recommending, representative traits of economic importance were modelled across a range of scenarios e.g. pulp yield and wood quality.

The economic models applied to the scenarios by TBA and SCION are well established and are regularly applied for economic analysis within the plantation forest industry. Discount rates of ^% and 8% were applied for calculating NPV’s ($/ha) and IRR’s. In terms of cumulative annual contribution to the forest industry (NPV$/year) an annual replanting/harvest of 23,333ha and 8,750 ha per year were applied within each respective scenario.[10]

[10] Estimates of annual replanting / harvest were provided by Dr. Dr. Milos Ivkovic (Tree Breeding Australia)

2.0 Background: The role of Modern Plant Breeding Technologies in Plantation Forestry

2.1 Introduction

The breeding process for plantation forest trees differs fundamentally from that of annual crops. The reason simply lies in the special characteristics of trees, as these are predominantly out-crossing and have extensive vegetative phases as well as a high, individual age. Unlike crop plants, which have a high degree of domestication and often a very limited number, if any in some species, wild relatives existing in the environment. Many “bred” varieties of plantation tree species are comparatively still with “wild plants” that are characterised by a high genetic diversity.[11]

The breeding process of an agricultural crop is pure cross-breeding, i.e. after an initial cross between a wild plant (carrying for example a resistance gene) with an elite line that is deficient of the resistance gene, repeated back-crosses and field testing ensures the presence of the resistance gene together with the accumulation of the genomic background of the elite line. In plantation forestry, the establishment of a second or third filial generation is practically excluded due to the long generation times of most plantation forest tree species.

Aligning breeding programs to future demands requires increasingly strategic choices:

- identification of rigorously prioritized, market-informed product profiles
- understanding current and future target population of environments
- balancing tree growers / processors and end user needs; and
- accounting for value chain participant concerns.

Potential areas of investment include identifying with a greater level of precision key target breeding traits (e.g. yield and quality), the potential occurrence of multiple-stress factor interactions (e.g. abiotic and biotic stress), the selection of trial sites, and the overall definition of appropriate methods for incorporating climate adaptation information into tree breeding programs.

Trait phenotyping and crop growth models are evolving to the point where breeders can access mechanistic information on the physiological determinants of plant adaptation for precise selection of ‘elite’ parents suitable for the target environment[12]. At different levels, the use of big data will help to refine the geospatial targeting and requirements of new varieties[13], therefore addressing the genotyping × environment × management (G×E×M) interaction. Growth models fed with region-specific parameters including climate conditions, soils, and

[11] Häggman, H., Sutela, S. and Fladung, M. (2016). Genetic Engineering Contribution to Forest Tree Breeding Efforts. 10.1007/978-94-017-7531-1_2.
[12] Furbank R. and Tester M. Phenomics – technologies to relieve the phenotyping bottleneck. Trends Plant Sci., 16 (2011), pp. 635-644
[13] Tesfaye, K. *et al.*Targeting drought-tolerant maize varieties in southern Africa: a geospatial crop modelling approach using big data. (2016) Int. Food Agribus. Manag. Rev., 19 (2016), pp. 75-92

crop management will help to refine geospatial targeting, define regions, and therefore, accelerate breeding advancement[14]. This is especially the case when addressing future climate change scenarios and the expected increases in temperature[15].

2.2 Advances in modern breeding technologies

Conventional plant-breeding approaches rely on the selection of plant germplasm with desirable agronomic and product characteristics (that is, phenotypes) from among individual plants created by using crosses and mutagenesis. Breeding used to be entirely phenotype-based; that is, plants were selected solely on the basis of features such as yield, without knowledge of the genetic composition of the plants. All plants of potential interest would be grown, phenotyped, and harvested, all of which are time-intensive and resource-intensive[16].

The entry of molecular biology into breeding programs in the 1980s enabled knowledge of genetic determinants of phenotypes and marker-assisted selection (MAS) in which DNA-based molecular markers are used to screen germplasm for individual plants that have desired forms of genes, known as alleles. MAS reduced plant sample sizes needed to select desirable individual plants and has been used in many crops to reduce costs and increase efficiency. MAS allows the identification and elimination of an individual plant from a population on the basis of its genetic composition and, as a consequence, reduces the costs associated with both continued propagation and downstream phenotyping[17].

MAS does not require knowledge of the specific genes that confer a trait; it only requires markers that are tightly associated with a trait, which may or may not be within the gene controlling the trait. MAS is not used in all plant-breeding programs, but its use might soon become universal as more genetic information is made available and screening costs are reduced.

As in all other disciplines of biology, plant breeding is now in the genomics era, in which paradigm-changing methods are being incorporated to accelerate and improve the efficiency of breeding. Incorporation of genomics into breeding and genetics research has resulted in an increased knowledge base on crop genetics, species diversity, the molecular basis of traits, and the evolutionary history of crop origins from primitive wild species. MAS and genomics greatly reduce the number of individual plants that need to be retained in the breeding pipeline for phenotyping. Genome-level datasets and genomic technologies have been used to identify causal genes, alleles, and loci important to relevant agronomic traits and have thereby become tools to accelerate breeding cycles.

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[14] Gbegbelegbe S. *et al.*Baseline simulation for global wheat production with CIMMYT mega-environment specific cultivars. (2017) Field Crops Res., 202 (2017), pp. 122-135

[15] Challinor A. *et al.* (2016) Current warming will reduce yields unless maize breeding and seed systems adapt immediately. Nat. Clim. Change, 6 (2016), pp. 954-958

[16] National Academies of Sciences, Engineering, and Medicine 2016. Genetically Engineered Crops: Experiences and Prospects. Washington, DC: The National Academies Press. https://doi.org/10.17226/23395.

[17] Ru, S., Main D., and Peace C. (2015) Current applications, challenges, and perspectives of marker-assisted seedling selection in Rosaceae tree fruit breeding. Tree Genetics & Genomics 11:8.

An array of genomic technologies can be used to generate large scale genetic-diversity data on any species that can be used to breed improved crop varieties through such techniques as MAS. For example, genome sequencing and resequencing whereby all or part of the genome is sequenced and single-nucleotide polymorphism (SNP) assays, where hundreds to millions of individual loci are assayed for allelic diversity, are genomic methods that are used routinely in the breeding programs of many crops. Several technological approaches can be applied to assay SNP loci, including platforms that use mass spectrometry, primer extension, or reduced-representation targeted resequencing to assay the polymorphism.

Major considerations for the plant breeder in the choice of technological platform are marker density, sample throughput, cost, and number of loci to assay. Depending on the crop, a publicly or commercially available SNP platform is used, as are custom SNP arrays for specific applications.

The coupling of continual advancements in genomic technologies with increased throughput and decreasing costs means that breeding programs now have access to a wealth of genetic-diversity data that can be used to link genes (and alleles) with phenotypes and agronomic traits. For example, large-scale, genome- diversity data on several major crops have been generated, including not only cultivated lines but related wild species and landraces. The information has provided insights into the genetic and molecular basis of agronomic traits, genetic bottlenecks that restrict major improvements in breeding gains, and key genes and events in domestication and crop improvement, all of which lead to more efficient breeding.

Currently, a reference genome for all nearly major crop species, including *Eucalypts* sp. are available for use in breeding programs. The quality of the reference genome sequences varies substantially, depending on technical and cost limitations. A complete genomic sequence with few or no gaps is considered the 'gold standard' for a reference genome, but incompletely characterised genomes are also useful.

For many crops, diversity panels[18] with their associated genome and phenotype datasets have been or are being developed. However, the availability of large-scale genetic information is not a panacea for plant breeding. A reference genome derived from a single individual or genotype does not provide full representation of the genome information needed for crop improvement; as a consequence, multiple reference genomes for each species are needed to adequately capture the genome diversity.

For various reasons—including lack of access to data, lack of computational tools, and insufficient analytical expertise in genomics—some researchers do not take full advantage of genomic data. However, as genomic technologies improve so that any individual plant's genome can be sequenced and analysed, as breeders acquire more expertise in using relevant genomic and bioinformatic technologies, and as genotyping methods improve in throughput and cost efficiency, those limitations will be overcome, and this will leave

[18] Diversity panels are collections of germplasm that represents a crop species. The panels include cultivars, landraces, and wild species related to the crop that collectively represent the genetic diversity of the crop or can be used to improve phenotypic traits in the crop.

phenotyping as the major limitation of efficient breeding. **Thus, it is likely that high-throughput, field-based phenotyping technologies will be developed to provide parallel datasets, increase efficiency, and reduce costs associated with tree breeding and genetic improvement**[19].

2.3 High Throughput field-based phenotyping technologies

Although there has been much success from the second half of the last century to now, the genetic gains in yields of major crops such as wheat (*Triticum aestivum* L.) have stabilised or even stagnated in many regions of the world[20], despite recent technical advances[21]. This stagnation makes it more urgent to increase the efficiency of breeding. Limitations on phenotyping efficiency are increasingly perceived as a key constraint to genetic advance in breeding programs[22,23,24]. Specifically, high-throughput field phenotyping may represent a bottleneck in conventional breeding, marker-assisted selection, or genomic selection, where phenotyping is a key informant for establishing the accuracy of statistical models[25].

The perceived challenges that currently limit the adoption of new phenotyping packages for breeding are:

a. validation of high-throughput field phenotyping
b. the need to develop flexible (mobile) and affordable approaches
c. the alignment of phenotyping under controlled conditions with targets for real (i.e., field) phenotyping; and, above all
d. data management, including user-friendly components and modelling and data integration.

Genetic gain within a breeding program can be accelerated in a number of ways[26], including

a. increasing the size of the breeding program to enable higher selection intensity
b. enhancing the accuracy of selection (higher repeatability)
c. ensuring adequate genetic variation

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[19] National Academies of Sciences, Engineering, and Medicine 2016. Genetically Engineered Crops: Experiences and Prospects. Washington, DC: The National Academies Press. https://doi.org/10.17226/23395.
[20] Acreche M, *et al.* (2008) Physiological bases of genetic gains in Mediterranean bread wheat yield in Spain. Eur. J. Agron., 28 (2008), pp. 162-170
[21] Sadras V., *et al.* (2011) Genetic gain in yield and associated changes in phenotype, trait plasticity and competitive ability of South Australian wheat varieties released between 1958 and 2007. Crop Pasture Sci., 62 (2011), pp. 533-549
[22] Araus J and Cairns J. (2014) Field high-throughput phenotyping, the new frontier in crop breeding. Trends Plant Sci., 19 (2014), pp. 52-61
[23] Ghanem M., *et al.*(2015) Physiological phenotyping of plants for crop improvement. Trends Plant Sci., 20 (2015), pp. 139-144
[24] Tardieu F. *et al.* (2017) Plant phenomics, from sensors to knowledge. Curr. Biol., 27 (2017), pp. R770-R783
[25] Desta Z and Ortiz R. (2014) Genomic selection: genome-wide prediction in plant improvement. Trends Plant Sci., 19 (2014), pp. 592-601
[26] Masuka B., *et al.*(2017) Gains in maize genetic improvement in Eastern and Southern Africa: I. CIMMYT hybrid breeding pipeline. Crop Sci., 57 (2017), pp. 168-179

d. accelerating the breeding cycles, and

e. improving decision support tools.

In all of these, reliable high-throughput precision phenotyping is involved in a direct or indirect manner (**Figure 3**).

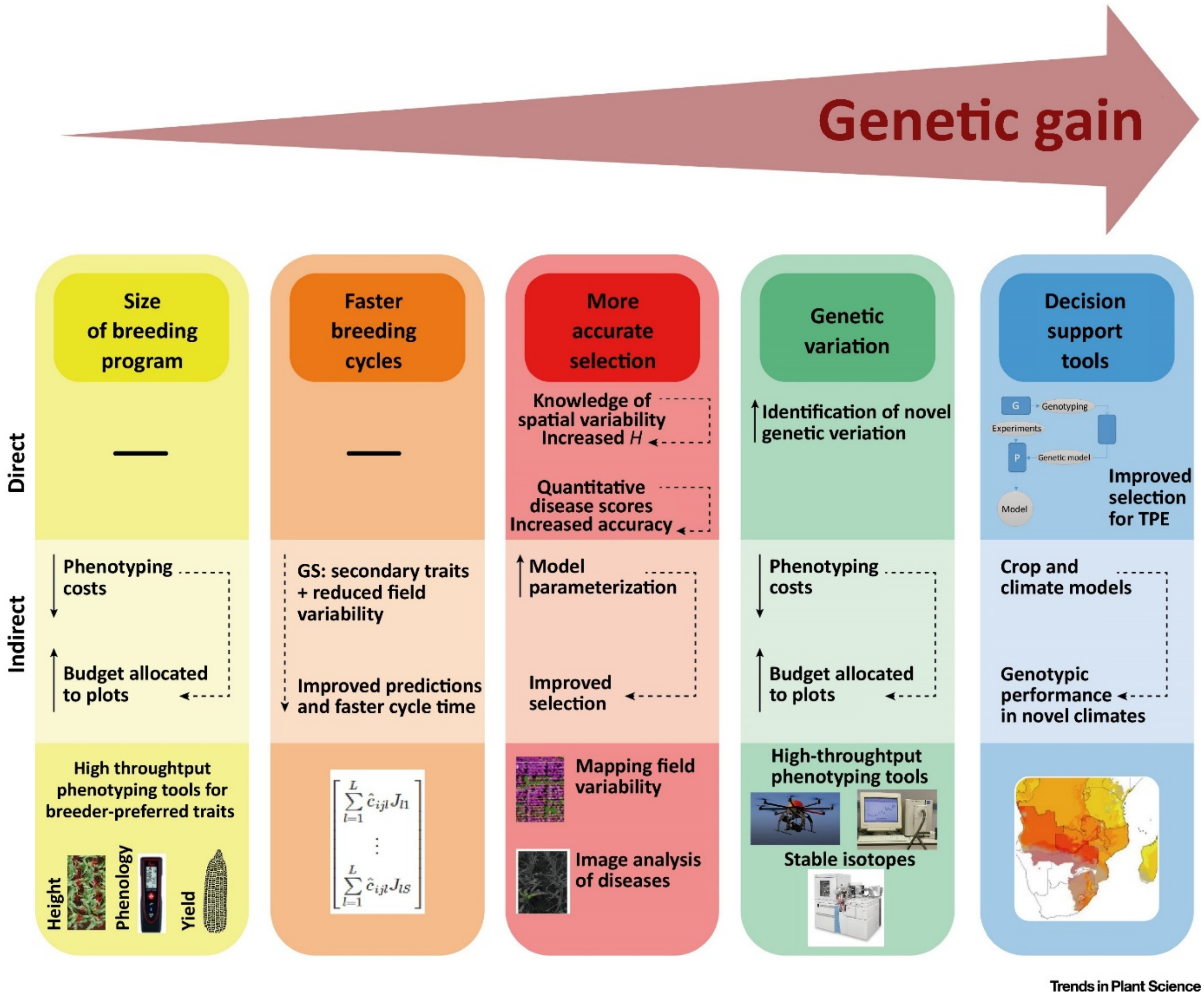

Figure 3: Five Pillars of Increasing Genetic Gain in Breeding Programs[27].

2.4 Phenotyping Technologies

Much of what is currently considered high-throughput phenotyping is based on remote sensing (**Figure 4**). The most common types of remote-sensing devices used for crop phenotyping include multispectral, hyperspectral, fluorescence, and thermal sensors (particularly for ground-based phenotyping platforms), or imagers (which may be deployed from aerial platforms or at ground level, when several plots at a time are measured) using the radiation

[27] Araus J and Cairns J. (2014) Field high-throughput phenotyping, the new frontier in crop breeding. Trends Plant Sci., 19 (2014), pp. 52-61

reflected or emitted by the canopy. Digital red–green–blue (RGB) cameras are widely being used across a range of crops.

