Forest & Wood Products Australia

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Research, development and extension investment plan

Research, development and extension priorities to minimise threats from forest damage agents.

2020

Adapted from *An investment plan for research, development and extension to minimise threats from forest damage agents*, prepared for FWPA by Tim Wardlaw, 2019.

This version of the Investment Plan, adapted by FWPA in December 2020, removes the cost and benefit estimates from the original Investment Plan, *An investment plan for research, development and extension to minimise threats from forest damage agents*, prepared for FWPA by Tim Wardlaw, 2019.

Author declaration of interest

The author, Tim Wardlaw, received income in the past year from RD&E carried out in the technical areas addressed in this investment plan, notably funds from Terrestrial Ecosystem Research Network (TERN) to manage infrastructure at the Warra OzFlux site and to provide datasets from that site to TERN. The author anticipates receiving income in the next five years from RD&E activities carried out by the author in the technical areas addressed by this investment plan, notably continued funding from TERN to manage the Warra OzFlux Site. The author anticipates no other pecuniary interests flowing from the adoption of this Investment Plan.

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Executive summary

This investment plan reviews opportunities for progressing the GRAC Vision through investments in RDE that reduce the risks of losses to plantations (softwood and hardwood) and production native forests from forest damage agents. The damage agents considered in this investment plan are: animal pests - both arthropod and vertebrate; pathogens[1]; and climate-induced (extreme events and climate change). Fire and weeds are not addressed in this investment plan: fire is dealt with in a separate investment plan and weeds are considered in the investment plan for plantation silviculture.

The suite of pests that threaten production forests includes native species; exotic species that have become established in Australia and exotic species that are not yet present in Australia. The investment plan reflects these different histories by independently considering each of three categories of damage agents: (i) long established damage agents (native species, long-established exotics and climate); (ii) newly established (within the past decade) exotic pests; and, (iii) exotic pests that are not present in Australia.

Long-established damage agents

Section 2 of the report describes in detail the work that is summarised below.

A national workshop, attended by technical and industry experts in the management of forest damage agents, shortlisted those damage agents of most concern in each of the main plantation types and then identified issues impinging on the ongoing management of those damage agents. Through this process an RDE agenda of priority projects was developed. Priorities were guided strongly by either cost of losses from un-managed / ineffectively-managed damage events or the value of maintaining or enhancing routine management for those damage agents with well-developed management procedures.

Managing the threat from damage induced by drought (in all production estates) and heatwave (in production native forests) events were rated high priorities for RDE investment because of the high cost of losses from recent events. Currently, neither have effective management procedures.

- For drought, the greatest need is for more and better observational data to so that site hazard-rating, which underpins decisions for deploying management (genetics, silviculture, rotation-length), can be reliably predicted and made readily accessible.
  Strengthening general forest surveillance capability through developing a national platform to host predictive tools, monitoring products and data portals is the proposed way of doing this.

- For heatwaves, the greatest need is to understand the mechanism that causes the sensitivity to heatwaves and to develop tools and procedures that enable screening for temperature sensitivity. Considerable social and political value would also flow from being able to prove and monitor effective adaptation responses as the measures would both dampen a substantial positive feedback to global warming and provide a financial return in future carbon markets.

The cost-effectiveness of current management for defoliating insects (chrysomelids and *Gonipterus*), *Sirex* and browsing mammals could substantially change with refinements to key procedures. Small projects are proposed for each of these to directly address their current procedural issues.

[1] For brevity, arthropod pests, vertebrate pests and pathogens are implicit when the term “pests” is used

Newly-established exotic pests

Section 3 of this report describes in detail the work summarised below.

Actions are proposed to manage the threat from two newly-established exotic species - myrtle rust and giant pine scale.

For myrtle rust, critical actions are to: (i) develop a capacity to cheaply and quickly screen rust infections on Myrtaceae to detect new arrivals of other rust biotypes that may be more damaging to commercial forests than the now-established pandemic biotype; (ii) identify and restrict high-risk pathways along which new biotypes may enter Australia.

For giant pine scale a critical action is to progress the development of an effective biocontrol. An effective biocontrol would strengthen actions to contain GPS to within its current peri-urban limits. It also provides a management option if GPS does escape from current containment areas and spreads into commercial plantations. The proposed action is the further evaluation of the predatory fly, *Neoleucopis kartliana*, which was identified as the most prospective biocontrol option in a recently-completed feasibility study.

Exotic pests not yet present

The National Forest Biosecurity Surveillance Strategy, which was endorsed by government and industry in 2018, is the key initiative to strengthen biosecurity measures against exotic forest pests not present in Australia. The Strategy and Implementation Plan are not reproduced here but can be accessed through the Plant Health Australia website using the links:

http://www.planthealthaustralia.com.au/wp-content/uploads/2018/03/National-Forest-Biosecurity-Surveillance-Strategy.pdf

http://www.planthealthaustralia.com.au/wp-content/uploads/2018/07/Forest-Biosecurity-Surveillance-Strategy-Implementation-Plan.pdf

Start-up funding from the Commonwealth Government has allowed progress in some actions in the Implementation Plan.

The anticipated outcomes during the initial five years of the investment plan are:

- Tools and structures for an operational High-risk Site Surveillance Program have been developed, implemented and integrated with the national biosecurity effort.
- A sustainable funding mechanism to maintain a national forest biosecurity program, including the role of a National Forest Biosecurity Co-ordinator, has been adopted

Maintaining the program in the longer term is expected to reduce the number of significant exotic forest pests that become established. The aim is to at least double the rate of successful eradication campaigns from the current 1 in 5 to 2 (or 3) in 5 (the world average) by 2040.

Research capacity

Section 7 of this report provides a detailed description of the work summarised below.

The dominance of research capacity has sharply shifted from state-based forestry agencies to universities over the past decade. There has been a decline in published output related to forest damage agents during the past decade matching the decline in the number of researchers. However, the nation still has the capacity to rapidly acquire new knowledge in response to emergency situations as was demonstrated from the publication output made in response to the introduction and establishment of myrtle rust in Australia.

The mix of discipline areas contributing to research capacity has shifted towards physiology and climate in recent times. This aligns well with the major priorities identified for management of the risks from established damage agents. There has been a sharp shift away from research capacity in the discipline areas of detection / surveillance and damage assessment over the latter half of the past decade. This runs counter to the need for strengthening capacity in surveillance and damage assessment. To address this the investment plan has a strong focus on developing tools and systems, at the national-level, to support the industry in forest surveillance. The shift towards national systems should help ensure access to expertise regardless of local availability. The shift towards using national supported systems should also speed up industry access to applications using newly developed technologies and to more accurate risk models through detecting and observing events at the national-scale.