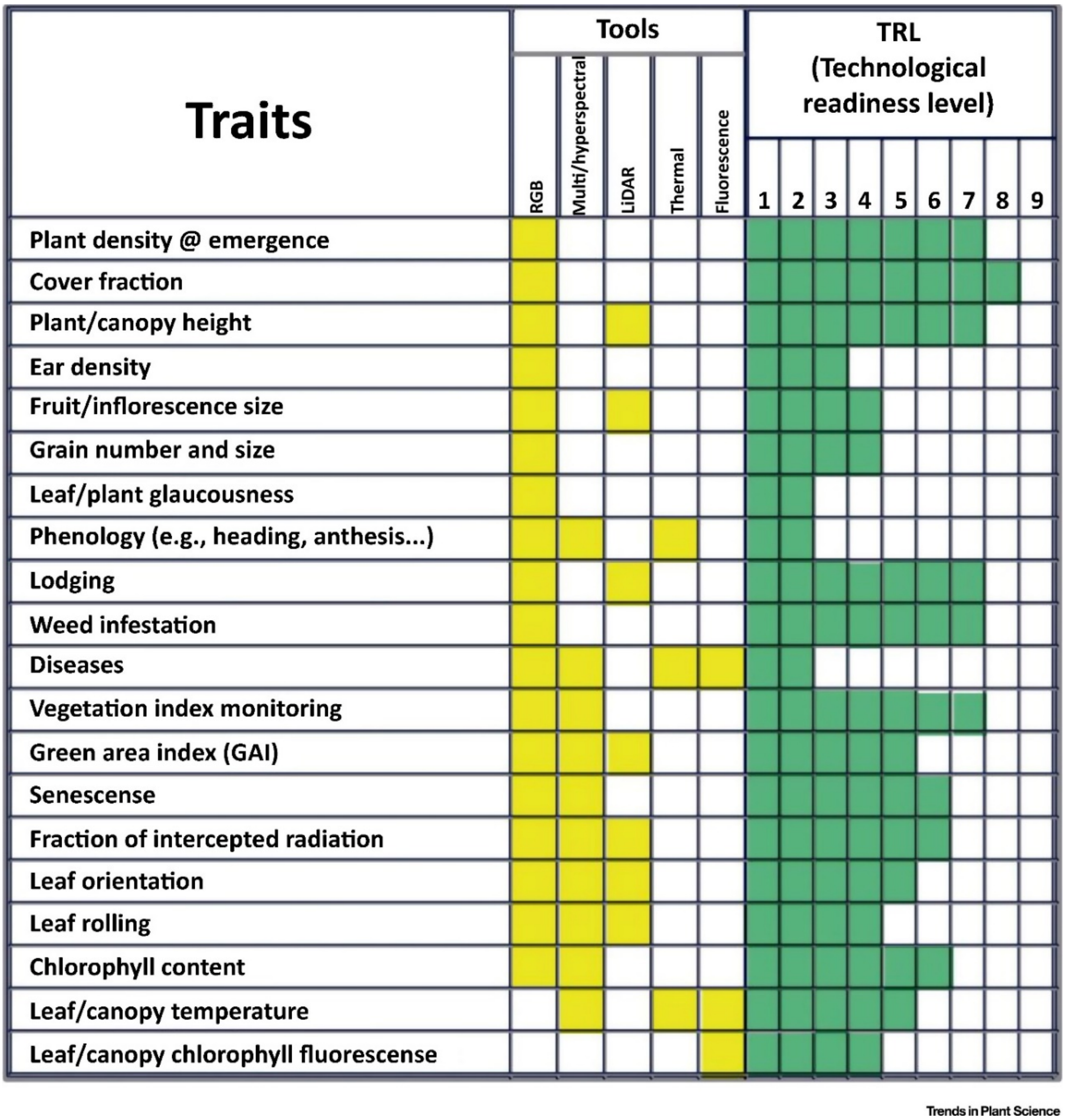

Figure 4: Summary of the Different Remote-Sensing Tools Most Commonly Used (*Source:* Araus et al, 2018)[28].

Remote-sensing tools allow assessment of physiological yield components that are clearly and conceptually related to crop productivity and stress adaption in terms of resource acquisition (e.g. radiation, water, nutrients, etc.), resource use efficiency, or downstream

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28 Araus J,Shawn C.Kefauver S, Mainassara Zaman-Allah M, Olsen M, and Cairns J. (2018) Translating High-Throughput Phenotyping into Genetic Gain. Trends in Plant Science. Volume 23, Issue 5, May 2018, Pages 451-466

biomass partitioning. Changes in yield components impact yield potential as well as adaptation of the crop to unfavourable abiotic or biotic conditions.

2.5 Phenotyping for Genetic Gain

The field of high-throughput phenotyping is rapidly evolving. As a result, there is a need to ensure that these advances find practical application in breeding programs and contribute toward increased genetic gain. While it is difficult to partition improvement within breeding programs to the adoption of specific technologies, placing technologies (including phenotyping) within the concept of genetic gain will assist in monitoring success.

Recently, there have been many advances in the development of high-throughput phenotyping tools for ‘breeder-preferred’ traits (**Figure 5**). Plant height sensors in plantation forestry have been developed using a range of sensors including LiDAR, ultrasonic sensors, and RGB images.

Adoption of recently developed high-throughput tools, carried out by ground and aerial phenotypic platforms, can involve large initial investment, particularly for use within testing networks covering large geographic areas. The challenge remains for high-throughput phenotyping to develop low-cost tools that can be applied across locations, especially when deployed in low- or middle-income countries where transportation may be expensive or difficult and where labour markets may result in relatively lower wages than in higher income countries.

While ‘robust sensors mounted on a field-deployable vehicle’ are considered imperative for a field-based high-throughput phenotyping platform, this is not necessarily the case. In terms of tools and platforms, effective and expensive are not necessarily synonymous. There are a wide range of options for using RGB imaging to generate vegetation indices and other applications in crop monitoring, together with flexible (e.g., ground hand-held and unmanned aerial) platforms that are easily deployable across a multi-trial network. Some of these applications are also amenable for installation as apps on mobile phones.

To capitalize on advances in phenotyping and molecular technologies, greater progress is needed in areas of environmental characterization and data collection and management.

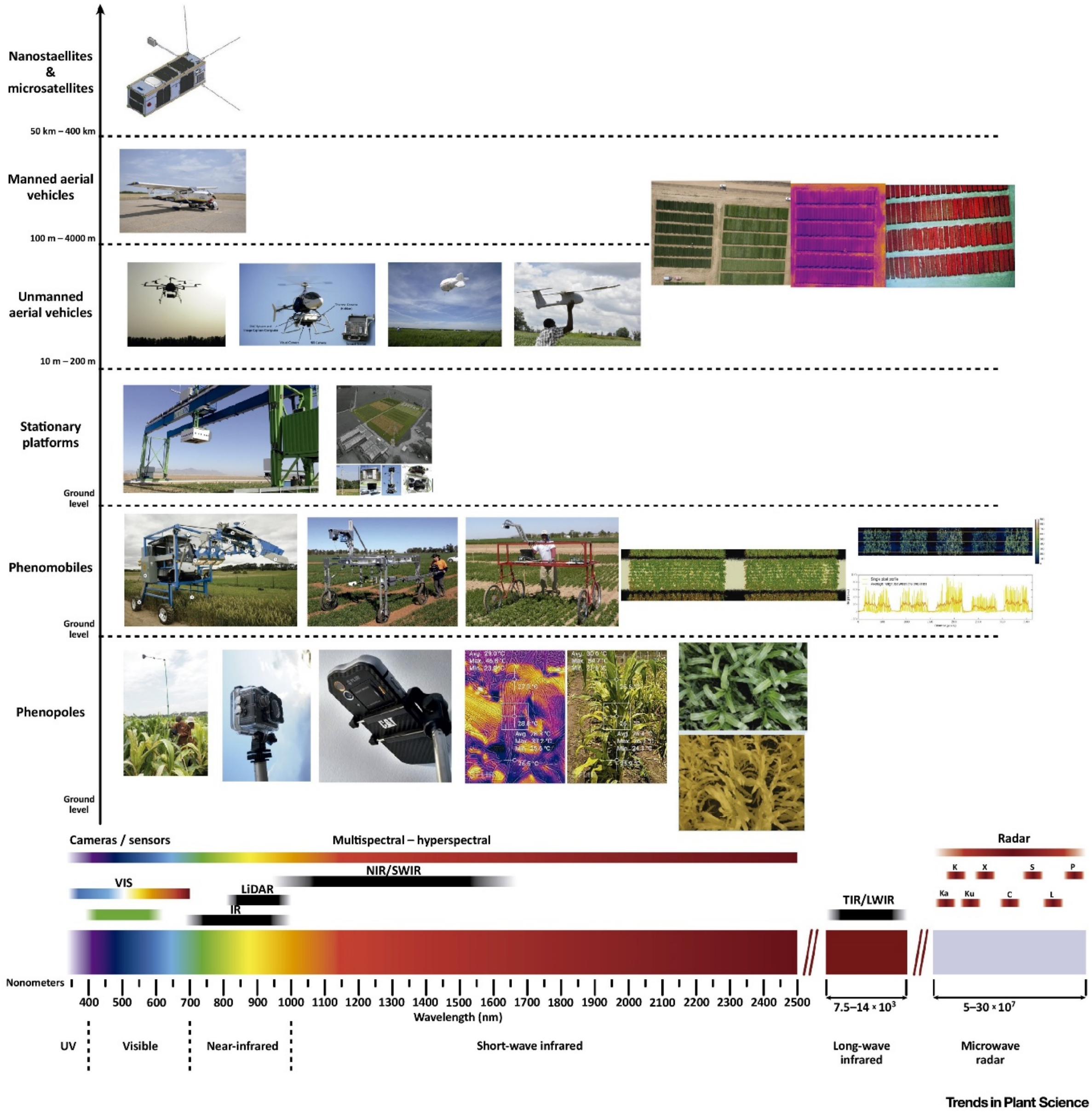

Figure 5: Different Categories of Potential and Actual Ground and Aerial Phenotyping Platforms, along with the Spectral Ranges Used for Different Remote-Sensing Tools[29].

[29] Araus J,Shawn C.Kefauver S, Mainassara Zaman-Allah M, Olsen M, and Cairns J. (2018) Translating High-Throughput Phenotyping into Genetic Gain. Trends in Plant Science. Volume 23, Issue 5, May 2018, Pages 451-466

2.6 Novel Breeding Strategies using Genomic Selection

The vast number of valuable germplasm collections in gene banks is a source of genetic variation to potentially raise genetic gain. However, there are two major constraints: (i) time and resources required to precisely characterize the accessions at large scale, and (ii) identifying and transferring the useful alleles into adapted germplasm.

Genomic selection has emerged as one of the most promising breeding strategies to increase genetic gain and its advantages over traditional practices have been demonstrated for major crops[30]. More recently, genomic selection has also proven a useful tool to accelerate genetic gain for heterosis breeding[31].

Several low-cost and high-throughput SNP chips and NGS (next generation sequencing)-based platforms have made it possible to genotype large breeding populations for genomic selection[32]. Genomic selection can be fine-tuned by incorporating high throughput phenotyping for yield-associated physiological traits, markers for well-characterized major genes, and parametric and nonparametric statistical and computational models.

Remarkably, there has been a three-million-fold increase in sequencing throughput since 1975 and a million-fold decrease in cost over a decade, which has led to huge progress in sequencing crop species[33]. Efforts are now focused on whole-genome sequencing of members of a gene-pool (pan-genome) to increase our understanding of the genetics underlying crop adaptability. Such insight could enable the adoption of several approaches already implemented in livestock genomics.

For example, haplotypes consisting of two or more SNPs with strong linkage-disequilibrium are multi-allelic in nature and are more informative than bi-allelic SNP markers. Highly conserved haplotypes selected by plant breeders during modern breeding could be replaced by more beneficial haplotypes from genetic resources.

2.7 Conclusion - Integrated Approaches and Collaborations

If applied in isolation, a tool or technology will unlikely accelerate the rate of genetic gain in crop breeding. However, the successful integration of several technologies has the potential to break stagnant yield barriers in various crops (**Figure 6**). For instance, high-throughput hyperspectral phenomics for yield-associated physiological traits could be used to discover haplotypes that are different from haplotypes of conventional phenotypes (plant height, flowering time, grain yield per se, etc.) that have been selected by plant breeders.[34] The fast-track replacement of historically fixed haplotypes with new beneficial haplotypes of

[30] Crossa, J. et al. (2017) Genomic selection in plant breeding: methods, models, and perspectives. Trends Plant Sci. 22, 961–975

[31] Jiang, Y. et al. (2017) A quantitative genetic framework highlights the role of epistatic effects for grain-yield heterosis in bread wheat. Nat. Genet. 49, 1741–1746

[32] Rasheed, A. et al. (2017) Crop breeding chips and genotyping platforms: progress, challenges and perspectives. Mol. Plant 10, 1047–1064

[33] Bevan, M.W. et al. (2017) Genomic innovation for crop improvement. Nature 543, 346–354

[34] Araus J, and Cairns J. (2014) Field high-throughput phenotyping: the new crop breeding frontier. Trends Plant Sci., 19 (2014), pp. 52-61

yield-associated traits could potentially make room to further improve the harvest index in crop plants[35].

Within the Australian plantation forestry industry the integration of modern breeding technologies such as ‘accelerated/speed breeding’ strategies along with advances in ‘omics’ platform technologies including but not limited to genomics, phenomics and bioinformatics could help the industry take advantage of the opportunities which exist in the short and long term.

The catalyst for effectively, efficiently and economically taking advantage of these opportunities will be the role of FWPA in facilitating through its investment in research initiatives a more collegiate and collaborative approach across the plantation industry to tree breeding and genetic improvement research, development and deployment.

These types of initiatives will help to modernize plantation tree breeding programs, by stakeholders individually and collectively embracing new technology and innovation. The tools, services, knowledge, resources, and peer interactions facilitated by FWPA, will allow tree breeders a transition into the digital era, including storage, retrieval, analysis, sharing, interpretation, and utilization of electronic data. This will enable tree breeders to adopt best practices, use new tools, and integrate breeding approaches, saving time in developing new higher yielding plantation tree cultivars, of better quality, and more resilient to weather extremes and local stress environments.

[35] Huihui L, Rasheed A, Hickey L, and He Z. (2018) Fast Forwarding Genetic Gain. Trends in Plant Science, March 2018, Vol. 23, No. 3

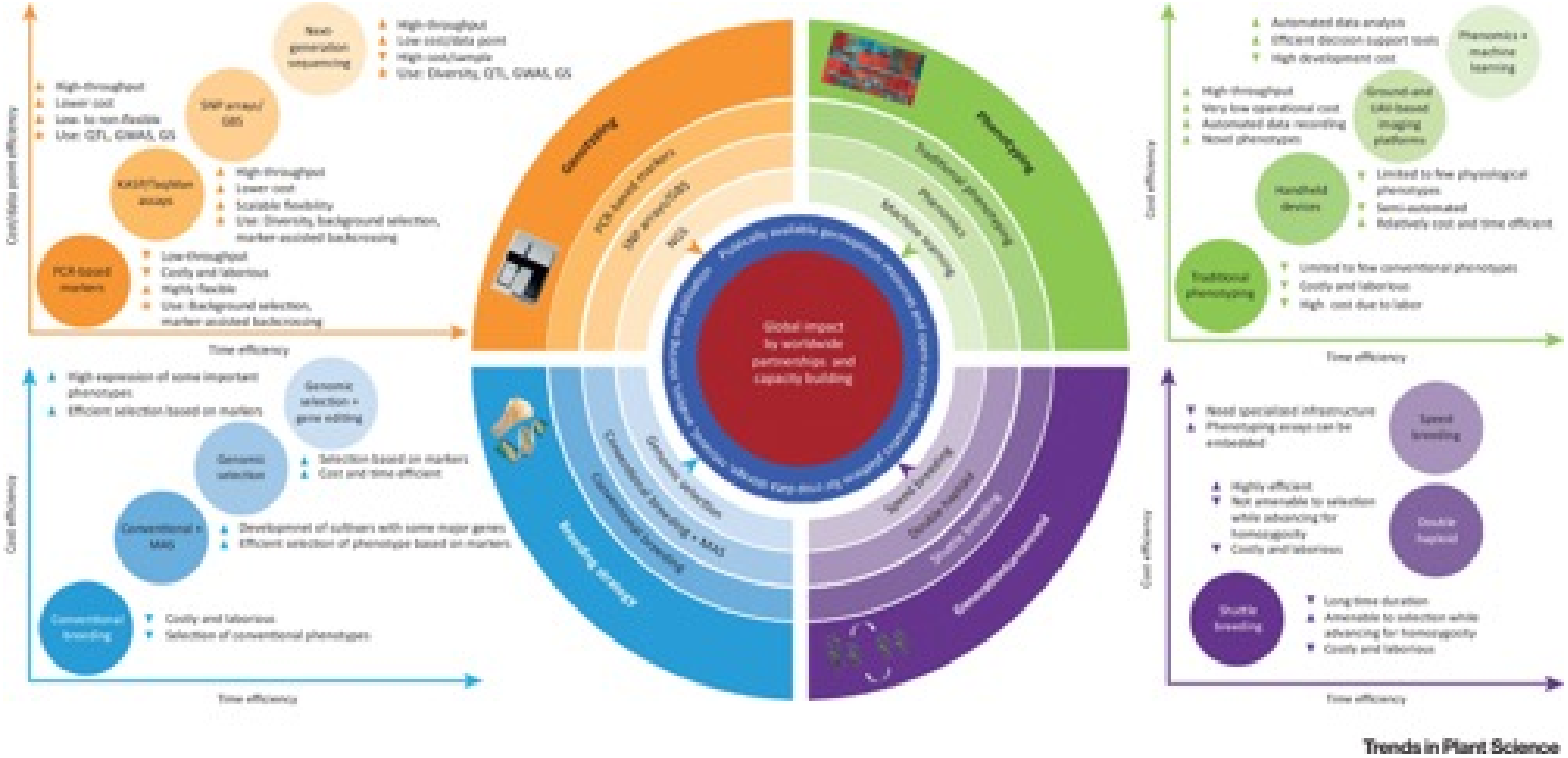

Figure 6: The Integrated Strategies Leading to a Common Decision Support Tool to Accelerate Genetic Gain Within the Context of New Technologies. The features of individual aspects, such as genotyping, phenotyping, generation turnaround, and breeding strategy are described in bi-plots, along with key advantages (denoted as △) and disadvantages (denoted as ▽). The low colour intensity indicates the higher possibility of technologies to integrate with other technologies**.** (*Source*: Huihui L. et al (2018)[36].

[36] Huihui L, Rasheed A, Hickey L, and He Z. (2018) Fast Forwarding Genetic Gain. Trends in Plant Science, March 2018, Vol. 23, No. 3

3.0 Industry driven opportunities for FWPA investment in tree breeding and genetic improvement research for plantation *Eucalyptus sp.* and *Pinus sp. (2019 – 2024 & beyond)*

The economics of plantation forestry in Australia are increasingly being challenged. The challenge of high upfront costs coupled with long lead times to return on investment, an increasing regulatory burden and the impact of climate change mean that several factors must align to allow plantation projects to generate a profit.

To address these challenges, the plantation industry will require a combination of policy, investment and innovation. Within the field of innovation, tree breeding and genetic improvement provides the opportunity for investment in initiatives that will contribute to the delivery of outcomes that will:

1. Within the context of adaptation for climate change, enhance the production and value of future products generated from *Pinus radiata, Southern Pines* and *Eucalyptus sp.* estates to supply chain stakeholders through improvements in yield and quality, together with increased tolerance to abiotic and biotic stress and enhanced silviculture practices.
2. Generate new high value product opportunities, such as the growing of 'elite' individual trees and plantations for the bio-economy which have been selected using 'next generation' modern breeding technologies such as genomics, phenomics, bioinformatics and genetic markers applied within an economic value based genome wide selection breeding program.

The current project has identified, through extensive consultation with industry participants and a review of trends within Australian and international tree breeding programs, a range of strengths and weaknesses from which the authors have identified various investment opportunities that have the potential to contribute to improving plantation productivity and forest product quality and ultimately the value of the *Eucalyptus sp. Pinus sp.* and Southern Pine plantation industries within Australia.

Advancement in modern breeding technologies over the last 30 years such as the development of molecular and quantitative genetics now offers the plantation forestry industry the opportunity to accelerate breeding by selecting either for known genes or quantitative trait loci using genetic markers, rather than effects on phenotypes.

The framework applied by the authors to the assessment and prioritisation of the opportunities identified is presented in **Appendix Two**.

3.1 Opportunity 1: Development and Application of Genomic Tools to Accelerate the generation of genetically improved forests with improved plantation productivity and forest product quality

3.1.1 Background

Molecular markers, the basis of genomic tools and genomic breeding

The development of molecular marker technology through the 1980s has revolutionised plant breeding. Different types of molecular marker classes have been developed and implemented through Marker Assisted Selection (MAS) in a number of crop and animal breeding programs. More recently, advancements in whole genome sequencing (WGS) technologies has enabled the development of genomic tools to capture variation across the entire genome, further accelerating agricultural productivity, particularly in animal production and broad acre cropping.

MAS is a technique where phenotypic selection is made predominantly on the basis of the genotype of a marker or set of markers. Plant breeders mostly use MAS for the identification of suitable dominant or recessive alleles across a generation and for the identification of the most favourable individuals across the segregating progeny. MAS, as a tool, helps avoid many of the difficulties and challenges with conventional plant breeding such as the amount of physical space for breeding populations and the waiting times required to make the next selections and progress to the next generation. This has the added benefits of reducing overall breeding costs and the time to deployment of new varieties.

The molecular marker class of choice for many genomic programs is the Single Nucleotide Polymorphism (SNP). A single-nucleotide base is the smallest unit of inheritance and as such SNPs offer the simplest and most abundant number of markers across the genome. SNPs are found in both coding and non-coding regions or between two genes (intergenic regions) with different frequencies. SNPs may be transitions (C/T or G/A) or transversions (C/G, A/T, C/A or T/G) on the basis of nucleotide substitution and can often be associated with insertion/deletions (InDel) within genes. The SNP frequency in plants ranges between 1 SNP in every 100–300 base pairs (bp). So, for the wheat genome with 17Gb (17,000,000,000 base pairs) there would be between 170 million to 57 million potential SNP markers.

SNPs are extremely useful for creating high-density genetic maps (e.g. Quantitative Trait Loci (QTL) maps–used to detect the genes which control a trait of interest; Association Mapping (AM)–significant association of molecular markers with a phenotypic trait) and for genome assembly. Such genomic based resources are useful to determine associations between markers and certain traits (e.g. yield, disease resistance, quality etc.), facilitating the selective breeding process. Each of the tools have both advantages and disadvantages but nevertheless offer a more targeted and informed approach to selecting improved varieties in less time.

Genomic Selection–accelerating genetic gain

Genomic selection (GS; **Figure 7**) is an advanced form of marker assisted selection. It is a technique that has the ability to predict the genetic values of selected candidates depending on a genome-estimated breeding values (GEBVs) predicted from a high density of markers that are distributed throughout the genome (e.g. genome wide SNPs). GEBV is a prediction model that combines both phenotypic data with marker and pedigree data in order to increase the accuracy of prediction.

As compared to traditional MAS, GEBV is dependent on all markers including major and minor marker effects. As such, the approach lends itself to genetic improvement of complex traits such as yield, quality and generation times etc.

An important feature of GS and key contributor to GEBV estimation is fast and accurate phenotyping of key traits. As such, development of high throughput phenotyping capabilities is essential in improving the accuracy and therefore benefit of GS.

Application of markers to forest tree breeding

The application of marker technologies to forest breeding is still in its infancy and limited to only a few species. This is largely due to the size and complexity of forest species genomes. For example, the genome size of radiata pine (approximately 25 billion base pairs) is some 8 times larger that of the human genome. Further, genomic resources that do exist can lack complete genome assembly and are often poorly annotated. Such complexity and lack of completeness has contributed to a lack of demonstrable benefit from investment in the development of genomic resources.

Of particular note is that much of the sequence data generated for forest species has been collected from gene expression libraries of various tissues across different stages of development. This approach ignores a substantial part of the genome and limits identifying markers associated with many quantitative traits, especially those that have complex genetic architectures. There is a need for whole genome assemblies for important forest species as well as generating and validating SNPs for use in high throughput genotyping and MAS.

Despite these limitations, there are some recent activities that are encouraging. The release of a reference genome sequence and gene catalogue for *Eucalyptus globulus* by Rigault et al (2012)[37] is providing the basis for tree improvement in a number of countries.

[37] Rigault, P et al. (2012). Generation of a *Eucalyptus globulus* Reference Genome and Gene Catalogue. Conference Presentation. Conference: Plant and Animal Genome XX. San Diego, USA. Volume: XX Forest Trees

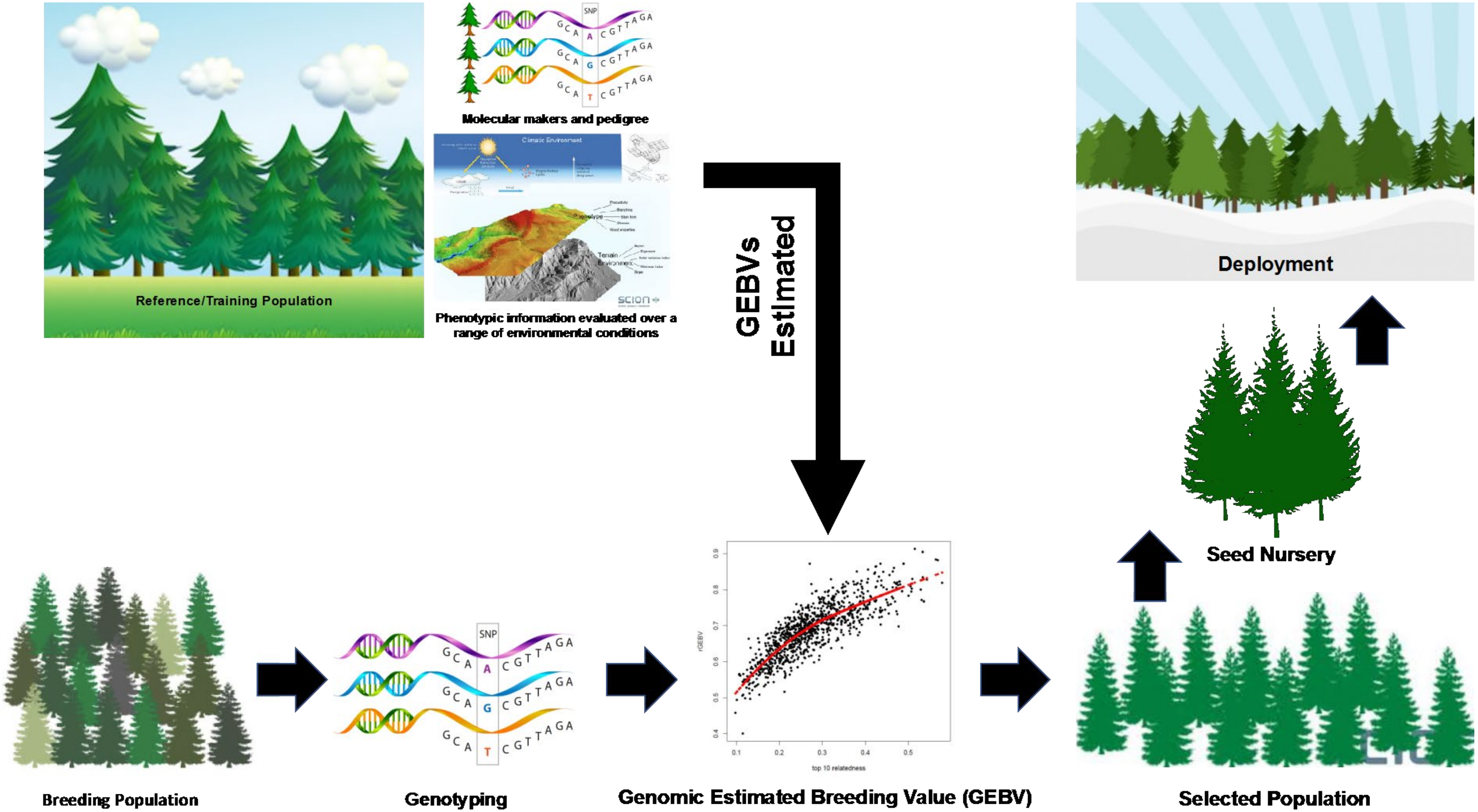

Figure 7. Genomic Selection.

Important steps in genomic selection include: 1. Development of a reference/training population using diverse germplasm; 2. Phenotyping and genotyping the training population and estimating GEBVs; 3. Selection of individuals from the breeding program having superior GEBVs on the basis of their genotypic information; 4. Using selected individuals with the highest GEBVs as parents for creating a selected population; and 5. Genetically improved plants bulked and deployed.

Likewise, the sequencing of the *Eucalyptus grandis* genome[38], together with the completed genome of *Populus*[39], serves as a model and reference for the study of fast-growing woody plants that are used as renewable feedstocks for a growing number of bio- based products.

In South Africa the genome sequences from *Eucalyptus* have also served as a reference for the development of a genome-wide DNA marker resource that has been deployed for genomic breeding and selection in two large pilot projects in *E. grandis* and *E. dunnii* initiated with industrial partners. The South Africans have leveraged this genome-wide DNA marker resource to also develop a SNP marker chip with 60,000 DNA markers (EUChip60K)40 to genotype over 3,000 *Eucalyptus* trees from *E. grandis, E. dunnii* and *E. grandis* x *E. urophylla* hybrids.

Similarly, in Australia, Tree Breeding Australia (formerly Southern Tree Breeding Association) have developed an 800,000 SNP panel for *E. globulus* and have plans to fine tune this resource to a low cost, low density array as well as develop a SNP panel for the other major *Eucalyptus* species *E. nitens*.

Gondwana Genomics offers a unique commercial MAS service for *Eucalyptus* sp. Utilising a next-generation genotyping platform, initially developed through the CSIRO, the company offers accurate marker predictions for tree performance and quality including increased growth, density, pulp yield, energy value and disease resistance. Further, their technology can be applied to reconstruct pedigrees of mixed populations of *Eucalyptus* open pollinated breeding populations in which behaviour data are difficult to obtain.

Collectively, these resources offer significant opportunity to deliver genetic gains to Australian hardwoods.

Advances in conifer species has been less advanced largely due to the increased complexity of gymnosperm genomes. There have been three low quality genome assemblies attempted: Loblolly pine (*Pinus taeda*)[41] [42]; Norway spruce (*Picea abies*)[43]; and White spruce (*Picea glauca*)[44]. More recently, the announcement of the first draft assembly of the radiata pine genome by SCION scientists in 2017[45] has set the stage for characterisation of the vast

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[38] Myburg A. A., Grattapaglia D., Tuskan G. A., Hellsten U., Hayes R. D., Grimwood J., … Schmutz J. (2014). The genome of *Eucalyptus grandis*. Nature, 510(7505), 356–362. 10.1038/Nature13308.

[39] Tuskan, G. A. et al. The genome of black cottonwood, *Populus trichocarpa* (Torr. & Gray). Science 313, 1596–1604 (2006)

[40] Silva-Junior O. B., Faria D. A., Grattapaglia D. (2015). A flexible multi-species genome-wide 60K SNP chip developed from pooled resequencing of 240 *Eucalyptus* tree genomes across 12 species. *New Phytol.* 206 1527–1540. 10.1111/nph.13322

[41] Neale DB, Wegrzyn JL, Stevens KA et al. Decoding the massive genome of loblolly pine using haploid DNA and novel assembly strategies. Genome Biol 2014;15(3):R59.

[42] Zimin AV, Stevens KA, Crepeau MW, et al. Erratum to: An improved assembly of the loblolly pine mega-genome using long-read single-molecule sequencing. *Gigascience*.; 6(10):1. doi:10.1093/gigascience/gix072

[43] Nystedt, B., Street, N. R., Wetterbom, A., Zuccolo, A., Lin, Y. C., Scofield, D. G., et al. (2013). The Norway spruce genome sequence and conifer genome evolution. Nature 497, 579–584. doi: 10.1038/nature12211

[44] Birol, I., Mohamadi, H., Raymond, A., Raghavan, K., Chu, J., Vandervalk, B.P., Jackman, S. and Warren, R.L. (2014) Spaced Seed Data Structures. In IEEE International Conference on Bioinformatics and Biomedicine (BIBM). Belfast UK.

[45] Anon. (2019) www.scionresearch.com/about-us/news-and-events/news/2017/radiata-pine-genome-draft-assembly-completed

genomic, metabolomic and phenomic diversity within *Pinus radiata,* however the assembly has yet to be formally published.

Associated with the radiata genome reference, a first-generation SNP panel has also been developed and being validated for implementation in a genomic selection program, but requires further development towards a practical, low cost, high-throughput genotyping resource[46].

Open pollinated breeding populations are also a feature of radiata pine improvement programs. It is understood that the Gondwana Genomics technology could, at low cost, be applied to radiata pine breeding[47]. Such an approach would complement SNP based high through put genotyping.

3.1.2 Investment Theme - Local tools for local applications and benefit

Genomic resources provide an unprecedented resolution to rapidly dissect complex traits in Forest tree species as well as develop predictive models for the genomic selection of growth and wood properties in tree breeding populations.

Radiata pine is the dominant softwood species grown in temperate Australia and New Zealand (74.5% and 91.8% respectively). In the sub-tropical areas of Queensland, southern pines are the major softwood. In Australia, softwoods are grown and managed for sawlog production.

In Australia, *E. globulus* is the dominant (51.7%) hardwood species (469,800 ha) grown in temperate areas, while *Eucalyptus nitens* (233,600 ha) is the major hardwood, cold-tolerant species grown mainly in Tasmania. Both estates are primarily managed for pulp log production. In New Zealand, *Eucalyptus* is a minor crop and accounts for around 1.3% of the total production area.

To deliver the greatest impact to Australasian forestry, genomic resources need to be developed that target the most relevant commercial species. Specifically, *Radiata pine*, Southern Pines, *E. globulus* and *E. nitens*. As mentioned above, there are some promising activities underway. However, in order to apply and capture the benefits of genomic tools, such as genomic selection, there is a need for fundamental whole genome assemblies and development and validation of SNP panels to facilitate the high throughput genotyping of forest tree breeding programs.

First and foremost, reference genomes for *Pinus sp.* and *E. nitens*. are required. The reference genomes, correctly assembled and adequately annotated, provide the ongoing foundations for genomic tool development, increase prediction accuracy and decreased risk of false positive selection, lower overall cost of further genomic tool development (e.g. SNP marker development) and demonstrate global leadership in advanced forest tree breeding. Genome references also offer a valuable resource that will facilitate collaboration and access to elite breeding material. Secondly, leveraging the reference genomes, informative SNPs from

[46] H. Dungey pers comm.
[47] B. Thumma pers comm.

across the entire genome can be identified from key founder plants and existing high value lines. SNP panels can be filtered and validated to provide low cost, high throughput genotyping assays (e.g. for radiata pine a 60KSNP V2.0 Chip). Thirdly, genotyping assays such as SNP V2 and the Gondwana Genomics platform can be applied to breeding programs facilitating genomic selection, accelerating the genetic gain of key traits of interest such as yield and quality, resolving mixed populations structures, and predicting the elite lines that will perform best at specific locations to ensure ongoing sustainability under climate change models.

3.1.3 Recommendations

- ✓ *It is proposed that FWPA support the establishment of a 'big picture' collaborative project between TBA and RPBC that would build on research already undertaken by Australian and New Zealand researchers. The proposed research projects would focus on the development of genomic resources and tools that will have wide and ongoing applications across forest improvement. The streams of collaboration include:*

  1. ***Build complete and annotated reference genomes for Pinus radiata, Slash x Caribbean pine hybrid, Eucalyptus globulus and E. nitens****.*

     The reference genomes of these four important forest species serve as the foundation for building all other genomic tools that will enable advanced forest tree breeding as well as tackling a number of existing challenges (e.g. impacts of climate change). The reference genomes will facilitate the development of genetic, QTL and association maps, alignment of SNPs for development of genotyping assays and elucidating the genetic basis of complex traits.