Table 1. List of projects and anticipated benefits / outcomes

Project	Anticipated benefits / outcomes	
1. Long-established damage agents		
1.1.1 Drought-risk - retrospective analysis 1.1.2 Delivering surveillance products	Short: interim site-level drought risk map; Medium: system supporting general surveillance implemented; Long: site-based drought management deployed	Avoided losses
1.2. Understanding and managing the threat from heatwaves	Short: causality determined; Medium: extent of vulnerability determined; Long: adaptation measures verified, deployed and marketed	Improved productivity
1.3.1 Sirex biocontrol	Short: Factors affecting parasitism success determined; Medium-long: high parasitism success maintained	Reduced costs
1.3.2 Leaf beetle integrated pest management	Short: Canopy permeability for drift modelled in AgDisp; Medium: pesticide label update; Long: Maintain high benefit of beetle management	Avoided losses
1.3.3. *Gonipterus* biocontrol	Short: *A. nitens* biotypes selected, reared & released; Medium-long: Insecticides not routinely used	Reduced costs
1.3.4 Risk-based management of mammal browsing	Short: Risk-factors identified; Medium: Risk-based management developed & deployed; Long: Lower cost socially-acceptable management	Reduced costs
1.3.5 Review *Teratosphaeria* research	Short: Prospective management options known; Medium-long: Management procedures developed & deployed	
2. Newly-established exotic damage agents		
2.1 Myrtle rust diagnostics and pathways	Short: Simple, cheap diagnostic tool; medium: pathways identified & managed; long: No new rust biotypes establish	Avoided losses
2.2 Giant pine scale biocontrol	Short: biocontrol evaluated and approved; medium: Biocontrol release & establishment; Long: GPS contained to peri-urban areas	Avoided losses
3. National Forest Biosecurity Surveillance Strategy		
3.1.1 Collate historical pest data	Short: All components of operational biosecurity surveillance program have been developed; structure and funding mechanism for national forest biosecurity surveillance program Medium: Operational forest biosecurity surveillance program fully implemented Long: Proportion of incursions of significant forest pests that are successfully eradicated, meet (40% of incursions) or exceed (>40% of incursions) the world average	Reduced costs
3.1.2 Guidelines to determine pest status (native or exotic)		
3.1.3 National blitz surveys		
3.2.1 Review diagnostic capability		
3.2.3 Develop National Diagnostic Protocols for forest HPPs		
3.2.4 Develop diagnostic methods and tools		
3.3.1 Review forest surveillance capability / capacity		
3.3.2 Develop National HPP Surveillance Protocols		
3.3.3 General surveillance for HPPs		
3.4 Data integration		
4.2.4. Design an optimised HRSS Program		
3.5.1 Threats not amenable to surveillance		

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1. General introduction

1.1. Background

The Vision of the Grower Research Advisory Committee is to double the value of Australia's commercial forests by 2040, by fostering an innovation culture in our enterprises, applying world's best practices, collaborating and investing into research and development as appropriate.

In support of the GRAC Vision, FWPA seeks to develop a suite of investment plans that enables industry investment in RDE through providing a business case for that investment. The investment plans will provide a high-level review of national and international research and operational practices aimed at sustainably maximising gains in forest value. Investment plans will include measurable stretch targets for maximising value gain across the sector and develop a pathway for investment in priority areas of research, development and extension (RDE) for the Australian plantation forest industry.

This investment plan reviews opportunities for progressing the GRAC Vision through investments in RDE that reduce the risks of losses from forest damage agents. Note, the investments considered in this plan put no boundary of the source of funds, i.e. FWPA is just one of the potential funding providers. The damage agents considered in this investment plan are: animal pests -both arthropod and vertebrate; pathogens; and climate-induced (extreme events and climate change). Fire and weeds are not addressed in this investment plan: fire is dealt with in a separate investment plan and weeds are considered in the investment plan for plantation silviculture.

The suite of pests that threaten production forests includes native species; exotic species that have become established in Australia and exotic species that are not yet present in Australia. The investment plan reflects these different pest / pathogen histories by independently considering each of three groups of damage agents: (i) long established damage agents (native species, long-established exotics and climate); (ii) newly established (within the past 1-2 decades) exotic pest and pathogen species; (iii) exotic pest and pathogen species that are not present in Australia.

1.2. Objectives

To develop an investment plan that establishes a blueprint for RDE for the Australian plantation sector from 2019 to 2023, with an outlook to 2028 and beyond to 2040. This investment plan will focus on actions that will minimise the risk of productivity and value- losses due to damage agents such as; pests (vertebrates / invertebrates), pathogens and climatic factors (including extreme weather events).

2. Developing RDE priorities and projects: threats from long-established damage agents

2.1. Background

This group of damage agents is diverse and includes native and exotic species of pests as well as damage associated with climatic events. Most have been present in the production forest estate for enough time to allow management procedures to be developed and adopted operationally. However, the threats posed by this group of damage agents is not static for a variety of reasons including:

- changes to the activity of the damage agent because of range expansion (the plantation estate and / or the damage agent) and changing climate;
- changes in the efficacy of key tools used to manage the risks posed by the damage agents; and
- access to, and use of, key management tools changes because of changes in the regulatory, social and political environments.

The status of the threat posed to the GRAC Vision by long-established damage agents is reviewed and any changes to the status of those threats are evaluated and opportunities to better manage their impacts are identified for potential RDE investments.

2.2. Methodology

Members of the Forest Health and Biosecurity (FHaB) Subcommittee of the Australian Forest Products Association (AFPA) provided the expert judgement used to identify the most important damage agents of production forests. This committee comprises a mix of technical experts and industry personnel overseeing operational management of production forests. A workshop held on 30th August 2018 in Melbourne provided the forum for eliciting the expert judgement of FHaB members. Also attending this workshop was a small number of additional invitees representing the next generation of technical expertise, operational forest health management expertise and national policy experts in biosecurity and forestry. Details of the workshop participants, the agenda and presentations of the background information can be found in Appendix 2.

The workshop invitees used group consensus to develop a shortlist of damage agents in each of the three main plantation estates – temperate softwoods, temperate hardwoods and tropical softwoods. In combination these three plantation estates represent nearly 80% of the current mill-door value of national forest harvest (Table 2, Figure 1). The invitees split into groups – one for each of the three plantation estates – to develop the shortlist of damage agents in each estate. After identifying the top five damage agents, the three groups then considered the current status of management of each of those damage agents. This involved identifying: (i) any gaps in knowledge that impedes management; (ii) any risks to the future access of the main management tools; (iii) any opportunities to refine management to make it more cost-effective. It was these three aspects of risk mitigation that were used to develop priorities for RDE investment.

Table 2. National area of softwood and hardwood plantations, and volume harvested from native forest in 2016-17. [1.] Estimates of the contribution to national value (mill-door) of each estate type for each State apportioned, *pro rata*, by area (plantations) or harvest volume (native forest).

	Softwood		Hardwood		Native forest	
State	,000 ha	% value[a]	,000 ha	% value[b]	,000 m^3	% value[c]
ACT	7.4	0.4	-	0	-	0
Northern Territory	1.9	0.1	45.6	1.5	-	0
NSW	307	16.2	87.1	3.0	1,130	4.1
Queensland	195.5	10.3	34.8	1.2	-	0
South Australia	127.2	6.7	48.5	1.6	-	0
Tasmania	75.9	4.0	233.9	7.9	1,227	4.5
Victoria	197.5	10.4	197.5	6.7	1,282	4.7
Western Australia	98.4	5.2	260.9	8.8	476	1.7
Total	1010.8	53.4	908.3	30.8	4,300[d]	15.8

[a.] Total national mill-door value of plantation softwood harvest in 2016-17 was $1,400 million (Commonwealth of Australia 2018). This represents 53.4% of the total national value of log supply to industry.[b.] Total national mill-door value of plantation hardwood harvest in 2016-17 was $807 million (Commonwealth of Australia 2018). This represents 30.8% of the total national value of log supply to industry.[c.] Total national mill-door value of native forest harvest in 2016-17 was $413 million (Commonwealth of Australia 2018). This represents 15.8% of the total national value of log supply to industry. [d.]185,850 m^3 of reported national harvest volume in 2016-17 could not be accounted for in collated harvest volumes reported in jurisdictional annual reports.