     This collaboration would leverage existing genomic resources such as the reference genome of E. globulus and the draft Pinus genome developed by SCION as well as an incomplete draft reference genome for E. nitens (AgriBio). In each case, concerted sequencing and bioinformatic efforts are required and could be achieved through a focused TBA and RPBC collaboration.

  2. ***Development and deployment of a radiata pine SNP V2.0 Chip for genotyping***

     It is understood that a first-generation SNP Chip has been developed by SCION and being validated for implementation in a genomic selection program, but requires further development towards a practical, low cost, high-throughput genotyping resource.

     SNP detection can be achieved through whole genome sequencing of germplasm from both Australia and New Zealand breeding programs (including the important founder lines) and aligning them to the reference genome. SNPs from geneic regions can also be added from RNASeq analysis of samples from various tissue types and stages of development. Once aligned to the reference genome, the SNPs can be filtered, selected and arranged into an array for validation. A subset of highly informative SNPs can then be arrayed providing a practical, low cost, high-throughput genotyping resource.

SNP chips for the parent species of the slash x Caribbean pine hybrid are being developed by a consortium led by North Carolina State University and the University of Pretoria. Key ancestors and hybrid progeny from Australian populations can be genotyped using an initial 440K chip to help select the most relevant SNPs for a 50K chip being designed for use in 6 tropical pine species (including Caribbean pine) and related hybrids. This chip could provide a very low-cost interim genotyping platform for the slash x Caribbean pine hybrid as soon as late 2019. During the 2019-2024 timeframe, it is expected that the most informative SNPs from the parental chips could be combined with additional SNPs discovered through sequencing and alignment with the hybrid reference genome, to create a slash x Caribbean pine hybrid SNP array.

3. ***Convert genomic tools for pedigree reconstruction***

   Many softwood and hardwood breeding programs are based on an open-pollinated (OP) breeding population. Therefore, when determining breeding values it is expected that there will be some inaccuracy due to unknown paternal contribution. Precisely recorded pedigrees and known ancestors of the breeding population individuals are prerequisites for accurate genetic evaluation and consequently, efficient breeding program management and boosted genetic gain in forest tree species.

   Molecular marker data are widely used to reconstruct pedigrees of Eucalyptus breeding populations in which behaviour data are difficult to obtain. It is understood that those genomic resources and tools that are available to reconstruct pedigrees from mixed populations of Eucalyptus plantations could be easily adapted to radiata pine.

   It is proposed that FWPA support research that would facilitate the conversion of genomic tools used for pedigree reconstitution of open pollinated Eucalyptus breeding material to be applicable for Radiata pine and Southern Pine breeding programs.

3.1.4 Economic Impact

The economic impact of modern tree breeding technologies within the Australian *Pinus* sp. plantation estate over the last three decades has been driven by Tree Breeding Australia (formerly Southern Tree Breeding Australia) implementing a breeding strategy that has delivered to its stakeholders genetically improved trees that have improved plantation productivity and forest product quality.

In relation to *Pinus* sp. results from 2017 estimated that the rate of genetic improvement delivered by TBA since 2002 had been improving at an annual rate of $39 NPV per hectare (8% Discount Rate)[48].

[48] Dr. T. McRae (2019) Tree Breeding Australia. Pers comm.

An increased rate of genetic improvement in breeding programs from using combined molecular and phenotypic information when deployed into a genome wide selection breeding strategy will further increase the internal rate of return on investing in tree breeding.

The proposed project deliverable of a standard high density SNP V2 assay that is tailored for the Australian and potentially the New Zealand Radiata pine population has the potential to accelerate the annual rate of genetic gain when deployed in the respective TBA and RPBC *Pinus* sp. genome wide selection breeding programs primarily by i) shortening the generation interval / breeding cycle, and ii) increasing the accuracy of predicted breeding values applied to commercially important harvest age traits for the purpose of selecting 'elite' lines for deployment seed nurseries and future plantations.

To demonstrate the economic impact of shortening the generation interval and increasing the accuracy of predicted breeding values the authors commissioned independent economic modelling to be undertaken by Dr. John Moore (SCION). The scenarios which were modelled to demonstrate the economic impact of developing and deploying a SNP V2 assay for the Radiata pine plantation industry were as follows:

1) Deployment of the SNP V2 assay into a genome wide breeding platform:

- Establishment of a Radiata pine plantation that generates a 10% harvested yield improvement at 30 years.
- Establishment of a Radiata pine plantation that generates the equivalent harvest yield at twenty-eight years of age as that of a 30-year harvest yield (I.e. accelerated growth).
- Establishment of a Radiata pine plantation with a combination of a shortened rotation cycle (-2 years) and increased yield (+10%).

2) Deployment of the SNP V2 assay into an accelerated breeding program strategy based on a genome wide selection platform:

- Establishment of a Radiata pine plantation based on a genome wide selection platform that results in a shortened generation interval/cycle from 17 years to 10 years (Including a 2-year initial allocation for setting up a genome wide selection platform).
- Establishment of a Radiata pine plantation based on a genome wide selection platform that results in a shortened generation interval/cycle which generates a 10% harvested yield improvement at 30 years.
- Establishment of a Radiata pine plantation based on a genome wide selection platform that results in a shortened generation interval/cycle which generates the equivalent harvest yield at twenty-eight years of age as that of a 30-year harvest yield (i.e. accelerated growth).

- Establishment of a Radiata pine plantation based on a genome wide selection platform that results in a shortened generation interval/cycle and combines a shortened rotation cycle (-2 years) and increased yield (+10%).

3.1.4.1 Economic Analysis

__Scenario One:__ ***Deployment of the SNP V2 assay into a genome wide breeding platform***

Under Scenario One the base case for comparison is maintain the current 17 year breeding cycle which it is estimated will generate based on a 6% discount rate a Net Present Value (NPV) at harvest equivalent to $6,719.09 /ha and $156.77m when applied to an annual estimated harvest of 23,333ha with an 11.13% Internal rate of Return (IRR). At an 8% Discount rate the base case generates an NPV of $2,849.68/ha and $66.49m on an annual harvest basis (**Table 3**).

Table 3. Economic benefits (NPV $ and IRR %) associated with an investment in the development and implementation of genomic tools to radiata pine breeding.

Discount Rate = 6%	Rotation Harvest Value NPV ($/ha)	Incremental NPV ($/ha)		Estate Harvest Value NPV $m (23,333ha)	Incremental NPV $m (23,333 ha)	IRR (%)
Scenario 1: SNP V2 Assay + Genome Wide Selection						
Base Case 17 Year Breeding Cycle	$6,719.09			$156.78		11.13%
+ 10% Yield	$7,795.45	$1,076.36		$181.89	$25.11	11.59%
- 2 Year Rotation	$7,646.81	$927.72		$178.42	$21.65	11.53%
Combination (+ 10% yield + - 2 Year Rotation)	$8,770.04	$2,050.95		$204.63	$47.85	11.93%
Scenario 2: SNP V2 Assay + Accelerated Breeding + Genome Wide Selection						
Base Case (10 Year GWS Breeding Cycle)	$6,894.02	$174.93		$160.86	$4.08	11.47%
+ 10% Yield	$7,970.38	$1,251.29		$185.97	$29.20	11.93%
- 2 Year Rotation	$7,821.74	$1,102.65		$182.50	$25.73	11.87%
Combination (+ 10% yield + - 2 Year Rotation)	$8,944.97	$2,225.88		$208.71	$51.94	12.27%
Discount Rate = 8%	**Rotation Harvest Value NPV ($/ha)**	**Incremental NPV ($/ha)**		**Estate Harvest Value NPV $m (23,333ha)**	**Incremental NPV $m (23,333 ha)**	**IRR (%)**
Scenario 1: SNP V2 Assay + Genome Wide Selection						
Base Case 17 Year Breeding Cycle	$2,849.68			$66.49		11.13%
+ 10% Yield	$3,464.04	$614.36		$80.83	$14.33	11.59%
- 2 Year Rotation	$3,379.20	$529.52		$78.85	$12.36	11.53%
Combination (+ 10% yield + - 2 Year Rotation)	$4,011.43	$1,161.75		$93.60	$27.11	11.93%
Scenario 2: SNP V2 Assay + Accelerated Breeding + Genome Wide Selection						
Base Case (10 Year GWS Breeding Cycle)	$3,024.61	$174.93		$70.57	$4.08	11.47%
+ 10% Yield	$3,638.97	$789.29		$84.91	$18.42	11.93%
- 2 Year Rotation	$3,554.13	$704.45		$82.93	$16.44	11.87%
Combination (+ 10% yield + - 2 Year Rotation)	$4,186.36	$1,336.68		$97.68	$31.19	12.27%

It is projected that with the introduction of a SNP V2 assay that enables breeders to more accurately select for parent material that generate a +10% improvement in yield in a 30 year rotation at harvest the NPV ($/ha) at a 6% discount rate would increase by $1,076.36/ha, which would generate an incremental $25.11m across the estate at harvest, resulting in an IRR of 11.59%.

Where breeders, in response to climate change, choose to select for a faster growing parent material that can be harvested 2 years earlier (i.e. 28 years vs 30 years) while maintaining current yield, the NPV at a 6% discount rate increases by $927.72/ha generating an incremental $21.65m across the estate at harvest with an IRR of 11.53%.

Where the SNP V2 assay is used within the genome wide selection program to select for 'elite' material with both faster growing and yield improvement traits the combined incremental NPV at a 6% discount rate generates an incremental NPV $2,050.95/ha and an additional $47.85m/ha across the estate at harvest with an IRR of 11.93%.

<u>Scenario Two:</u> Deployment of the SNP V2 assay into an accelerated breeding program strategy based on a genome wide selection platform

As noted by Grattapaglia (2018)[49] and Li and Dungey (2018)[50], apart from increasing the level of accuracy in selecting for key traits of interest through the introduction of the V2 SNP assay, a key benefit of introducing of genome wide selection program is the potential to reduce the breeding cycle by nearly half (i.e. from 17 years to 10 years). From an economic perspective this accelerates the introduction and establishment of plantations with 'elite' material. An additional benefit of the accelerated breeding program is the lower cost of generating 'elite' parent material due to the expenditure savings generated from the projected reduction (i.e. 7 years) in the breeding cycle. This saving will be reflected in a potential reduction in the cost of planting material (i.e. stems) due to the shorter breeding cycle.

In the base case scenario of reducing the breeding cycle from 17 years to 10 years the incremental NPV at a 6% discount is increased by $174.93/ha and an additional $4.08m across the estate at harvest with an IRR of 11.47%.

However, when the benefit of the accelerated breeding cycle is combined with a 10% increase in yield, at a 6$ discount rate the additional NPV generated is $1,251.29/ha which generates an additional $29.20m across the estate at harvest with an IRR of 11.93%.

Similarly, when the benefit of the accelerated breeding cycle is combined with a 2-year reduction in the crop rotation, while maintaining the same yield as at 30 years, the additional NPV generated is $1,102.65/ha and an additional $25.73m across the estate at harvest with an IRR of 11.87%.

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[49] Grattapaglia D, Silva-Junior OB, Resende RT, Cappa EP, Müller BSF, Tan B, Isik F, Ratcliffe B, El-Kassaby YA. Quantitative Genetics and Genomics Converge to Accelerate Forest Tree Breeding. *Front Plant Sci*. 2018 Nov 22;9:1693. doi: 10.3389/fpls.2018.01693. PubMed PMID: 30524463; PubMed Central PMCID: PMC6262028
[50] Li Y, Dungey HS (2018) Expected benefit of genomic selection over forward selection in conifer breeding and deployment. PLoS ONE 13(12): e0208232. https://doi.org/10.1371/journal.pone.0208232

When all breeding improvements are combined (i.e. accelerated breeding cycle, +10% yield, -2-year rotation) at a discount rate of 6% the incremental NPV generated equates to $2,225.88/ha and an additional $51.94m across the estate at harvest with an IRR of 12.27%.

Contingent on the Radiata pine plantation industry capturing the value of advances in tree breeding and genetic improvement, such as the proposed SNP V2 assay, will be its ability to deploy and fully integrate genomic based platforms such as genetic markers and genome wide selection into breeding strategies and deployment operations. Underpinning this will be:

1. The need for current and future stakeholders such as breeders, seed orchard managers and estate mangers as well as millers to be trained and be provided with advisory services which will ensure they capture maximum value from the deployment of these modern breeding innovations; and
2. The need for consistent sustainable investment by plantation owners and third-party investors into supporting the continued development and adoption of modern breeding technologies, including building tree breeding and genetic improvement capability and capacity within the industry.

3.2 Opportunity 2: Enhance public and private sector investment in the capability and capacity required to support the adoption and use of modern breeding technologies across the plantation industry value chain for improvement in productivity and profitability.

3.2.1 Background

Modern breeding technologies such as genomics, phenomics and bioinformatics and their application through the use of molecular markers, marker arrays and Genome Wide Selection (GWS; Genomic Selection or GS) will become increasingly important methods in future *Pinus radiata*, Southern Pines and *Eucalyptus sp.* plantation tree breeding and genetic improvement. In combination with the increased throughput and decreased cost of genome-wide Single Nucleotide Polymorphism (SNP) genotyping and the improved accuracy and power of statistical methods, these modern breeding technologies represent the future of tree breeding and genetic improvement within the plantation industry.

Plantation industry participants attending the recently held softwood and hardwood workshops, together with individual interviews and response to an industry survey which formed the platform for the research that supports the current project, identified a range of barriers which have the potential to impact on the advancement of tree breeding and genetic improvement in *Pinus radiata,* Southern Pines and *Eucalyptus sp.* plantations in Australia.

These barriers essentially related to non-research areas of concern and can be regarded as being the external enabling platforms which are required to support the short, medium and long-term viability of tree breeding and genetic improvement for the plantation industry in Australia.

3.2.1 Investment Theme - Leadership

A view held by a number of leading researchers and value chain participants is the plantation forest industry is at a disadvantage to the majority of resource based industries in Australia due to the absence of a lead government agency (i.e. Federal, State and/or Territory) that represents the forestry industry within the National R, D & E Strategy. This is despite the forest industry, via FWPA, having released in 2010 a **RD&E strategy for the forest and wood products sector**[51] that was based on the National Primary Industries R, D & E Framework developed under the Primary Industries Ministerial Council.

The release of the **R, D & E strategy for the forest and wood products sector** initiated a process of strategy development designed to ensure that investment in R, D & E met the future needs of the forest and wood products sector and the Australian public.

[51] Anon. (2010) R, D & E strategy for the forest and wood products sector. FWPA. www.fwpa.com.au

3.2.2 Recommendation

- ✓ *In the absence of a current state government lead agency for the plantation forestry research within the National R, D & E Strategy it is proposed that FWPA engage with a government agency such as the Department of Jobs, Precincts and Regions, Agriculture Victoria for the purpose of nominating the state as the lead agency for coordinating Federal, State and Territory government investment into capacity and capability that supports the plantation industry in Australia.*

3.2.3 Investment Theme – Industry investment in Tree breeding and genetic improvement research

There is a perception that investors within and external to the industry have a poor understanding of the value that tree breeding and genetic improvement generates both currently and into the future. As a consequence, this is impacting on the level of investment in the capability, capacity and infrastructure required to generate value that can be achieved through tree breeding and genetic improvement. This has become more critical due to the declining investment by the Federal, State and Territory governments in forest related capability, capacity and infrastructure.

There are multiple reasons that contribute to this strategic issue for the industry:

- The industry does a poor job in promoting the value proposition for breeding and the corresponding returns on investment that can be achieved through such an investment to value chain participants, governments and the general public. Hence, research dollars are only sufficient to support trials in the near term and not enough to support long-term strategic investment in research capability.
- The industry has a fragmented approach to funding for public sector research relying on government grants such as the Australian Research Council along with funding for CRC's and the FWPA to support tree breeding and genetic improvement research – all of which are in decline.
- The forestry industry lacks vertical integration, compared to many international competitors. As such, it is perceived difficult to capture the value of genomics and innovative plant breeding. This has the effect of limiting industry investment with a reliance on the public sector to fund Research and development.
- The lack of an effective long-term (i.e. versus short-term) government policy and strategy for the plantation industry together with the loss of investment from federal, state and territory government along with the asynchrony of political cycles to that of forestry cycles is leading to under resourcing and loss of strategic infrastructure investment for the industry.

3.2.4 Recommendation

- ✓ *It is proposed that FWPA coordinate a communication strategy aimed at promoting to value chain participants (e.g. Seed nursery and Estate Managers, Commercial Growers, Millers etc.) along with government agencies and the investment community as to the long term economic value (e.g. ROI) of investing in tree breeding and genetic improvement breeding programs.*

3.2.5 Investment Theme - Communication

A feature of the Australian plantation industry when compared to industries in South – East Asia, Scandinavia and North America is the lack of vertical integration from breeding through to milling and marketing. The growers of trees are generally different organisations from those that process logs. The returns to the grower are based primarily on volume, reducing the incentive to improve or consider wood quality. The log processors gain a return for both the volume and quality of their product, and wood quality impacts significantly on the dollar return.

As a result, industry stakeholders associated with tree breeding and genetic improvement perceive there is a lack of connectivity and alignment along the value chain in terms of the delivery and adoption of technologies and strategies that can enhance plantation production and value.

The lack of connectivity is in part due to the traditional industry view of the 'value/supply chain' which is viewed as commencing with commercial forestry production, as distinct from including pre-plantation establishment activities such as tree breeding as being part of the industries value/supply chain. This is exemplified in the follow quote from a 2014 industry report[52].

> "*The Australian forest (Plantation) industry value chain is complex with many levels of interaction. The value chain starts with the commercial forestry segment. This segment grows and manages the forests that supply the log resources. These logs are processed into a wide array of products for domestic and export use…….*" For the purpose of the report five broad segments have been demarcated within the value chain:
>
> 1. Commercial forestry.
> 2. Paper and packaging.
> 3. Construction materials.
> 4. Energy and biochemical.
> 5. (Distribution) end use markets.

This view of where the value/supply chain starts within the forest plantation industry is somewhat antiquated when compared to many other plant-based industries such as grains

[52] Anon, Megatrends in the Forests and Wood Products Sector. (2016) Ernst & Young report prepared for FWPA.

and horticulture where each industry includes research, development and extension as the starting point of the value/supply chain.

The reason for this lack of alignment according to stakeholders is the lack of appropriately skilled people to effectively engage with industry stakeholders along the value/supply chain. Especially in relation to communicating the value contribution of tree breeding and genetic improvement to the value of products generated from the plantation. The lack of effective extension and communication within and external to the plantation industry value/supply chain is resulting in the parts of the industry not being in a position to take advantage of modern breeding technologies and their outputs when deploying and establishing commercial plantations.

3.2.6 Recommendation

- ✓ *It is proposed that FWPA support the engagement of a suitably qualified and experienced person to assist industry participants in their adoption and deployment of modern breeding opportunities such as the use of advanced phenomics technologies, integration of adaptation deployment strategies based on genomic selection of traits for climate change, together with the integration of 'value added traits' from genomic selection for next generation wood based products for the bio-economy*.

3.2.7 Investment Theme – Capacity (Human Resources)

A challenge for the tree breeding and genetic improvement sector is the lack of a succession plan to train and engage both male and female graduates, PhD’s and Post Doc’s within the sector. This is a growing concern with the ageing male dominated research population within the industry.

The issue is in part due to the university sector not being as engaged with the forestry industry, especially the plantation sector. A key problem with the current limited education and training programs for forestry within universities is that the majority of new students are focused on the research fields of climate adaption, restoration, landscape - genomics which are more aligned to the native forest estate versus research fields that are associated or aligned with tree breeding and genetic improvement for the plantation industry.

As a result and due to a combination of i) the low levels of investment; ii) the cost of employment; iii) a limited pool of employers; and iv) the capacity of companies to integrate genetics skills into their programs, many students who complete Masters and/or PhD’s in research fields associated with tree breeding and genetic improvement are switching to alternate areas of interest where there are more likely to be positions with commensurate salaries available (e.g. crops, animals, human research) or alternatively they may move overseas and obtain positions in tree breeding and genetic improvement programs in competitor public and/or private sector programs.

3.2.8 Recommendation

- ✓ *On behalf of the plantation industry it is proposed that FWPA establish fully funded post graduate (2) and post - doc (2) positions within Australian public sector research institutions with a focus on undertaking research in fields that are associated or aligned with tree breeding and genetic improvement for the plantation industry.*

3.2.9 Investment Theme – Capability

National cooperative tree improvement programs have been established for *Pinus* sp. and *Eucalyptus* sp. These have resulted from the amalgamation of genetic resources and activities of various private, state and federal government breeding programs over time.

Tree Breeding Australia (formerly Southern Tree Breeding Australia) with support from the SA and Federal Governments (FWPA) purchased 28 ha land in 2005 at Mount Gambier for the purposes of consolidating breeding operations, introducing efficiencies with rolling front strategies, increasing the rate of gain and, minimising any risk against catastrophic loss of these strategic biological assets.

Breeding activities have been building each year as new genotypes are selected from the network of field trials spread across the softwood and hardwood estates and established in the arboreta. The consolidation of breeding resources largely on one location has delivered efficiencies but has also increased workloads as expected with progressive national programs. Genetic material is also archived on other sites to mitigate risk against catastrophic loss. The existing on-site demountable laboratory, established as a temporary facility, is no longer adequate to service the technical and safety requirements of the operational programs.

The scale of field operations has increased to the extent that existing infrastructure is no longer adequate to service the programs effectively and meet modern workplace health and safety requirements.

3.2.10 Recommendation

- ✓ *To ensure that the national cooperative tree improvement programs continues to deliver the accelerated generation and delivery of improved plantation productivity and forest product quality it is recommended that FWPA co-contribute together with TBA, local, state and Federal government agencies to the replacement of the current field-based infrastructure at Mt. Gambier.*

3.2.11 Investment Theme – Collaboration

Industry participants identified a range of issues relating to the topic of capability within the tree breeding and genetic improvement sector, these included:

- It is difficult for tree breeders to respond to market cycles as there is a value chain disconnect primarily due to the lack of vertical integration, resulting in a disconnect in the timely delivery of price signals related to product traits that the breeder can improve in the final product. This is further exaggerated by the constant changes in management and volatility of investment which often leads to removal of resources or lack of investment in resources (including people) especially related to forest products. This situation has led to where values are not aligned and the establishment of conflicting objectives.

- The loss of federal and state government investment both in terms of funding and support of institutions such as various CRC's and CSIRO to maintain their capabilities in a range of forest related research fields has had a significant impact on the industry. An example of the loss or absence of capability is in the fields of clonal propagation and hybrids – both research fields representing significant opportunities for the industry to make meaningful advancements in tree breeding and genetic improvement.
- A key challenge for researchers is that the tools that are being applied to tree breeding and genetic improvement in New Zealand are different to that being applied in Australia. This is potentially limiting the level of collaboration and transfer of information. This is being further complicated with the lack of ability to transfer material between Australia and New Zealand due to quarantine constraints on both sides of the Tasman.
- Within the softwood industry, participants identified that the key opportunity for advancement in tree breeding and genetic improvement was for greater collaboration and sharing of information (and germplasm) between Australia and New Zealand. It was highlighted by workshop participants that there was scope for increased collaboration in research between Tree Breeding Australia, Radiata Pine Breeding Company (RPBC) in softwood tree breeding and genetic improvement.

  It was recognised that within each of these organisations the key technology capabilities, people capacity and resources required to support accelerated advancements in tree breeding and genetic improvement were present and with appropriate commitment could be collectively applied to the advancement of softwoods in both countries.

  Industry participants suggested that the initial step in achieving the level of collaboration aspired too was to ensure there is alignment with their respective counter parts breeding goals and breeding strategy[53]. Recognising that there may be some areas which will be different, however as along as each party was aware of these then the proposed collaborations could proceed where there was common interest.

Examples proposed by workshop participants as to where greater collaboration between TBA and RPBC, together with opportunities to engage with the New Zealand Radiata pine plantation industry included:

[53]Dungey, H. & Brawner, J.T. & Burger, F & Carson, Michael & Henson, M & Jefferson, Paul & Matheson, A.C.. (2009). A New Breeding Strategy for Pinus radiata in New Zealand and New South Wales. Silvae Genetica. 58. 28-38. 10.1515/sg-2009-0004.

- The development and generation of a SNP assay (V2) for Radiata pine and its deployment in the respective TBA and RPBC breeding programs.
- The application of modern breeding technologies including genomics (incl. Genomic selection), phenomics, bioinformatics and molecular marker
- Sharing of IT Systems and information
- Germplasm exchange and evaluation
- People sharing / exchange - graduates, post graduates, PhD's and Post Doc's being engaged in activities such as Internships, Summer students, work experience and guest lecturers
- Attracting collaborative research projects from domestic and international organisations and governments. In particular, collaborations with international organisations in South Africa, Brazil and Scandinavia
- Leverage research investment from respective industries and governments with a focus on attracting 'block funding' for i) operational breeding and research; and ii) training and retention of the 'next generation' of softwood tree breeders and specialists in modern breeding technologies.

3.2.12 Recommendations

- ✓ *TBA, RPBC and HQP further evaluate opportunities to collaborate in the field of tree breeding and genetic improvement with an initial opportunity being co-investment to the generation of SNP assay V2 for Radiata Pine.*
- ✓ *To address industry wide issues related to declining capability within the sector and to facilitate closer research collaborations between Australia and New Zealand it is proposed that FWPA contribute funding to support the activities of Tree Breeding Australia's Technical Advisory Committee. The Technical Advisory Committee is made up of industry representatives, technicians, breeders and research scientists from the public and private sectors in Australia and New Zealand.*

3.2.13 Economic Impact

Details of the potential economic impacts of enhancing public and private sector investment in the capability and capacity required to support the adoption and use of modern breeding technologies across the plantation industry value chain for improvement in productivity and profitability are outlined in Section 3.1.4.

3.3 Opportunity 3: Breeding Plantation *Pinus* sp. and *Eucalypt* sp. for Climate Change

3.3.1 Background

Recent decades have seen an increase globally in the incidence and severity of droughts, catastrophic fires, heatwaves and intense storms, as well as a trend towards warmer mean temperatures and reduced precipitation over much of the temperate plantation estate. These changes may have dramatic effects on the productivity of the plantation estate in both the short and longer term. Such changes in climate also affect pest distribution and abundance, and fire hazard. The consequence of these hazards is that the plantation estate has been classed as vulnerable in the face of future climate projections[54].

Adaptation has become an issue of concern during the last decade due to impending climate change[55]. Climate change could noticeably impact growing conditions of new and existing temperate and sub-tropical forest trees, affecting the length of time to maturity and stand losses due to spring and autumn frosts, droughts and new pests and diseases[56] [57] [58] [59]. On the other hand, the phenomenon of global warming could also increase the production per area unit[60].

Changes in growth and vitality caused by climate change will have a significant economic effect on boreal forestry, and thereby, a potentially profound impact on communities. To prepare for climate change, genetic material must be adapted to a wide range of environments, characterised by conditions different from those of today[61]. Hence, we must ensure that the currently developed genetic material can also produce healthy forests that have high values of biomass and produce high-quality wood into the future. Forestry with long rotation species need strategies for genetic diversity to make it possible for selection to occur in areas where climate change is expected to have its strongest impact[62]. In essence, there is

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[54] AGO, 2005. Climate change risk and vulnerability. In: Office, A.G. (Ed.). Allen Consulting Group for the Department of the Environment and Heritage, Canberra, p. 159.

[55] Jansson,G. Hansen,J. Haapanen,M. Steffenrem, K & A (2017) The genetic and economic gains from forest tree breeding programmes in Scandinavia and Finland, Scandinavian Journal of Forest Research, 32:4, 273-286, DOI: 10.1080/02827581.2016.1242770

[56] Jönsson AM, Bärring L. 2011. Ensemble analysis of frost damage on vegetation caused by spring backlashes in a warmer Europe. Nat Hazards Earth Syst Sci. 11:401–418.

[57] Dale VH, JoyceLA, McNultyS, NeilsonRP, AyresMP, FlanniganMD, Hanson PJ, Irland LC, Lugo AE, Peterson CJ, et al. 2001. Climate change and forest disturbances. BioScience. 51:723–734.

[58] Woods A.2011.IsthehealthofBritishColumbia's forests being influenced by climate change? If so, was this predictable? Can J Plant Path.33:117– 126.

[59] Jönsson AM, Harding S, Krokene P, Lange H, Lindelöw Å, Økland B. Ravn H, Schroeder L. 2011. Modelling the potential impact of global warming on Ips typographus voltinism and reproductive diapause. Climate Change. 109:695–718.

[60] Bergh J, Nilsson U, Kjartansson B, Karlsson M. 2010. Impact of climate change on the productivity of Silver birch, Norway spruce and Scots pine stands in Sweden with economic implications for timber production. Ecol Bull. 53:185–195.

[61] KSLA. 2006. Klimatet och skogen - The climate and the forest – Foundation for a national research program. KSLAT. 9:1–44. ISSN 0023-5350. (Swedish).

[62] Fady B, CottrellJ, AckzellL, Alía R, MuysB, Prada A, González-Martínez, SC. 2016. Forests and global change: what can genetics contribute to the major forest management and policy challenges of the twenty-first century? Reg Environ Change. 16:927–939.

a need for forest genetics that can grow and remain productive across the expected volatility and variability in climate.

3.3.2 The future impact of climate change within the context of Australia's forestry plantations

In the seminal report prepared by Pinkard et al., (2014) for the FWPA and the Federal Government the authors built on previous foundation climate change related research by Battaglia et al (1996, 1998a, 1998b, 2000, 2004a, 2004b, 2009a, 2009b, 2011a, 2011b) to develop a range of tools for assessing the risks and impacts of climatic variability, on productivity and wood properties, and for making decisions about cost-effective management options to moderate the effects of climatic variability and change.

The summary from each of the reports chapters provides a detailed insight into the challenge the forest plantation industry faces in terms of long-term sustainability. These are presented in detail so as to illustrate the future contribution and importance of tree breeding and genetic improvement in addressing climate change.

a) Recent past and projected future climatic trends

- Over the past 40 years many parts of Australia have experienced an increase in mean annual temperature compared with the preceding 50 years. There has been an increase in the number of days with maximum temperatures more than 35 ˚C; and a decline in mean annual rainfall. These warming and drying trends have been observed throughout the main plantation-growing regions, located primarily in southern, south western and eastern Australia. Unprecedented increases in intensity of extreme events such as heatwaves and droughts also have been observed.
- Annual rainfall is projected to decrease across most of south eastern Australia with smaller changes in south west Western Australia, although projections vary with the climate model used. A general warming of the climate is projected, although as with rainfall the intensity and pattern of change varies with the climate model used.
- Only small changes in relative humidity are forecast by models, with the reduction strongest in inland areas and Victoria, south-east of Melbourne. There may be a small increase in relative humidity in northern NSW, and a decrease in Tasmania. A small decrease in wind speed is predicted by models, particularly in south west Western Australia but also across Victoria and NSW. There may be a small increase in wind speed in Tasmania.

b) Direct effects of climate change on future *E. globulus* and *P. radiata* plantation productivity

- Some regions of the Radiata pine and blue gum estates may show decreased productivity in 2030 compared to now. Other regions may show increased productivity however the response will be strongly determined by local conditions of soil depth and fertility.

- Model predictions are highly sensitive to the responsiveness of plantation species to eCO2. If forests are not responsive to eCO2 and sustained photosynthetic rate increases are not observed, 5-15% or higher decreases in productivity may be seen in the Green Triangle, Gippsland and south-west Western Australia may be seen for both blue gum and radiata pine. These are currently some of the most productive plantation areas. If plantations respond favourably to eCO2, then productivity is predicted to increase in most regions except at the drier margins of the plantation estate where increased mortality will reduce expected production.
- Cold wet sites (for example plantations in the highlands of Victoria) where nutrients are limited may see an additional growth response due to increased nitrogen mineralisation under warmer temperatures. This benefit is not predicted for drier environments where water is the main resource limiting to growth.
- The report predicts a general decrease in survival in warm dry regions if the response to eCO2 is limited. In cold environments, survival generally improves in response to warmer temperatures.
- Those sites currently in the well performing core of the plantation estate may be slightly affected in production (up or down) by climate change, but our modelling shows little change by 2030 or even 2050. However, areas at the dry margins of the estate are vulnerable and in the worst instances look highly likely to fail.

c) Climate impacts on wood properties: an overview

- Within a tree, wood properties vary radially and longitudinally. Sampling protocols can determine the variation patterns reported. Predicting variability is best achieved through process-based models that capture the logic and nature of interactions between environment and physiology.
- Environmental changes over seasons and rotations affect patterns and rates of growth. Patterns of growth affect average wood properties as wood properties vary seasonally.
- Temperature generally tends to increase wood density, but opposite trends have been observed.
- The effects of water availability on wood properties are largely mediated through changes in growth phenology. In general, increased water availability reduces wood density, via increased growth rates and the production of larger diameter cells with thinner walls.
- Direct effects of elevated CO2 on wood density are small but tend to increase cell wall thickness and hence density increases. Effects of elevated CO2 are small relative to effects of temperature and water availability.

d) Case study: modelling the effects of varied temperature and rainfall on wood density and stand volume of *Pinus radiata*

- The process-based model eCambium predicted that under varied temperature and rainfall conditions, in some stands of *Pinus radiata* there may be gains in both wood density and stand volumes. In general, however, gains in stand volume will probably be accompanied by a reduction in wood density.
- On the other hand, the reductions in stand volume more likely in hotter, drier conditions will probably be accompanied by increases in wood density. But whether or not any potential improvements in wood quality would be sufficient to compensate for overall stand volume losses, will require further, detailed economic analysis.
- Trees grown under much lower rainfall conditions predicted to result in higher density wood, were not predicted to have the reject quality boards in the juvenile core that were predicted under the higher rainfall (and higher temperature) conditions that produced much lower density wood. The larger trees in the latter cases, however, were predicted to produce 6 more boards per tree, all of high stiffness, which may make up for any product losses in the juvenile core.
- Exploratory comparison of blue gum and radiata pine found similar patterns of change in wood density with changing temperature/rainfall, and overall wood density was predicted to decrease with increasing rainfall in both species.

e) Indirect effects of climate change on future *E. globulus* and *P. radiata* plantation productivity

1. Fire Hazard

- Fire weather was predicted to worsen over the entire study area when measured as both annual sum of fire danger index and number of days with fire weather likely to be associated with damaging and difficult to control fires. The largest changes were predicted for inland areas with smaller changes for Tasmania, coastal areas of SA, WA, and VIC and northern NSW.
- Fuel loads increased in almost all locations in response to changes in photosynthesis and water use efficiency predicted by the forest growth model. Increases were smaller in the drier climate scenario and regional changes in litter load were correlated with local changes in rainfall.
- The number of fire damage days, calculated as days with fire intensity above 4000 kW/m, was higher than the number fire weather days because for most of the country fuel loads were quite high. For a fuel load of 22.8 t/ha, the national average, fire damage days occur for FFDI above 12, much lower than the cut-off of 25 used to calculate fire weather days. This means that for stands with high litter loads, damaging fires may occur under even moderate conditions.