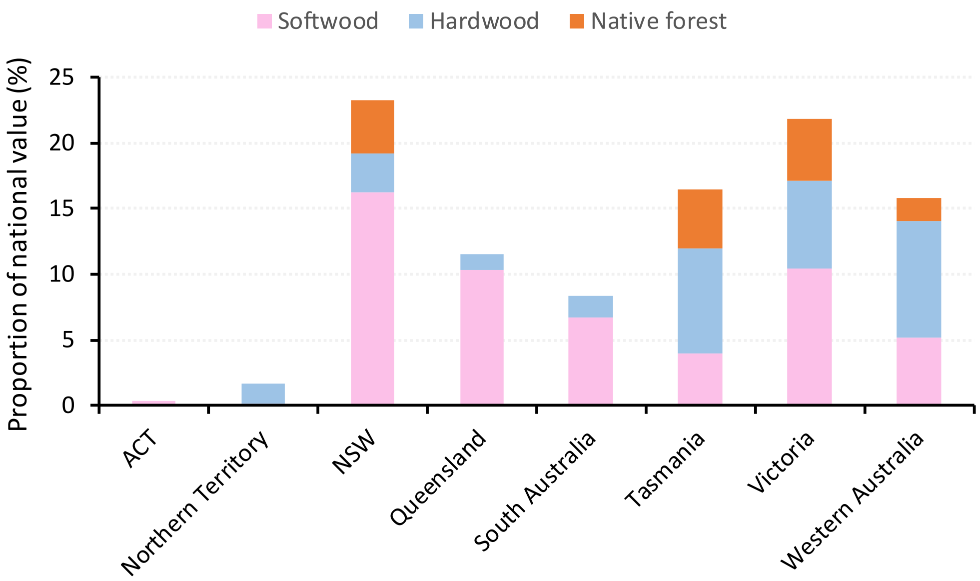

Figure 1. Proportion of national mill-door value, by jurisdiction, contributed by softwood and hardwood plantations and by native forest. Proportional values are based on data given in Table 2.

2.3. Outcomes 1: Shortlists of established damage agents

The shortlist of damage agents for each of the three plantation estates developed at the workshop are listed in Table 3. Drought was listed in all three of the plantation estates. Vertebrate pests were listed in both the temperate softwood and hardwood plantation estates. *Sirex* was listed in both the temperate and tropical softwood plantation estates. Defoliating insects and/or pathogens were listed for both temperate softwood (*Essigella* and *Dothistroma*) and hardwood (*Teratosphaeria* spp. and defoliating insects) plantations.

Native forests were not considered at the workshop, however logs harvested from native forests make significant contributions to national value, particularly in Tasmania, Victoria and NSW (Table 2). On the basis of the consultant's experience a shortlist of damage agents was proposed - drought and heatwaves.

TABLE 3. SHORTLIST OF DAMAGE AGENTS in each of the three main plantation estates and in production native forests in Australia.

Temperate softwood	Temperate hardwood	Tropical softwood	Native forests
1. *Sirex*	1. Drought	1. Cyclone	1. Heatwave
2. Drought	2. Defoliating insects	2. Blue stain & associated insects	2. Drought
3. Vertebrate pests	3. *Teratosphaeria* spp.	3. *Sirex*	
4. *Essigella*	4. Vertebrate pests	4. Drought	
5. *Ips*			
6. *Dothistroma*			

2.4. Outcome 2 – Evaluation of management issues of established damage agents

Data measuring impact and management costs could be collated for 9 of the 16 shortlisted damage agents. Those data, together with detailed evaluation of the status of issues identified at the workshop, can be found in Appendix 3. The evaluation process gave the following outcomes:

i) Two damage agents – drought and heatwaves – have been associated with significant damage events over the past two decades (Table 4, Figure 2) and key management procedures for reducing their impacts are lacking;

ii) Three damage agents – *Sirex*, defoliating insects (chrysomelids and *Gonipterus* spp.) and vertebrate browsers – have management procedures in use, or available to use, but the cost, effectiveness or availability of those procedures could substantially change, i.e. they have procedural vulnerability (Table 5, Figure 3). A fourth, *Teratosphaeria* spp., was added because there are currently no routinely-used management procedures despite moderate unmanaged losses. An extensive body of research has been completed but has yet to be reviewed with the aim of identifying prospective options for management.

TABLE 4. DAMAGE AGENTS IN EACH OF THE FOUR COMMERCIAL FOREST ESTATES THAT ARE HAVE CAUSED SIGNIFICANT LOSS-EVENTS (>$5M total cost per event) and do not currently have routine management procedures in place. Red fill indicates where management procedures have not been developed; orange fill indicates management procedures are under development / have been developed and awaiting evaluation of outcomes.

Temperate softwood	Temperate hardwood	Tropical softwood	Native forests
Sirex	Drought	Cyclone	Heatwave
Drought	Defoliating insects	Blue stain & associated insects	Drought
Vertebrate pests	*Teratosphaeria* spp	*Sirex*	
Essigella	Vertebrate pests	Drought	
Ips			
Dothistroma			

TABLE 5. DAMAGE AGENTS IN EACH OF THE FOUR COMMERCIAL FOREST ESTATES THAT ARE SUBJECT TO ROUTINE MANAGEMENT, but the cost or effectiveness of management procedure(s) is or could substantially change (procedural vulnerability). Red fill indicates those damage agents that meet the criteria and measures to address procedural vulnerability are not being investigated; orange fill indicates those damage agents that meet the criteria and measures to address procedural vulnerability are under development / have been developed and awaiting evaluation of outcomes.

Temperate softwood	Temperate hardwood	Tropical softwood	Native forests
Sirex	Drought-injury	Cyclone	Heatwave-injury
Drought-injury	Defoliating insects	Blue stain & associated insects	Drought-injury
Vertebrate pests	*Teratosphaeria* spp	Sirex	
Essigella	Vertebrate pests	Drought-injury	
Ips			
Dothistroma			