- There was significant regional variation in fire danger and damage estimates which has implications for management of fire in plantations. Inland areas which currently have the greatest exposure to fire risk are also likely to experience the greatest increases in fire risk on all three measures examined here.
- The areas experiencing the largest changes are inland areas of Victoria and the northern end of the plantation area in Western Australia. For these areas, management of fuels or silvicultural treatments to reduce fire intensity may be suitable management options to reduce risk of damage.

2. Pest Hazard

- Of 20 key pest species of eucalypt and pine plantations in Australia identified in the study, 15 were defoliators. Leaf chewers, sap suckers and foliar pathogens were all represented. They have a range of modes of action, targeting plantations of different ages, and imparting different patterns of damage in different seasons.
- Current distribution, drivers of host susceptibility and anticipated responses to climate change are summarised in detail for each of the 20 identified pests.
- Warmer temperatures may have a positive effect on the distribution and abundance of leaf chewers and sapsuckers, through increased overwintering survival, increased developmental rates and an extended host growing season. Declining rainfall may have a negative effect on species requiring high relative humidity, such as foliar pathogens.
- Stressed host trees may become more susceptible to stem borers and some sap-sucking insects. Drought stress in particular may result in increased damage from stem borers.
- Modelling analysis of climatic suitability for seven pest species suggested that only small changes are likely in the distribution of key plantation species between now and 2030 or 2050. Abundance of some pests may increase, suggesting more frequent or intense pest outbreaks in some areas.

3.3.3 Plantation forestry responses to climate change

Hallegatte (2009)[63] suggests five possible strategies that may be beneficial when dealing with longer time-frames. They aim to improve the robustness of decision-making when faced with uncertainty.

1. The first is to implement 'no regret' strategies, which yield benefits even in the absence of climate change. Examples of this might be the development of genotypes more

[63] Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Global Environmental Change 19, 240 - 247.

resistant to warmer and drier conditions, or diversifying products such that there is the flexibility to change the rotation length depending on climatic conditions, such as plantations for bio-sequestration. Another example is the shift to lower stocking in Western Australian hardwood plantations described earlier which has little or no impact on yield in average years, decreases harvesting cost (less stems) and greatly reduces drought mortality risk.

2. The second is to implement reversible strategies that aim to limit the cost of making the wrong management decision. For example, a decision could be made not to establish plantations in an area considered to be at high risk of severe drought. If climate change is less extreme than projected, then the decision can be reversed.
3. The third is to add safety margins into management strategies, which reduce vulnerability, and can help deal with uncertainty. For example, in areas where drought is projected to be an increasing problem, making the decision to establish all plantations at a low stocking, or to routinely practice pre-commercial thinning, could be implemented. Another example might be the extension of rotation lengths, which can potentially decrease the proportion of the rotation when plantations are most vulnerable and drought most impacts on yield and has little negative effect on production (Battaglia et al 2009)[64].
4. The fourth is to reduce decision time-frames, so that there is more certainty around climatic conditions during that timeframe. For instance, species or products needing a shorter rotation length could be selected for high risk areas. So instead of looking to produce sawlogs from longer rotation hardwood plantations with big logs for example, a decision might be made to supply small logs for engineered wood products.
5. The final approach advocated by Hallegatte (2009) is labelled ‘soft strategies’, which recognise that in some cases institutional or financial tools can contribute to climate change adaptation. Developing a legislative framework for groundwater allocation in dry environments with appropriate community engagement, so that there is certainty around future water allocation to the forestry sector, is an example of such a strategy.

Of these five options, tree breeding and genetic improvement can contribute to significantly abating the impact of climate change on future Australia plantation forest estates.

3.3.4 Investment Theme - Development of Plantation Eucalyptus sp. and Pinus sp. genotypes for climate change

Agricultural industries are focusing on genomic and phenomic innovations to rapidly advance breeding programs to ensure sustainable production through the volatility and variability predicted under climate change. Importantly, whole genome sequence information provides

[64] Battaglia, M., Bruce, J., Brack, C.L., Baker, T., 2009a. Climate change and Australia's plantation estate: analysis of vulnerability and preliminary investigation of adaptation options. CSIRO, Hobart, Australia, p. 128.

an important platform for building further genomic and genetic experimentation including genetic and QTL (quantitative trait loci) map development, genetic association, genomic selection, and further whole genome sequencing of elite material. Collectively, this provides breeders the information required for elucidating the genetic basis of complex traits and the ability to tailor selections which take into account the potential impacts of climate change.

The announcement of the first draft assembly of the radiata pine genome by SCION scientists in 2017[65] has set the stage for characterisation of the vast genomic, metabolomic and phenomic diversity within *Pinus radiata*. This complimented the release by Rigault et al. (2012)[66] of a reference genome sequence and gene catalogue for *Eucalyptus globulus* which is a target for tree improvement in a number of countries. However, in both cases there is more genomic and bioinformatics information is required and in the case of *Pinus radiata,* the draft assembly requires more information and annotation to have a complete genome assembly that can be used as a reference.

The opportunity exists for the Australian and New Zealand research communities to combine their modern breeding technology capabilities and capacity that exists within TBA and Radiata RPBC to undertake a comprehensive collaborative research program aimed at characterising the vast genomic, metabolomic, and phenomic diversity that exists within *Pinus radiata*, Southern Pines, *Eucalyptus globulus* and *Eucalyptus nitens* within the context of achieving genetic improvement while breeding for climate adaptation.

There is an opportunity to link current datasets and tools that exists within TBA and RPBC to assess and identify candidates from various provenances that could have value in current and future breeding programs for Australia and New Zealand. Further, there exists a substantial phenotypic data set (including site and environmental characterisation) for existing forests within TBA and RPBC that could be readily assessed by genomic tools which can be accessed in research capabilities such as SCION, AgriBio, CSIRO and Gondwana Genomics.

In addition, increasingly processors and millers are collecting vast data sets that coupled with genomic assessment would offer substantial value in generating refined breeding values for current key productivity and quality traits as well as non-key traits such as internal checking (INC), external resin bleeding (ERB) and number of heartwood rings (NHR)[67].

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[65] Anon. (2019) www.SCIONresearch.com/about-us/news-and-events/news/2017/radiata-pine-genome-draft-assembly-completed

[66] Rigault, P et al. (2012). Generation of a Eucalyptus globulus Reference Genome and Gene Catalogue. Conference Presentation. Conference: Plant and Animal Genome XX. San Diego, USA. Volume: XX Forest Trees

[67] Li Y, Dungey H, Yanchuk A, Apiolaza LA (2017) Improvement of non-key traits in radiata pine breeding programme when long-term economic importance is uncertain. PLoS ONE 12(5): e0177806. https://doi.org/10.1371/journal.pone.0177806

3.3.5 Recommendation

✓ *It is proposed that FWPA support additional 'big picture' collaborative projects between TBA and RPBC. The proposed research would include the following streams of research:*

1. *Characterising diversity within ecologically and economically important softwoods and hardwoods – having a lens on the national breeding program and natural provenance genetic resources – Such a program would utilise and compliment the genomic tools developed through Opportunity 1. This program would specifically identify important germplasm that would assist in the breeding of elite material suited to climate variability including new and untested plantation sites.*
2. *Assist with the genomic assessment (genotyping) of existing populations that have extensive phenotypic data (including site and environmental characterisation). Where applicable, integrate processing information to add to the phenotypic dataset. Target genomic assessment of 100,000 trees. Collectively this information can be used to establish genetic breeding values for key productivity and quality traits as well as 'future traits' such as for abiotic and biotic stress.*
3. *It is proposed that part of the research be focused on identifying and characterising non-key traits such as internal checking (INC), external resin bleeding (ERB) and number of heartwood rings (NHR). The genotypic information along with the identification of genetic markers can then be translated into the development of breeding values which can be incorporated into the Pinus radiata and Southern Pines genome wide selection programs.*

The proposed projects would require agreement to share biomaterial and to undertake a program of work to add the required data sets – these could be long sequence reads, HiC data, MinION data, Optical mapping data etc. and hard bioinformatics skills and infrastructure.

The proposed projects will also require commitment from industry and government to provide the significant funding for the project together with a significant contribution from project participants of capability, capacity and resources so as to meet the requirements for dedicated time, effort and engagement of specialised people.

The proposed collaborative research projects between TBA and RPBC will generate a resource that links extensive germplasm collections from a diversity of environments with genomic data that will lead to a better understanding of trait adaptation and diversification. This is especially important as plantation forestry is being threatened by climate and land use change often requiring facilitated migration and adaptation of plantations in order to survive and thrive under challenging conditions.

3.3.6 Economic Impact

Impacts on plantation forestry production are experienced through several demographic and genetic processes. Some are directional and gradual, such as trends in increasing temperature and reducing rainfall, while others involve abrupt change, including drought, flood, fire and sudden pest invasions. If environmental change is directional and continuous, fast-maturing trees in particular may have the potential to adapt genetically[68].

To exemplify the economic impact of implementing the recommendations in relation to breeding for climate change, the authors have evaluated the impact of introducing a future Radiata pine and a *Eucalyptus globulus* varieties which had been selected for accelerated growth rate. The aim would be to select and progress varieties that are 'fast maturing' and which could be harvested two years (Radiata Pine) and one year (*Eucalyptus globulus*) respectively earlier than current practice, while maintaining yield and quality within a changing climate.

The Base Case scenario for the Radiata pine assumed was:

- Growth Rate: MAI 22.7 (m3/ha/y)
- Total Volume 750 (m3/ha)
- Harvest age: 33 years of age
- Three thinning's (at 12, 20, and 27 years)
- Annual area planted of 23,333 ha
- NPV Discount Rates (6% & 8%).

At a discount rate of 8% the evaluation demonstrated that by reducing the length of the rotation by two years to 31 years the marginal profit increased by 42%, generating an incremental $882 NPV per hectare. This compared to a 20% increase in marginal profit and an incremental $1,202 NPV per hectare when a 6% discount rate is applied (**Table 4**).

Table 4: Evaluation of the economic impact (NPV $/ha) in response to selecting a 'fast growing' *Pinus radiata* variety harvested two years earlier than base case. (*Source:* M. Ivkovich, Tree Breeding Australia, June 2019).

Scenario	Discount Rate (%)	MAI (m^3/ha/y)	Total VOL (m^3/ha)	CF age (y)	Marginal Profit ($NPV/ha)	Marginal Profit Change (%)	Marginal Profit Change ($NPV/Annual Area Planted)
Base Case	8.0	22.7	750	33	2,100		
Harvest age -2y	8.0	24.2	750	31	2,992	42%	**20,813,333**
Base Case	6.0	22.7	750	33	5,964		
Harvest age -2y	6.0	24.2	750	31	7,166	20%	**28,046,667**

The base case scenario for *Eucalyptus globulus* assumed:

- Total Volume: 209 m^3/ha
- Basic Density: 538 kg/m^3

[68] Alfaro R, et al (2014). The role of forest genetic resources in responding to biotic and abiotic factors in the context of anthropogenic climate change. Forest Ecology and Management, Volume 333, 2014, Pages 76-87, ISSN 0378-1127.

- Harvest age: 56% harvested at age 10, 7% at age 11, 2% at age 12, 12% at age 13 and the remaining 23% at age 15
- Annual area planted of 8750 ha
- NPV Discount Rate (8.0%).

At a discount rate of 8.0% the evaluation demonstrated that by reducing the length of the rotation by one year the marginal profit increased by 54%, generating an incremental $483 NPV per hectare (**Table 5**).

Table 5. Evaluation of the economic impact (NPV $/ha) in response to selecting a 'fast growing' *Eucalyptus globulus* variety harvested one year earlier than base case. (*Source*: D. Pilbeam, Tree Breeding Australia, June 2019)

Scenarios	Discount Rate (%)	Harvest VOL (m^3/ha)	Basic Density (kg/m3)	Wt Avg Harvest age (yr)	Marginal Profit ($NPV/ha)	Marginal Profit Change (%)	Marginal Profit Change ($NPV/Annual Area Planted)
Base Case	8.0	209	538	11.6	893		
Harvest age -1y	8.0	209	538	10.6	1,376	54%	**12,040,000**

In order to take advantage of these potential economic gains from an investment in breeding for climate change it is becoming increasingly evident that such research needs to be undertaken in current environments which reflect the future impacts of climate change. Ivkovic et al., (2015)[69] noted that climate change could threaten the realisation of genetic improvement in plantations due to suboptimal matching of improved planting stock to new climate conditions.

Based on the research undertaken the authors went onto state "that by 2050, future climates of some important plantation regions are expected to match climates currently present in different regions. For example, future climates of Green Triangle, a key plantation region in Australia, will better match current climate of Western Australia. The Central North Island of New Zealand will shift to warmer and wetter climate with no current analogue, and Western Australia, to warmer and drier no-analogue climate. The latter is also likely to fall outside the climate niche where radiata pine can be grown in the future."

This was further reflected in the 2019 EucGen Conference which devoted a number of sessions to Population and Adaptation Genetics[70]. For example, Dr. Justin Borevitz outlined

[69] Ivković, M., Hamann, A., Gapare, W.J. et al. A framework for testing radiata pine under projected climate change in Australia and New Zealand. New Forests (2016) 47: 209. https://doi.org/10.1007/s11056-015-9510-8
[70] Anon (2019) www.eucalyptgenetics2019.com.au

a precision breeding and landscape regeneration approach to identify and deploy adaptive genetic diversity in Eucalyptus sp. to restore degraded ecosystems.

3.4 Opportunity 4: Maintaining Genetic Diversity within Australia's *Pinus* sp. plantations

3.4.1 Background

The importance of plant genetic diversity is now being recognised as a specific area of research since exploding population with urbanisation and decreasing cultivable lands are the critical factors contributing to food insecurity in developing world.

Agricultural scientists have realised that plant genetic diversity can be captured and stored in the form of plant genetic resources such as gene banks and DNA libraries. However, conserved plant genetic resources must be utilised for crop and plantation forest improvement in order to meet future global challenges in relation to food and fibre security[71].

[71] Govindaraj M, Vetriventhan M, Srinivasan M. Importance of genetic diversity assessment in crop plants and its recent advances: an overview of its analytical perspectives. *Genet Res Int*. 2015; 2015:431487. doi:10.1155/2015/431487

Since plant breeding research and cultivar development are integral components of improving plantation tree production, availability of and access to diverse genetic sources will ensure that Australian plantation production remains sustainable.

Pinus radiata, is the most widely planted exotic conifer worldwide with approximately 1 million hectares in plantations in Australia[72]. The natural diversity of the species, however, is restricted to 5 discrete populations encompassing a total of about 8400 ha in western North America[73].

In Australia, *Pinus radiata* of an unknown source was introduced into the Victorian and South Australian Botanic gardens around 1860 and the first forest plantings were in the 1870's. Since the turn of the century plantations have been established on a large scale. Selections from these first-generation plantations have subsequently been cloned into seed orchards to provide genetically improved stock for reforestation and to provide material for advanced generation breeding.

In 2017–18 the softwood plantation estate was dominated by Radiata pine (74.5%) and Southern pines (15.1%), both of which are managed for sawlog production. These proportions are similar to those reported in previous years.

Most Radiata pine plantations are in the Murray Valley (New South Wales/Victoria - 24%), Green Triangle (South Australia/Victoria - 23%), Central Tablelands (New South Wales - 11%) and Tasmania (10%). The majority of Southern pine plantations are in South East Queensland (74%). Other regionally important softwood species are Maritime pine which is grown in the Western Australia NPI region and Hoop pine which is also grown in South East Queensland.

3.4.2 Investment Theme - Future proofing genetic diversity within Australia's Pinus sp. plantation industry

Underpinning current and future softwood breeding program strategies is the need to ensure that genetic diversity is preserved and where appropriate built on so as to meet future challenges such as climate change and to take advantage of future market opportunities such as producing source material for the bio-economy.

The need for genetic diversity was identified by industry participants at workshops held as background to the current project concurs with the findings of Wu et al. (2009)[74] who suggested that to ensure genetic sustainability and further increase genetic gain it would be critical to ensure the infusion of new genetic material from the range-wide collections available.

At a local level, industry participants from Australia and New Zealand believe that the quarantine restrictions placed on the movement of germplasm into Australia acts as a

[72] Downham, R & Gavran, M 2019, Australian plantation statistics 2019 update, ABARES technical report 19.2, Canberra, May. CC BY 4.0. https://doi.org/10.25814/5cc65ae71465f
[73] Moran, G.F. & Bell, J.C. Theoret. Appl. Genetics (1987) 73: 616. https://doi.org/10.1007/BF00289203
[74] Harry X. W, Ken G. Eldridge, A. Colin. Matheson, Mike B. Powell, Tony A. McRae, Trevor B. Butcher & Ian G. Johnson (2007) Achievements in forest tree improvement in Australia and New Zealand 8. Successful introduction and breeding of radiata pine in Australia, Australian Forestry, 70:4, 215-225, DOI: 10.1080/00049158.2007.10675023

significant constraint to genetic improvement for the industry[75]. This view concurs with comments expressed by participants attending workshops held as part of the background to the current project.

To support the maintenance of genetic diversity within the current softwood breeding programs in Australia it will require a significant effort on behalf of the industry. There are two strategies that the industry can implement to maintain and where appropriate build on its current diversity. This is especially pertinent to the softwood industry where a relative narrow base exists.

1. Prevent decline in current genetic diversity through the impact of introduced disease and pests which are currently not present within Australia, and
2. Introduce genetic diversity from the introduction of germplasm from overseas breeding programs and native forests.

A watch out for the softwood industry in its desire to introduce genetic diversity from overseas into the Australia germplasm base is that to lower current quarantine requirements runs the risk of introducing new pests and diseases which do not currently exists within the national estate.

Burgess and Wingfield (2002)[76] noted that in its natural environment on the West coast of the United States, *P. radiata* has been decimated by an epidemic outbreak of pitch canker caused by *Fusarium circinatum*. Hence, why strict quarantine conditions must be maintained at Australian and New Zealand borders.

3.4.3 Recommendation

✓ *There are four key activities that are proposed for FWPA to address / coordinate if the plantation industry is to maintain its current genetic diversity:*

1. *Tree Breeding Australia (TBA), Radiata Pine Breeding Company (RPBC) in collaboration with Plant Health Australia (PHA) establish an 'off-shore' research program in the US (i.e. California), Chile and South Africa for the purpose of evaluating the current level of susceptibility / tolerance / resistance of Australian Pinus sp. germplasm when exposed to major plantation diseases (e.g. Pitch Canker) and pests that do not currently exist within Australia Pinus sp. plantations.*

   The aim would be to identify and characterise genotypes which demonstrated increased levels of tolerance and/or resistance to various diseases and pests. The genotypic information (e.g. parameters and correlations of resistance/tolerance to survival, early growth and other commercially important traits) along with the identification of genetic markers can then be translated into the development of a

[75]Anon. (2019) http://www.agriculture.gov.au/import/goods/timber
[76] Burgess, T and Wingfield, J. (2002), Quarantine is important in restricting the spread of exotic seed-borne tree pathogens in the southern hemisphere. The International Forestry Review. Vol. 4, No. 1 (January 2002)

breeding values for resistance which can then be incorporated into the Pinus radiata and Southern Pine genome wide selection programs.

2. *As a precursor to introducing and evaluating genetically diverse germplasm from international sources, it is recommended that FWPA actively engage with Biosecurity Australia and the Ministry of Primary Industry (NZ) to undertake a review of current quarantine restrictions with the objective of creating more amenable regulations and processes that will facilitate import/ export of genetic material.*
3. *To support the review of current quarantine restrictions it is recommended that FWPA invest in establishing research that aims at identifying and evaluating methods and processes for germplasm exchange/transfer that meets current and future biosecurity requirements of exporting/importing countries. The scope of the research will need to evaluate techniques such as tissue culture together with the protocols and methodology for identification of DNA and RNA based pathogens and pests. Additional evaluation will need to be undertaken of the current and future capacity and capability of quarantine procedures and facilities.*
4. *Engage with international tree breeders and organisations to facilitate germplasm exchange from international breeding programs that will allow joint evaluation across a range of environments.*

3.4.4 *Economic Impact*

To exemplify the economic benefit of investment in maintaining genetic diversity in Australia's *Pinus radiata* plantations the authors through an extensive literature search identified a number of research papers which predicted the economic cost to the industry if Pitch Canker was present in Radiata pine plantations.

The fungus *Fusarium circinatum*, which causes the condition known as pine pitch canker in radiata pine (*Pinus radiata*), presents a serious biosecurity threat to Australia[77]. Infection of mature trees by the pathogen causes a resinous canker from which pitch flows. Although bark is retained, the wood beneath is deeply resin soaked. Dieback of branches is the common result of infection, although younger trees may be killed if attacked near the base of the tree. The fungus also causes mortality in bare-root nurseries[78].

The discovery of pine Pitch Canker in countries (USA, Spain, Chile, South Africa) which are geographically widely separated suggests that *F. circinatum* can be transmitted relatively easily and that the large exotic plantations of Australia (1 million ha) and New Zealand (1.5 million ha) are also at risk.

Cook and Matheson (2008)[79] estimated that over a 30-year simulation the estimated present value of expected damage to producers by the successful exclusion of Pitch Canker was approximately $3 million per year. At the time of publishing this was equivalent to a loss of 0.4% of the annual Gross Value of Production (GVP) of radiata pine in Australia. The authors noted that due to the uncertainty and variability of the parameter estimates used in the calculations their confidence intervals were broad, and that they could only suggest that they were 90% sure of avoiding damages between $0.3 million (0.04% of GVP) and $12.4 million (1.6% of GVP) per annum. These losses were comparable to previous estimates of annual losses put forward (e.g. Gadgil et al. (2003),- $3.1 million and Beare et al. (2005)[80] - $2 million).

The authors went on to note that their results indicated that if efforts to exclude *F. circinatum* were successful the likely returns to the radiata pine industry are high enough to warrant a significant investment in preventative measures. For instance, if they were to take the minimum-exclusion benefit scenario (i.e. 5% confidence interval), risk mitigation and management activities could be approved up to a value of $0.3 million per annum before the ratio of benefits to costs becomes less than one. In contrast if they were to take the maximum

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[77] Gadgil, P., Dick, M., Simpson, J., Bejakovich, D., Ross, M., Bain, J., Horgan, G. and Wylie, R. (2003) Management Plan Response to an Incursion of Pine Pitch Canker in Australia or New Zealand. Commissioned and published by the Forest Health Committee on behalf of the Forestry and Forest Products Committee, Canberra.

[78] Gordon, T., Storer, A. and Wood, D. (2001) The pitch canker epidemic in California. Plant Disease 85, 1128–1139.

[79] Cook, D. and Matheson, A. (2008). An estimate of the potential economic impact of pine pitch canker in Australia. Colin Matheson Australian Forestry. 71. 107-112.

[80] Beare, S., Elliston, L., Abdalla, A. and Davidson, A. (2005) Improving Plant Biosecurity Systems: A Cost-Benefit Framework for Assessing Incursion Management Decisions. Australian Bureau of Agricultural and Resource Economics, ABARE eReport 0510. Prepared for the Victorian Department of Primary Industries, Canberra.

exclusion benefit scenario from the 95% confidence interval, the breakeven level of investment would be as high as $12.4 million per year.

On a regional basis the authors demonstrated that the largest benefits from such a strategy would be expected to accrue to the Green Triangle (crossing the borders of South Australia and Victoria), Murray Valley (New South Wales and Victoria) and Central Tablelands (New South Wales) regions being the largest growers of Radiata pine.

3.5 Opportunity 5: Building an Australian plantation industry platform for the future bio-economy

3.5.1 Background

The global economy is currently dependent on fossil feedstocks to generate electricity and heat for industrial and domestic markets and to produce liquid fuels for the transport sector. These fossil reserves drive our global economy but are finite in nature, with the major proven reserves of oil and gas being located in politically unstable, or environmentally sensitive, environments. Also, the declining quality of these reserves requires energy-intensive technologies for their use in conventional petrochemical refineries. In addition to their use in energy generation, heating and fuels, petrochemicals also have a high-value use as feedstocks for the chemical and pharmaceutical industries, being used as raw materials for the manufacture of a wide range of consumer goods including plastics, healthcare and drug products, agrochemicals and fertilizers.

There is a growing realisation that our current industrial manufacturing practices, which are dependent upon fossil oil and gas, will be unsustainable in the coming century. Energy production and the growth of the transport sector in developed and emerging economies are placing a burden on our environment, particularly through greenhouse gas (GHG) emissions and their contribution to climate change. GHG emissions are twice their pre-industrial revolution level and, with increasing industrial and economic growth in the BRIC (Brazil, Russia, India and China) countries and other emerging economies, it will be challenging to reduce society's impact on the environment with a rapidly expanding transport sector and increasing demands for consumer products.

There are therefore significant drivers to move all industrial sectors currently dependent on petrochemicals towards a more sustainable manufacturing platform that uses renewable feedstocks from agriculture, forestry and aquatic resources to reduce society's dependence on fossil-derived energy and raw materials for industrial production.

The adoption of lignocellulose as a primary source of biofuel alcohols has renewed interest in the use of plants as feedstocks for multiple non-food applications in the chemicals and materials industry and has established the concept of biorefining. In biorefining, we can consider plant biomass as a direct replacement for petrochemicals, from which we can derive all the chemicals needed to sustain a modern industrialised society.

The development of integrated biorefineries, which incorporate several technologies to generate multiple product through a combination of chemical and biological processes, is now seen to be essential in underpinning this new technology and hastening the move to a competitive bio-economy[81].

The following provides a schematic of the current thinking behind the biorefinery concept and follows the process flow from biomass input through to value-added products via biochemical or thermochemical transformation (**Figure 8**). The development of integrated biorefineries, which incorporate several technologies to generate multiple product through a combination of chemical and biological processes, is now seen to be essential in underpinning this new technology and hastening the move to a competitive bio-economy[82,83].

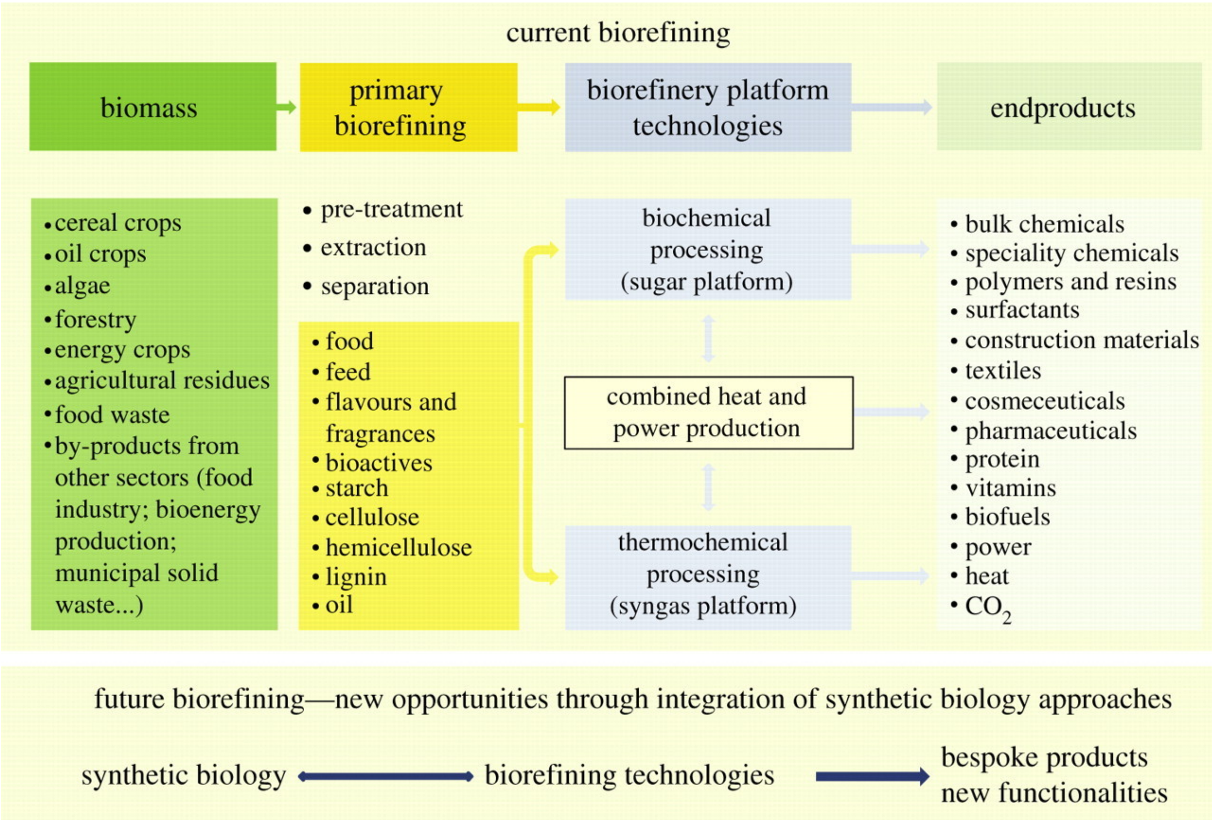

Figure 8. Developing synthetic biology technologies for future biorefinery applications (*Source: Jenkins, 2008*).

[81] Jenkins, T. Boyi, A. and Robert, E. Plants: biofactories for a sustainable future? (2011) *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*.
[82] Jenkins T. 2008 Towards a bio-based economy: examples from the UK. *Biofuels Bioprod. Bioref* **2**, 133-143doi:10.1002/bbb.62
[83] Wright M. M. & Brown R. C. 2007Comparative economics of biorefineries based on the biochemical and thermochemical platforms. *Biofuels Bioprod. Bioref* **1**, 49-56doi:10.1002/bbb.8

The opportunity for the softwood industry to move towards the use of *Pinus sp.*as bio-factories to generate new products is exemplified by SCION in New Zealand with their focus on the "Bio-economy"[84].

For SCION the bio-economy encompasses:

I. the production of renewable biological resources, and

II. their conversion into food, feed, bio-based products and bioenergy via innovative and efficient technologies.

The bio-economy offers great opportunities and solutions to a growing number of major societal, environmental and economic challenges, including climate change mitigation, energy and food security and resource efficiency.

SCION is engaged in research that enables New Zealand to move from a non-renewable petrochemical based economy to one using biological processes and renewable materials from planted forests. The biotechnologies we are developing are part of the growing global bio-economy and are an exciting prospect for the New Zealand forest industry.

Two of SCION's research priorities over the next five years are to:

I. Expand opportunities in the wood fibre, pulp, biopolymer, packaging and biochemical industries and from their biomass side stream; and

II. Increase New Zealand's energy security through the use of forest and waste biomass for bioenergy[85].

SCION is focused on using biological approaches, such as enzyme-based or microbial fermentation, in industrial processes associated with biorefineries[86] (**Figure 9**).

[84] Anon. (2019) www.SCIONresearch.com/about-us/the-forest-industry-and-bioeconomy/the-bioeconomy
[85] Anon. (2019) www.SCIONresearch.com/about-us/the-forest-industry-and-bioeconomy/the-bioeconomy
[86] Anon. (2019) www.SCIONresearch.com/about-us/the-forest-industry-and-bioeconomy/the-bioeconomy

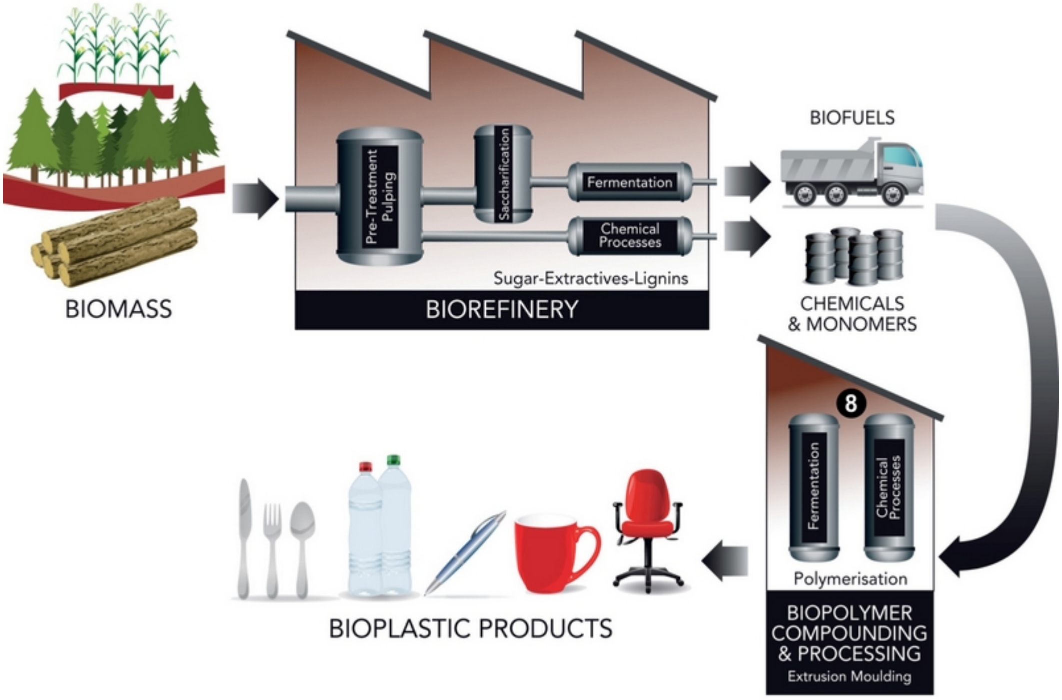

Figure 9. SCION bio-economy value chain based on raw material from plantation forests (*Source: Anon, 2019*)[87]

3.5.2 Building an Australian plantation industry platform for the future bio-economy

The potential for the forest plantation industry in the bio-economy has been recognised in the Queensland Governments Biofutures 10 Year Road Map and Action Plan (2016) in which the future role of the plantation forests industry providing feedstock for the generation of products for the bio-economy has been identified as key resources for the future[88].