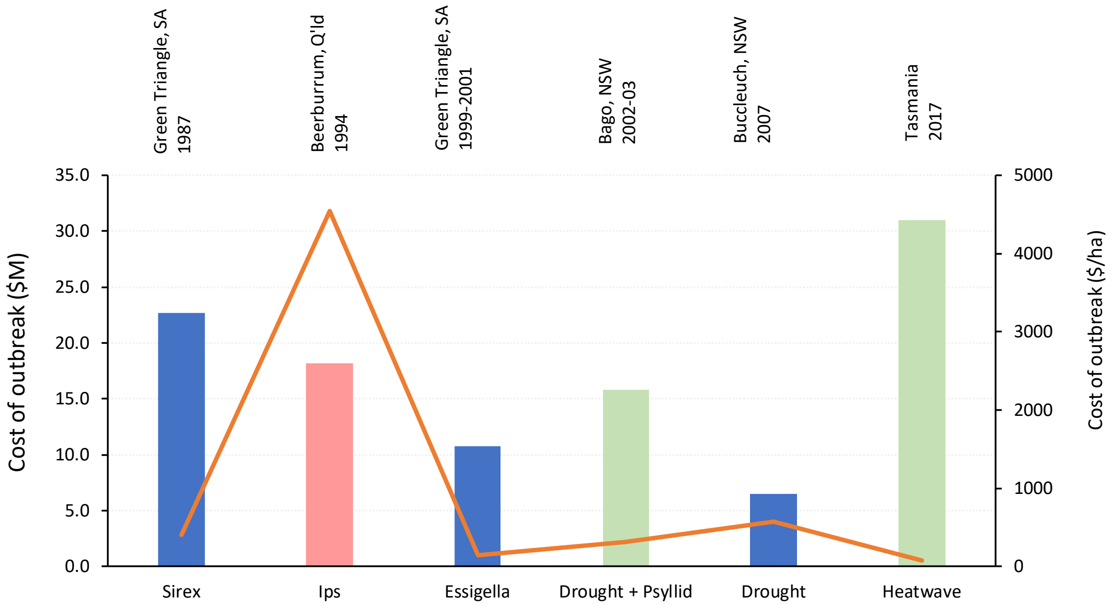

FIGURE 2. REPORTED OR CALCULATED COSTS OF MAJOR OUTBREAK EVENTS FOR SHORTLISTED DAMAGE AGENTS affecting temperate softwood plantations (blue columns), tropical softwood plantations (pink column) and production native forest (green columns). Source data used for calculations are given in the relevant section for the damage agent.

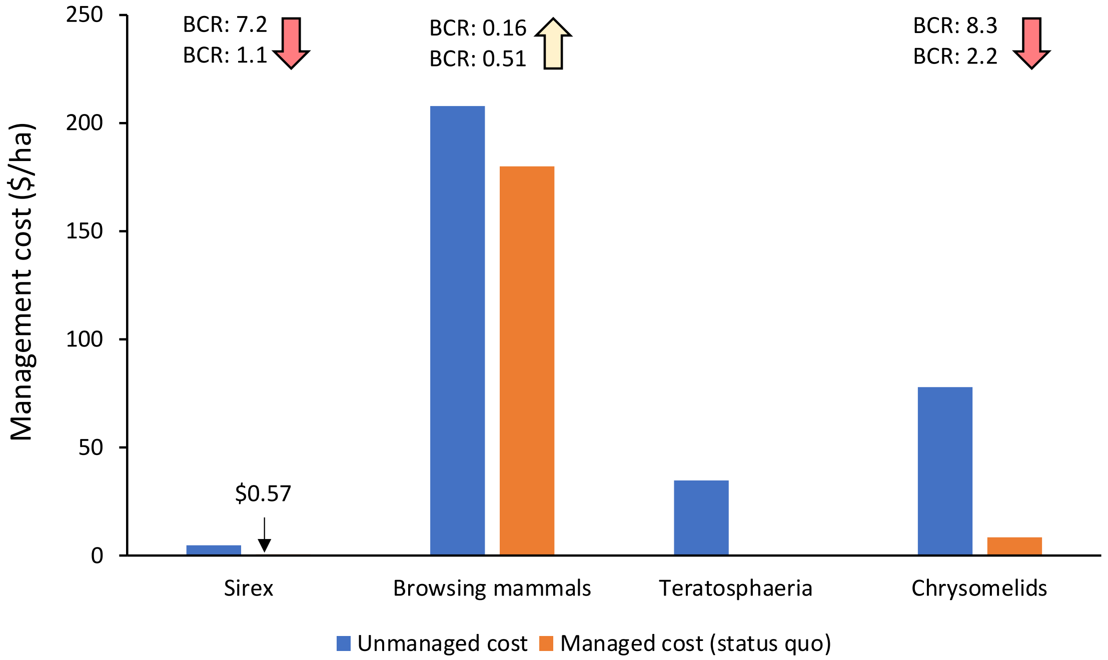

FIGURE 3. COMPARISON OF THE SIZE OF LOSSES (UNMANAGED COSTS) AND COST OF CURRENT ROUTINE CONTROL OPERATIONS (MANAGED COST), WHERE DONE, FOR FOUR SHORTLISTED DAMAGE AGENTS. The BCR value shown (upper value of each pair) represents the ratio of the unmanaged : managed costs. Potential movement in benefit : cost ratio if vulnerabilities in current procedures are not satisfactorily addressed are indicated with red arrows, and with yellow arrows if weakness in current procedures are successfully addressed.

2.5. RDE priorities for managing threats from long-established damage agents

Project 1.1 Drought-induced damage

Ten drought-related management issues were identified at the August 2018 workshop. Subsequent evaluation of the status of those identified issues found little progress had been made over the past decade in resolving them. The stumbling block has been that the process modelling approach adopted to develop site-based predictions of drought risk have been constrained through the lack of observations (Pinkard et al. 2014, Battaglia and Bruce 2015, Battaglia et al. 2015, Battaglia and Bruce 2019). **Site-based predictions of drought risk are the starting-point for developing and deploying management** (Stone et al. 2012).

The way to progress the development of site-level predictions of drought risk is to accelerate the collection of observations. General forest surveillance is an efficient way to collect the observations needed for risk modelling. However, current surveillance capability is limited to a small number of growers (Carnegie et al. 2018a). In addition, the analysis of research capability documented in section 7 of this report shows a decline in research output in surveillance / detection and impact assessment – the two key elements underpinning general forest surveillance. What we do have though, is two decades of health surveillance observations covering a substantial proportion of the plantation estates, particularly in the eastern states (Carnegie et al. 2008, Smith et al. 2008, Wotherspoon 2008, Carnegie et al. 2018a).

Project 1.1.1 Retrospective analysis - comparison of historical FHS observation with timeseries of climate anomalies and remotely-sensed vegetation condition indices

There is the opportunity of using historical health surveillance observations retrospectively to "calibrate" against timeseries of climatic data and satellite remotely-sensed vegetation indices. There have been recent examples of retrospective analysis to link in-forest health observations with existing data products. They include the analysis of Landsat imagery to monitor defoliation and mortality in forests (Meigs et al. 2015, Mitchell et al. 2016, Zhu et al. 2018) and the analysis of climate data to detect / predict drought events (Mitchell et al. 2014). Mitchell et al. (2016), brought these two elements together into an Ecoclimatic Framework that links drought injury (observed by remote sensing or surveillance) with the magnitude of the climate anomaly (as measured by the degree of departure from normal) probabilistically. This approach has great potential to accelerate the development of an initial drought-risk map derived from surveillance-calibrated probabilistically-measured climate anomalies.

Project 1.1.2 Methods, systems and platforms for efficiently delivering surveillance products to the industry

The retrospective analysis will provide the foundation from which several operational products could developed. Those products include:

- Automatically updated (as new observations are added) drought-risk mapping derived from "calibrated" climate anomaly mapping
- Grower alerts generated from real-time analysis of climate and satellite remote-sensing data to detect events that depart from normal by a prescribed amount
- Tools to efficiently capture and process surveillance data collected by direct observation and digital data from platform-mounted (e.g. UAV) sensors
- Data warehousing and data portals
- Maintain documentation and data standards

Figure 4 provides a conceptual design for a platform to deliver such products. The project will precisely determine the surveillance products the industry wants and how they are delivered. Once products and delivery have been defined the project would then evaluate existing technologies[2] and hosting options, and once determined develop algorithms and systems to efficiently capture and process data and generate outputs for industry users.

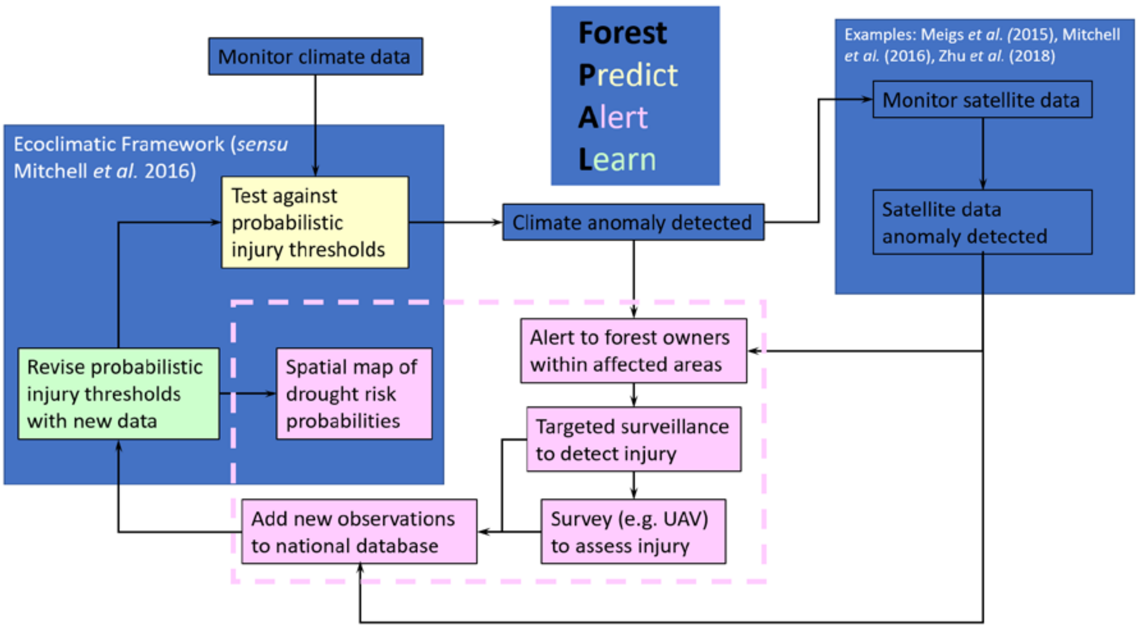

FIGURE 4. A PROPOSED FRAMEWORK TO LINK SEVERAL EXISTING TOOLS TOGETHER TO PROVIDE A SYSTEM TO SUPPORT GENERAL FOREST SURVEILLANCE. Components in blue boxes are data streams harvested and processed by the system. Components in pink boxes are delivered products to industry or actions by industry.

Anticipated benefits:

- Reduce drought losses by deploying site-specific silvicultural (e.g. Stone et al. 2012), genetic (e.g. Dutkowski and Potts 2012, Ivkovich et al. 2015) and species-choice options according to accurately predicted site-level drought risk.
- Deployment of site-specific management to reduce drought risk flows-on to reduced risk of secondary pest effects (amplification of pest activity requiring more intensive management)
- Easier to incorporate up-to-date drought risk into forestry business risk evaluation and decisions
- Opportunity to capture greater value from extended rotation options when drought risk can be more accurately predicted (*sensu* Leech 2014)
- Greater salvage recovery of wood in drought affected areas through early warning and damage detection

[2] This includes existing tools that could be adapted e.g. CSIRO's Forest Climate Risk Tool

Potential collaborations:

- Terrestrial Ecosystem Research Network (looking for industry partners to develop applications such as predictive tools using their data infrastructure)
- Environment and conservation agencies
- CSIRO
- Geosciences Australia
- Agriculture industries (parallel needs for climate-driven surveillance and predictive systems)
- Commercial businesses based on delivery of knowledge from data

Capacity building:

- Strengthen general surveillance capacity within the industry, complementing project to support general surveillance for high-risk pests (Project 3.3.3)
- Provide national system and structure to acquire observations (direct and digitally-sensed) on forest health events to build a "history" that can supplement knowledge from long-term forest health specialists.
- Potential commercial structure for providing forest health products

Project 1.2 Understanding and managing the threat from heatwaves

Damage agents of production native forests were not ranked at the August workshop. However, a report prepared after that workshop documented the impact of an extreme heatwave in Tasmania's highly productive tall *E. obliqua* forest (Wardlaw 2018). The estimate of the impact of that event place it as one of the most damaging, in terms of growth reduction, to be documented for Australia's production forests. The event was due to the recently discovered sensitivity to warming temperatures of tall, wet eucalypt forests in south-eastern Australia (Wardlaw 2016).

The temperature sensitivity occurs along a latitudinal gradient and decreases with latitude such that the level of sensitivity of the tall eucalypt forests in Central Victoria is about half that measured in southern Tasmania. The predicted increases in temperature by the middle and end of the century would result in 5-10% reduction in productivity from Tasmania's wet eucalypt forests (Wardlaw 2016). Natural populations of both *E. nitens* and *E. globulus* are contained within this latitudinal band of temperature sensitivity. None of the physiological studies that have been done to date on these two species can tell us whether they share a similar temperature sensitivity (Libby Pinkard pers. comm.).

The reason for the sensitivity of Tasmanian, and to a lesser degree Victorian, tall eucalypt forests to warming temperatures has not yet been proved but the evidence suggests a supra-optimal temperature depression of the photosynthesis reaction. Research to determine the physiological mechanism would use well-developed techniques and technologies and has a high likelihood of success (Mark Hovenden and Tim Brodribb, pers. comm.).

An understanding of the physiological mechanism would pave the way to develop a procedure to screen genotypes for temperature sensitivity. This step is key for accurately delimiting which parts of the commercial forest estate are sensitive, and to what degree. This knowledge could be used to reduce the risks associated with uncertainty when balancing future supply commitments with expected yield.

A screening method would also enable verification of the effectiveness of adaptation measures (e.g. modified geographic seed-zoning) in reducing temperature sensitivity. This could potentially provide access to carbon markets through being able to verify gains in carbon sequestration through forest management.

Anticipated returns

- 3-5% gain in productivity (assume 5m³/ha/yr in merchantable stem of eucalypts) by 2050 (revised seed-zoning) and 5-10% gain in productivity by 2070 if adaptation measures are successful.
- Quantum of gains relate to the predicted increase in temperatures and empirical relationship between temperature and productivity measured at the Warra Flux site (Wardlaw 2016).
- Anticipated gains are only claimed for approximately 120,000 ha of tall, wet eucalypt forest in Tasmania. Temperature sensitivity does extend north into Central Victoria, where the decline in productivity with temperature is about 50% that measured in southern Tasmania.