To take advantage of these opportunities softwood industry workshop participants identified that due to the long lead times in production and breeding it is paramount that value chain participants work more closely together to ensure that market signals are communicated as early as possible. This is essential so that each step of the value chain understands and agrees on the value of these new product traits and that they can prepare for potential operational changes that maybe required to meet the demand for new product opportunities.

Despite the investment made by countries in South America, North America, various Scandinavian countries and New Zealand into developing breeding programs with a platform for the bio-economy it is important that the Australian industry initially evaluate the long-term economics of investing in developing a similar platform in Australia.

[87] *IBID* (2019)
[88] Anon, (2019) The Queensland Biofutures 10-Year Roadmap and Action Plan. (2016) State of Queensland, Department of State Development, Manufacturing, Infrastructure and Planning, June 2016.

3.5.3 Recommendation

- ✓ *It is proposed that FWPA invest in research that:*

    1. *Identifies the bio-economy generated products that will be generated from a plantation forestry-based bio-economy*
    2. *Identifies the current status of Australian and international research and investment in forestry related tree breeding for the bio-economy; and*
    3. *Quantifies the economic opportunity (e.g. ROI) and investment required for the Australian plantation forestry industry to commit tree breeding and genetic resources to building a germplasm platform with traits that will be required to deliver products into the bio-economy.*

- ✓ *Following the completion of the initial market evaluation and providing it delivers a positive recommendation to proceed and establish a Pinus sp. based tree breeding program in Australia, it is proposed that FWPA initiate discussions with Tree Breeding Australia, RPBC and SCION for the purpose of establishing a collaboration that would create and support a national Pinus sp. tree breeding program in Australia for the bio-economy.*

3.5.4 Economic Impact

The following provides an example of the potential economic opportunities that can be derived from the plantation forests industry participation in the bio-economy.

The region of Central Finland has a strong agriculture and forestry sector and long traditions in forest-based bio-economy. Forests in the region account 9% of the national forest resources. The export rate of high added value bio-based products is high and the sector employs professionals throughout the region.

Forest based bio-economy derives from sustainable forestry and consists of diverse use of forest biomass. The region has a strong level of specialization in machinery and equipment, paper and pulp, wood products, forestry, production of vehicles, and education and training related to forest-based bio-economy. Increased activity in forest pulp utilization also creates a momentum for construction sector due to increased availability of round wood[89].

The Metsä Group designed and built the world's first next-generation bio-product mill in Äänekoski in Central Finland in 2017. This is a perfect example of new business opportunities in the bio-economy (**Figure 10**).

[89] Anon (2019) https://www.wfeo.fi/focusareas/food-and-bioeconomy/forestbioeconomy/

Case Study: Bioenergy and innovative bio-products from plantation forestry

MetsäFibre produces high quality pulp and side products, such as pine oil, electricity and solid biofuels. The mill produces bioenergy equivalent to 2% of national increase in renewable energy, provides 2 500 jobs in the value chain and creates new possibilities especially for SMEs to produce innovative high value-added bio-products.

Biogas production in Central Finland is based on the utilization of municipal waste, waste waters and side streams from the agricultural sector (manure, grass). The region has technological know-how on this area, and the potential to replace over 10 % of the region's fossil oil use in transport by biogas has major importance for regional economy. New production and refining methods require novel machinery and equipment; in Central Finland there are skills and know-how to provide these. Innovative professionals participating in the development of these tools create modern solutions and competitive businesses.

The growing bio-economy sector requires variety of skills and competences. Education institutes cooperate closely with firms to create motivated and skilled professionals. Enterprises and education institutes together with actors from the public sector create capacity for bio-economy in the region. Joint development projects of research institutes, universities, and businesses increase the competence of energy sector and create employment for researchers. Researchers and universities are valuable resources in product development, and the innovations are efficiently brought to the markets. Energy innovations create jobs on other sectors as well; bio-plants utilize the side streams from agriculture and forestry, and skilled workers are needed for the maintenance of energy production plants.

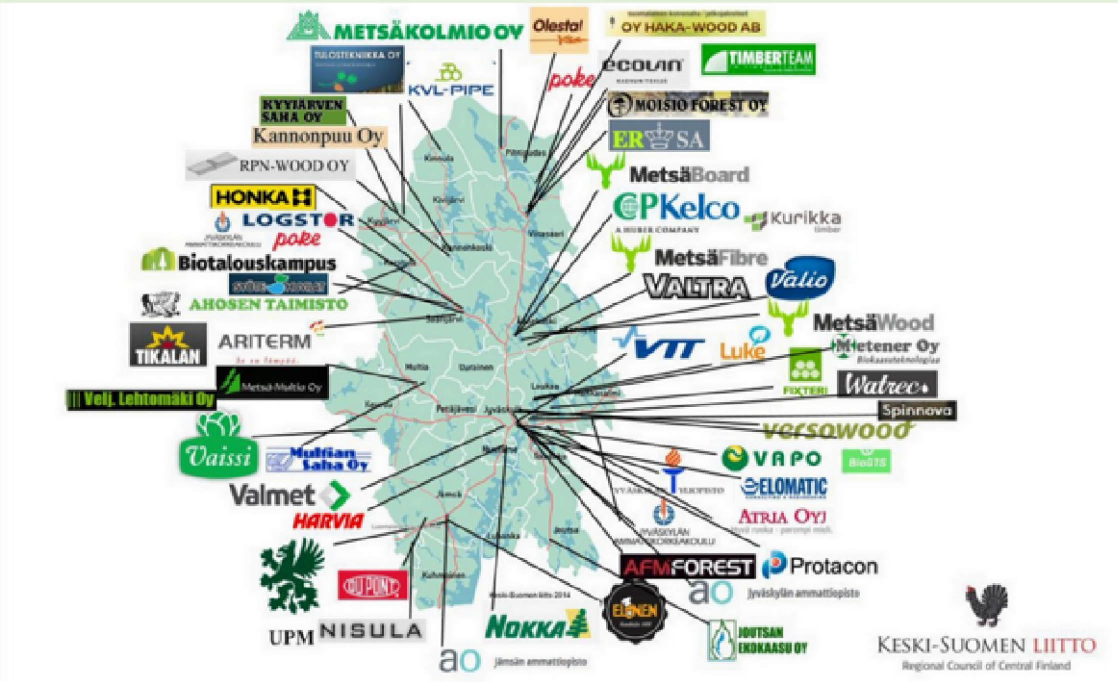

Figure 10. Forest-based bio-economy participants in Central Finland.

3.6 Opportunity 6: Plantation Tree Breeding and Genetic Improvement for Enhanced Value Capture

3.6.1 Background

Since the first establishment of *Pinus radiata* in the Southern Hemisphere, there have been substantial improvements in the management of commercial log production from this important timber species. However, greater volumes achieved by improvements in breeding and silviculture have frequently resulted in commercially harvestable volumes at younger ages. These gains have led, in many cases, to the production of logs with a less valuable distribution of products and radiata pine plantations grown over shorter and shorter rotations are increasingly experiencing quality issues related to lower stiffness, strength and poor dimensional stability[90].

Ivkovic et al (2006)[91] demonstrated in economic terms the difference in objectives stakeholders are seeking from a tree breeding and genetic improvement program. For a forest plantation grower, who gets paid on the volume of logs sold the key driver for value is growth rate (MAI m^3/ha/year), whereas a miller is seeking to maximise the volume of highest quality – high value cuts of timber, therefore wood quality (MoE) is the key driver of value. A fully vertically integrated operation will be evaluating value on the basis of a combination of both attributes MAI and MoE.

The conundrum for tree breeding and genetic improvement within the softwood industry has been:

'Plantation softwood forests need to generate fibre fast, but trees that grow fast tend to be deficient in the wood qualities required to successfully convert that raw fibre into high-value commodity and specialty products.'

As a result, in recent years there has been a shift in the management and breeding of Radiata pine towards wood quality improvement in addition to volume and form[92].

Opportunities for capturing wood quality gains from breeding are described in nearly all the softwood literature as "good"[93]. For example, a review of over 90 different wood and product qualities of *Pinus radiata* showed that the vast majority of these traits were under mostly strong genetic control and offered good potential from gains from breeding, with gains limited primarily by lower coefficients of variation.

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[90] Downes G, Drew D, Moore J, Lausberg M, Harrington J, Elms S, Watt D and Holtorf. (2016) Evaluating and modelling radiata pine wood quality in the Murray valley region. FWPA Project No: PNC325-1314.
[91] Ivković, M, Wu, H, McRae, T and Powell, M. (2006). Developing breeding objectives for radiata pine structural wood production. I. Bioeconomic model and economic weights. Canadian Journal of Forest Research. 36. 2920-2931. 10.1139/x06-161.
[92] Gapare, W.J., Ivković, M., Baltunis, B.S., Matheson, C.A., Wu, H.X., 2010. Genetic stability of wood density and diameter in Pinus radiata D. Don plantation estate across Australia. Tree Genetics & Genomes 6, 113-125
[93] Sorenson, C.T. (2008). Improving the relevancy of breeding for wood quality in *Pinus radiata*. New Zealand Journal of Forestry Science. 38. 36-55.

While some easily-captured gains in wood properties are small, financial benefits can sometimes be leveraged considerably via manufacturing[94]. For example, processors are progressively introducing new innovations in the saw mill to improve efficiencies and product recovery, especially of high value quality related components of the saw log. Increasingly quality related data is being captured on the saw log as it enters the mill and on the various products recovered during processing. Each log is individualised to facilitate sawing patterns that ensure that yield from the high value - high quality grades of each log are optimised[95] (**Figure 11**).

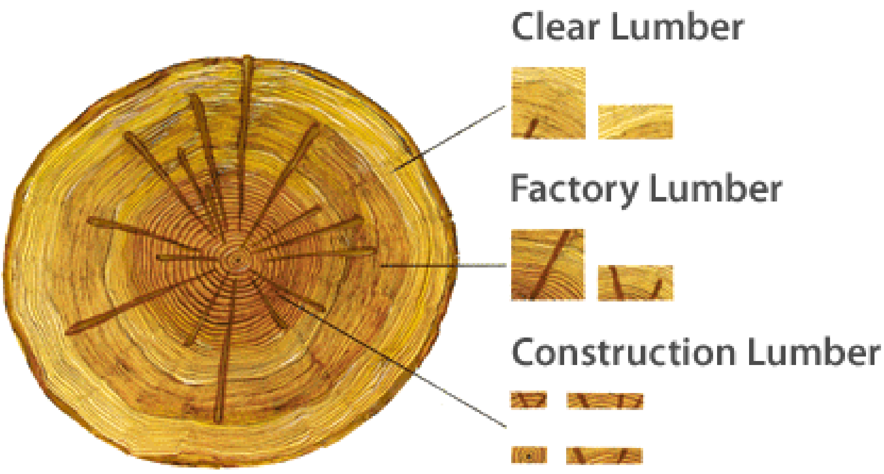

Figure 11. Saw Log Schematic Cross Section[96].

Extensive investment to identify wood trait heritability has produced impressive genetic gains (Wu et al., 2008), and improving the quality and reducing the amount of juvenile wood through breeding has been a major focus of the FWPA-funded Juvenile Wood Initiative[97]. A tremendous advance in the last decade has been the ability to select for important wood quality traits from very young trees, rather than those at harvest age[98,99].

The national genetic improvement programs for forestry aim to improve the generation of breeding values for traits that influence both quality and productivity in hardwood and softwood plantations. Whilst this is informative, this and other prediction models rely heavily on assumptions and outputs that are influenced by a range of factors such as genetic potential of

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94 Shelbourne, C.J.A. 1997: Genetics of adding value to the end-products of radiata pine. Pp. 129–141 in Burdon, R.D.; Moore, J.M. (Ed.) "IUFRO '97 Genetics of Radiata Pine". Proc. of NZ FRI-IUFRO Conf. 1–4 December and Workshop 5 December, Rotorua, New Zealand. FRI Bulletin No. 203.
95 McRae, T. Tree Breeding Australia. Pers Comm. (April 2019)
96 Anon (2019). http://www.coastforest.org/products/product-directory/types-and-grades-page-1
97 Baltunis, B.S., Wu, H.X., Powell, M.B., 2007. Inheritance of density, microfibril angle, and modulus of elasticity in juvenile wood of Pinus radiata at two locations in Australia. Can. J. For. Res. 37, 2164-2174.
98 Chauhan, S., Sharma, M., Thomas, J., Apiolaza, L., Collings, D., Walker, J.F., 2013. Methods for the very early selection of Pinus radiata D. Don. for solid wood products. Annals of Forest Science 70, 439-449.
99 Wu, H.X., Powell, M.B., Yang, J.L., Ivković, M., McRae, T.A., 2007. Efficiency of early selection for rotation-aged wood quality traits in radiata pine. Ann. For. Sci. 64, 1-9.

a tree, site conditions for establishment and growth rate, together with biotic and abiotic stresses which may or may not be influenced by climate change.

Opportunities exist for plantation tree breeders to identify and characterise quality traits including:

- fast-growing softwoods for improved stability, durability and appearance
- wood fibres in a range of products such as wood fibre composites.

The breeding value for these new traits can be evaluated through the use of modern breeding technologies such as genomics, phenomics and bioinformatics. Once established the breeding values for the new traits can be combined with current traits (growth / harvest volume), form (log straightness and branch size) and timber stiffness into a revised economic index that reflects their combined commercial value.

However, adding any new trait as a selection-criteria has the potential to carry penalties in the form of diverted selection pressure from traditional mainstream traits such as growth, form, and disease tolerance. In addition to this challenge, some key wood quality traits can be adversely correlated to fast growth, particularly stem diameter. Sorenson (2008)[100] suggested that the primary response from breeders to address this risk is to increase genetic diversity of parents (in the hope of finding gene combinations that are not competitive) and candidate population size (to get more gain through increased selection pressure).

The opportunity exists to complement and enhance existing databases and prediction models that incorporate quality traits through the utilisation of genomic breeding information (i.e. outputs from genomic selection breeding programs and correlating this to quality data generated by millers).

Data generated will need to be stored in a secure, easily accessed database where multiple researchers can gain confidential access for the purpose of utilising the datasets to support current research and where appropriate contribute to the generation of future research (e.g. PhD students).

3.6.2 Recommendations

- ✓ *To enable the collection of miller data sets it is proposed that FWPA facilitate access on behalf of the industry and that the data be available confidentially to researchers engaged in tree breeding and genetic improvement activities and research. This would enable the integration of the datasets into models for forecasting the best performance of genetic material in relation to preferred end product quality traits (identifying 'elite' material) in hardwoods and/or softwoods, especially related to high value quality components of the log. The aim being to increase the volume of high value quality*

[100] Sorenson, C.T. (2008). Improving the relevancy of breeding for wood quality in *Pinus radiata*. New Zealand Journal of Forestry Science. 38. 36-55.

wood harvested from each saw log resulting in incremental value per log which can captured by the miller.

- ✓ *In addition to current quality related traits it is proposed that research be initiated to identify and characterise 'new product' traits including improved stability, durability, appearance and wood fibre traits. The genotypic information along with the identification of genetic markers can then be translated into the development of a breeding values which can be incorporated into the TBA and RPBC Pinus radiata genome wide selection programs.*

3.6.3 Economic Impact

To demonstrate the potential economic impact of investment in improving wood quality the authors commissioned TBA to model the impact on production and economic returns from the selection of Radiata pine lines that generated improvements in wood quality. Where improvements in wood quality were assessed as either being driven by a 10% increase in modus of elasticity/stiffness (MoE) or a reduction of 10% in average branch size (BRS).

The Base Case scenario for the Radiata pine assumed:

- Growth Rate: MAI 22.7 (m3/ha/y)
- Total Volume 750 (m3/ha)
- Harvest age: 33 years of age
- Three thinning's (at 12, 20, and 27 years)
- Annual area planted of 23,333 ha
- NPV Discount Rate (8.0%).

Where BRS was reduced by 10% versus the base case there was an increase in marginal profit of 7% which equated to an increase in profit equivalent to NPV$143/ha (**Table 5**).

Table 5. Economic impact through breeding for decreased average branch size (BRS) by 10%.

Scenario	Discount Rate (%)	MAI (m^3/ha/y)	Total VOL (m^3/ha)	Harvest Age (yr)	Marginal Profit ($NPV/ha)	Marginal Profit Change (%)	Marginal Profit Change ($NPV/Annual Area Planted)
Base	8.0	22.7	750	33	2,100		
BRS -10%	8.0	22.7	750	33	2,243	7%	**3,347,300**
MOE +10%	8.0	22.7	750	33	2,670	27%	**13,309,758**

The model showed increased recovery of high-grade (MGP15 and MGP12) boards and a reduction of lower grade (MGP10 and F grades) boards. The total percentage of MGP grade timber increased from 72.7% to 73.6% after a 10% reduction in BRS. These changes after the reduction in branch size were not great, but their financial impact may be important for sawmills.

By contrast a 10% increase in the modus of elasticity/stiffness (MoE) generated an increase in marginal profit of NPV$433/ha which represented a 27% increase over the base case scenario.

The model predicted a decrease in lower grade (F grades and MGP10) boards and an increase in higher grade boards (MGP12 and MGP15). The percentage of F grades decreased from 27.3% to 14.2% and 15.1% using clear-wood and acoustic MoE, respectively. In contrast, the percentage of MGP15 timber increased from 2.3% to 10.1% and 9.2% using clear-wood and dynamic MoE, respectively.