Anticipated benefits:

- Greater certainty in future wood supply thorough more accurate delimitation of temperature sensitivity
- Verify adaptation measures are working
- Capture value of verified adaptation measures in carbon markets
- Social and environment benefit of greater carbon sequestration as the result of management in production forests

Potential collaborators:

- Industries seeking to offset emissions
- Environment and conservation agencies

Project 1.3 Maintaining effective management procedures

Table 4 and Figure 3 showed two damage agents (*Teratosphaeria* excluded) that were assessed to have key procedures that need strengthening to maintain their current strong benefit : cost ratios (*Sirex*, leaf beetles), or that need modifying to improve their cost-effectiveness (browsing mammals). A further two damage agents – *Teratosphaeria* spp and *Gonipterus* spp. can benefit from projects that develop new or improved operational practices based on the findings from current and past research.

Project 1.3.1 Sirex

Levels of *Sirex* parasitism by the Kamona strain of the nematode *Beddingia siricidicola* are remaining low in many treated plantations. This carries the risk that nematode inoculations will be less efficient in maintaining *Sirex* activity at the desired low levels necessitating a higher intensity of trap tree inoculations. Low levels of parasitism by the Kamona strain of *B. siricidicola* is a problem that is being experienced in other countries as well as Australia. A PhD project is currently being done in South Africa at FABI (Food and Agricultural Biotechnology Institute, University of Pretoria) to test various possible factors affecting the success of inoculations with the Kamona strain of *Beddingia*. Australia is participating in that study by contributing Australian collections of *Sirex* and nematodes.

Anticipated outcomes (next five years and beyond):

- Maintain an efficient and effective biocontrol for *Sirex*
- Avert the risk of needing more intensive inoculation to maintain low *Sirex* populations.

Potential collaborators:

- Existing collaboration with South Africa (FABI)

Project 1.3.2 Leaf beetle integrated pest management

Current management of leaf beetles has a high benefit : cost ratio (Cameron et al. 2018a). The benefit flows from the value of the avoided losses from controlling high beetle populations far exceeding the cost of the control operation. That benefit will decline if there are restrictions on managing above-threshold beetle populations. APVMA are moving to a system that prescribes stream buffer widths for each registered pesticide based on predictions of spray drift generated using the AgDisp Model. Under typical field conditions measured during Tasmania leaf beetle spray operations (wind speed >0 and <15 kph) the AgDisp model predicts 300m buffers would be needed around very small streams. This is because the model predicts a higher concentration of insecticide in smaller streams for a given amount of spray drift. However, the model does not account for interception by the canopy of vegetation over the streams. A study is needed to get data measuring canopy permeability, with the data used to parameterise the AgDisp model.

Anticipated outcomes:

- Defensible guidelines for conducting aerial spray operations that properly account for field conditions (particularly for certification)
- Maintain a healthy and productive eucalypt plantation estate by continuing to be able to protect from severe defoliation by above-threshold leaf beetle populations

Potential collaborations:

- Chemical companies
- Pesticide users in other situations

Project 1.3.3 Gonipterus biocontrol

A key outcome from the current FWPA project “A model system for the discovery and development of biocontrol agents against forest pests” (VNC418-1617) is the identification of biotypes of the parasitoide, *Anaphes nitens* (the most likely biocontrol candidate), that are climatically-matched to the environments where they would be deployed. The benefit from this work will come with the deployment of the biocontrol once the host-climate matching has been completed and the appropriate biotype(s) of the biocontrol agent chosen. To get to that point will require mass-rearing of the selected biocontrol agent followed by either inoculative or inundative release into plantation areas. Note: it is anticipated the likely candidate for final deployment will be a biotype of *A. nitens*, the most commonly encountered parasitoid emerging from *Gonipterus* species in WA *E. globulus* plantations in the current FWPA project.

Accordingly, it is not expected that will a need to screen chosen biotypes of *A. nitens* for non-target impacts.

Anticipated return:

- Valente et al. (2018) calculated that the management of *Gonipterus platensis* in *E. globulus* plantations in Portugal using biological control (with *Anaphes nitens*) provides a 2-4 times the economic benefit of management by using insecticide.

Anticipated benefits:

- Little ongoing management intervention needed after release of chosen biocontrol agent
- Significant reduction in insecticide use (currently all new plantings are treated with insecticide pills)
- More certification-compliant management

Potential collaborations:

- Brazil, Portugal and South Africa are collaborating in the current FWPA project and may extend collaboration into new project.

Project 1.3.4 Browsing mammals

Current management of browsing mammals in temperate hardwood plantations is expensive and has a low benefit : cost ratio compared with management programs for other pests (Figure 3). One reason for this is that a high intensity of management involving costly population control is uniformly applied. Past research (Bulinski 1999, Walsh and Wardlaw 2011) has shown that browsing pressure in many plantations is sufficiently low that those plantations could be successfully established with much lower levels of population control. However, attempts to identify factors that could reliably predict browsing risk have, so far, been unsuccessful. The likely reason is the low number of measured plantations used in those two studies to identify risk factors. This was a similar problem that frustrated early attempts to identify risk factors for predicting high leaf beetle populations. That problem was overcome when analysis made use of a much larger dataset accumulated from several years of operational monitoring of beetle populations (Edgar 2011). Similar datasets from monitoring of browsing management operations are now being captured by forest managers. A small project would be able to analyse those more extensive operational monitoring data in a renewed attempt to identify factors that can reliably predict browsing risk.

Anticipated benefits:

- Greater social acceptability of management through reducing the need for lethal population control measures against mammal browsers (particularly native species).
- Defensible management for certification.

Potential collaborations:

- Agricultural sector
- Government primary industries agencies
- Centre for Invasive Pests Solutions

Project 1.3.4 Teratosphaeria spp.

The area of *E. globulus* growing in areas conducive to *Teratosphaeria* spp. is increasing through the shift to regions with moister climates (Western Australia) and shift away from *E. nitens* on warmer sites that are suitable for *E. globulus* (Tasmania). While young *E. globulus* plantations can quickly recover growth rates following severe defoliation during leaf disease epidemics (Smith et al. 2017), the cost of those growth losses is nonetheless appreciable (Wardlaw 2010). There has been a large body of research done to understand the taxonomy (of the pathogens), pathology, aetiology, and impact of *Teratosphaeria* leaf disease and options for management through site-hazard identification, genetics (including maker-aided selections) and fungicidal control. A review of research would enable the most prospective opportunities to target for further development into operational procedures for management.

Anticipated benefits:

- Leverage maximum benefit from existing knowledge to identify most prospective options to develop into management programs

3. Developing RDE priorities and projects: threats from newly-established damage agents

Two exotic forest pest incursions, one a priority pest, established in Australia in the past decade – myrtle rust (*Austrolpuccinia psidii*) in 2010 and giant pine scale (GPS - *Marchalina hellenica*) in 2014. Eradication responses were initiated for both incursions but were unsuccessful. The process of transitioning to management has been completed for both species.

Myrtle rust diagnostics and pathways (Project 2.1)

A. psidii has rapidly spread to occupy a significant proportion of it's potential range in Australia (Berthon et al. 2018, Fernandez Winzer et al. 2018). The biotype *of A. psidii* that has become established – the Pandemic biotype – is causing severe biodiversity impacts (Carnegie et al. 2016, Pegg et al. 2017) to native Myrtaceae but is causing little damage to commercial forest species (Carnegie 2015). The Pandemic biotype of *A. psidii* may eventually become more damaging to commercial forestry species through mutation (Machado et al. 2015) or recombination (McTaggart et al. 2018). However, it is the further introduction of other *A. psidii* biotypes from the America's, particularly those infecting eucalypts (Stewart et al. 2018), that poses the greatest threat to the production forests. Two tools to reduce the risk of other myrtle rust biotypes from entering and establishing in Australia are rapid diagnostics and pathways analysis to identify and restrict high-risk pathways.

Detecting the entry of new *P. psidii* biotypes into Australia will be a challenge. Reviewing and updating diagnostic protocols for *P. psidii* as part of the Forest Biosecurity Surveillance Strategy should be a priority. New technologies that can screen rust isolates cheaply and quickly should be evaluated as part of such a review. Two such technologies, Recombinase Polymerase Amplification (RPA) and Loop-mediated Isothermal Amplification (LAMP), looks particularly promising. Cha et al. (2019) describes an application using RPA technology for rapid (30-minutes) in-field screening for Pine Wilt Nematode in wood tissue samples. Sillo et al. (2018) describe an application using LAMP technology for rapid (40-

minutes) diagnosis of *Heterobasidion irregulare* from environmental samples. Project 3.2.4 in the Implementation Plan for the National Forest Biosecurity Surveillance Strategy, which deals with developing or adapting diagnostic methods and tools, may be an appropriate vehicle for evaluating and potentially developing an RPA test for differentiating the Pandemic biotype from other myrtle rust biotypes. There is a high potential for this work to be done cooperatively with international collaborators. For example, a group in the USDA Forest Service (Rachael Sitz, Ned Klopfenstein, Mee-Sook Kim, Jane Stewart, and Phil Cannon) have submitted a grant proposal to develop a diagnostic protocol using LAMP technology for the rapid identification of myrtle rust biotypes and are looking for international collaborators, including Australia (Geoff Pegg, pers. comm.).

Australia is fostering links with other countries to develop a regional approach to identifying and managing high-risk pathways (currently functional links with NZ, USA, Sth.Afr., Sth.Am.). These links need to be maintained. South-east Asian countries are potentially the biggest pathway threat for other rust biotypes given their unregulated pathways between countries. Australian forest health specialists already have strong links with several Southeast Asian countries through ACIAR forest health projects. Australian specialists developing new forest health projects in Southeast Asian countries should seek to include, where appropriate, capacity building in myrtle rust surveillance and diagnostics.

Anticipated return:

- 3-4% of national value from hardwood based on the following:
- 6.6% of *Eucalyptus* and *Corymbia* plantations are in areas that are highly conducive to myrtle rust (based on Singh et al. 2016)
- Alvares et al. (2017) state productivity losses in eucalypt plantations on sites highly suitable for myrtle rust in Brazil

Anticipated benefits:

- Avoided operational complexity from addition pests requiring management
- Avoided additional pest burden in approx. 60,000 ha hardwood plantation and 3.5 million ha multiple-use forests in areas predicted to be highly suitable for myrtle rust (based on Singh et al. (2016)
- Avoided adverse environmental / conservation impacts from additional rust biotypes

Potential collaborations:

- Plant Research & Development Corporations - Plant Biosecurity Research Initiative
- Government agencies (biosecurity, agriculture, environment)
- Horticulture and nursery industry
- ACIAR (particularly S.E. Asian countries)
- International collaborators, particularly USA, NZ, Sth.Afr., Sth. Am.

Capacity building:

- Strengthens diagnostic support and provides a stronger linkage between those who make detections in the field and diagnosticians
- Strengthens forest industry capacity to contribute to national and international biosecurity effort

Giant pine scale biocontrol (*Project 2.2*)

The decision to discontinue eradication of the GPS incursion and switch to a transition to management was made in October 2016. Unspent funds from the eradication program were transferred to funding the first year of the transition to management with five elements: (i) strategic tree removal; (ii) further evaluation of insecticides; (iii) impact on tree growth and wood quality; (iv) life history and biology of GPS; and, (v) review the potential for biological control. The threat posed by GPS to Australian softwood plantations is still not understood based on damage but elsewhere incursions into new environments has been attributed with the progressive decline and eventual mortality of infested *Pinus* trees (Yeşil et al. 2005, Petrakis et al. 2010). The susceptibility of sub-tropical and tropical pines to GPS in Australia is unknown at this stage.

Strategic tree removal and chemical options will be controversial with some sections of the community and gaps in coverage are likely. These gaps could become the escape route for GPS to move from the peri-urban areas into plantation areas. Once there it will be much more difficult to contain as past experience with *Sirex* has demonstrated (Cameron et al. 2018b). If a suitable biocontrol can be developed then such gaps in coverage will largely be eliminated, offering good prospects for substantial delays in GPS spreading out of the peri-urban areas.

A proposal to screen biocontrol agents has been developed by Agriculture Victoria Research following a feasibility study completed in 2018 as part of the year one Transition to Management for GPS (Lubanga et al. 2018). The feasibility study identified two candidate species of chamaemyiid flies from the genus *Neoleucopis* that are predators of GPS, feeding on eggs and nymphs. The research proposal has been presented to FHaB for review. The proposal if supported will:

- Identify the two co-occurring chamaemyiid species and assess their respective distribution;
- Determine abundance and role in the natural control of GPS populations in their native range;
- Improved understanding of the biology, ecology and behaviour of *N. kartliana*, GPS and the Australian native scale insects that have been prioritised for host-range studies
- Investigate parasitoids of the two chamaemyiid species and their role in limiting the effect of the predatory flies on scale populations.
- Developing rearing techniques necessary for maintaining sufficient numbers of pest, agent and non-target species in quarantine for host-range experiments;
- Predict the host-specificity of *N. kartliana* through native-range field studies, and quarantine laboratory host-range experiments conducted in Australia;
- If results from host-specificity studies and risk analysis are favourable, apply for introduction of *N. kartliana* to Australia and develop a biological control agent release and impact assessment strategy in conjunction with industry.

- **Anticipated benefits:**
  - delay GPS spreading from the current peri-urban containment areas into commercial softwood plantations
  - lessen the severity of injury caused to trees in infested areas
  - reduce the economic and environmental costs of large-scale insecticide application programs

Potential collaborators:

- Agriculture Victoria
- European counties with GPS (mainly Greece and Italy)

4. Developing RDE priorities and projects: threats from damage agents not present in Australia

Funding from the Commonwealth government as an initiative flowing from the Agricultural Competitiveness White Paper (Commonwealth of Australia 2015) has allowed the development of a framework and strategy to properly resource and better integrate forest biosecurity within the national biosecurity system (Tovar et al. 2017, Department of Agriculture and Water Resources 2018a). The Strategy and its accompanying Implementation Plan (Department of Agriculture and Water Resources 2018b) were endorsed by the Commonwealth Government, Plant Health Australia and AFPA prior to its public release in 2018. Start-up funding provided by the Commonwealth government (by DAWR) has allowed some of the high priority actions identified in the Implementation Plan to commence. Those actions were focussed on key elements of Goal 1 – *Providing national forest biosecurity leadership and coordination* – and Goal 4 – *Reduce the risk of establishment of exotic forest pest in Australia*.

The actions detailed in the Implementation Plan were again reviewed at the National Workshop and reaffirmed. The subset of those actions that were determined to be RDE and that will remain to be done when start-up funding for the Implementation Plan provided by DAWR finishes (June 2019) have been brought into this investment plan. The specification of those actions has not been modified but the timing of some actions has been adjusted to synchronise with related actions identified for the other threat categories. Table 1 lists the actions, anticipated benefits and outcomes. Table 6 shows the indicative timing for each action over the first five years of the investment plan.

Anticipated returns:

- Australia's rate of successfully eradicating incursions of significant forest pests over the past 20 years is 20% - half the world average (Carnegie and Nahrung 2019).
- If we assume the implementation of national forest biosecurity surveillance strategy will lift rate of successfully eradicating significant forest pest to the world average one less significant pest will become established over the next 20 years
- A stretch target would be to exceed the world average and successfully prevent three[3] significant exotic forest pests from becoming established over the next 20 years

Anticipated benefits:

- Avoided operational complexity from addition pests requiring management
- Reduced risk of market access restrictions through regulation or economic barrier from greater phytosanitary cost-burden
- Reduce risk of unforeseen catastrophic consequences of exotic pest establishment

Potential collaborations:

[3] Of the three significant pests that biosecurity measures prevent establishing one would represent the status quo (i.e. what historically we would expect to prevent establishing), and two would be the additional prevented establishments above the status quo and thus represent the benefit derived from the strengthened measures.

- Plant Research & Development Corporations - Plant Biosecurity Research Initiative
- State and commonwealth government agencies (biosecurity, agriculture, environment)
- Other primary industries, particularly agriculture
- Local government
- International, particularly countries with comparable biosecurity targets (e.g. NZ, SthAf and SthAm)

Capacity building:

- Strengthens forest industry capacity to contribute to national biosecurity effort
- Strengthens and supports capacity within the forest industry to contribute to forest biosecurity effort, particularly through a focus to general surveillance effort
- Strengthens diagnostic support and provides a stronger linkage between those make detections in the field and diagnosticians

Forest & Wood Products Australia

5. Indicative schedule for RDE investment priorities

TABLE 6. INDICATIVE SCHEDULE OF PROPOSED INVESTMENTS IN RDE FOR DAMAGE AGENTS AMONG CATEGORIES, THEMES AND PROJECTS OVER THE FIRST FIVE YEARS OF THE INVESTMENT PLAN.

Damage agent category	RDE theme	RDE projects	Year 1	Year 2	Years 3	Year 4	Year 5
1. Long-established threats	1.1: Development of forest surveillance methods	1.1.1 Retrospective analysis	X	X			
		1.1.2 Development of systems, methods and products			X	X	X
	1.2 Climate change - adapting to heatwaves	1.2 Climate change - adapting to heatwaves	X		X	X	X
	1.3 Maintaining effective management procedures	1.3.1. *Sirex* - nematode inoculation / tropical pines	X	X	X		
		1.3.2. AgDisp parameterisation for drift / canopy permeability	X				
		1.3.3 *Gonipterus* biocontrol			X	X	
		1.3.1. Risk model for mammal browsers	X	X			
		1.3.1. *Teratosphaeria* review	X				
2. Newly-established threats	2.1 Myrtle rust diagnostics & pathways		X	X	X	X	X
	2.2 GPS biocontrol		X	X	X	X	

Damage agent category	RDE theme	RDE projects	Year 1	Year 2	Years 3	Year 4	Year 5
3. Threats not present	3.1: Reducing the risk of exotic threats through improved surveillance	3.1.1 Collate available historical forest pest data				X	
		3.1.2 Develop guidelines to determine if pests are native or exotic				X	
		3.1.3 Conduct forest specific national blitz surveillance				X	X
		3.2.1. Review diagnostic capability		X			
		3.2.3 Develop National Diagnostic Protocols for forest HPPs		X	X	X	X
		3.2.4 Develop diagnostic methods and tools to support forest biosecurity		X	X	X	X
		3.3.1 Review forest surveillance capability / capacity	X				
		3.3.2 Develop National Surveillance Protocols for forest HPPs		X	X	X	
		3.3.3 Support general forest surveillance		X	X	X	
		3.4 Data integration			X	X	
		4.2.4 Design an optimised National Forest Pest HRSS Program			X		
	3.2 Reducing the risk of exotic damage agents not amenable to surveillance	3.2.1 Review threats not amenable to surveillance. Develop & implement control activities	X	X	X		

6. Audit of capacity to undertake RDE

6.1. Background

Managing the threats posed by pests, diseases and climate change to minimise the risk of productivity / value losses relies on both the rapid application of specialist know-how in operational settings, and the development and conduct of RDE over longer time frames to provide the new knowledge and practices needed to successfully manage constantly evolving situations[4]. While the review of priorities for investment in RDE will be focussed on addressing those longer term RDE needs, realising the Vision of the GRAC will also require ongoing access to the specialist knowhow needed to support time-critical decisions. The component of the review dealing with research capacity provides the forum to consider that capacity in specialist know-how needed in operational and often time-critical situations.

The decline in technical expertise in forest health management within Australia has been documented by Carnegie et al. (2018a). They report a decline of more than 50% from numbers employed in 1995. This is part of a general decline in non-university scientific expertise in the forestry sector. Turner and Lambert (2012) documented nearly a 50% reduction in non-university forest scientists between 2008-12.

While the decline in the number of scientists has been documented, the impact of that decline on research activity and the capacity to acquire new knowledge in response to new forest health threats is unknown. Here, publication output is used as a surrogate for research activity.

6.2. Methods

The audit of research output was done by evaluating collations of three separate searches of the published literature to:

- detect changes in research activity by Australian researchers over the period 2008-18
- detect shifts in the types of institutions conducting research over the period 1980-2018
- document the demographics of researches involved in studies done between 2010-19 that underpinned the myrtle rust transition to management

6.2.1. Changes in research activity 2008-18

Google Scholar search engine was used to locate papers published in peer-reviewed journals between the period 2008-18 of studies relevant to the damage agents and their management for the main production forest species (*Pinus* and *Eucalyptus*), and that were written by Australian authors (senior or co-author). The studies were separated into nine subject areas: pathology, entomology, browsing mammals, fire / storm, climate (extreme climate events), host physiology, host impact, genetics, detection / surveillance. Inclusion of the main damaging pathogen and insect species of Australian production forests in the search terms were used to locate publications in the subject areas of pathology and entomology, respectively. Publications in the subject area of genetics were restricted to studies that included, as a component, resistance / tolerance to damage agents.

The number of published papers in all subject areas relevant to damage agents of Australia's wood production forests were summed for each year between 2008-18 and plotted to visually identify trends in publication rates (as a surrogate of research activity) over the period. The number of papers in each listed subject area published each year between 2008-18 were tallied. The average annual publication rate, by subject area, was calculated for two periods – 2008-12 and 2013-18. The ratio of the average 2012-18 publication rate : average 2008-12 publication rate was calculated for each subject area to

[4] Situations is used in the broad sense to reflect changes in operational and financial settings, changes in the biological settings (new pests/pathogens, new host crop species) and changes in the physical settings (changes to areas where crop is grown and climate change).

detect subject-specific changes in research activity across the period. Ratios of < 1 and >1 reflected declines and increases in research activity during the last half of the period, respectively.

6.2.2. Changes in institutions conducting research

The index of each issue of *Australian Forestry* from 1980 onwards was searched to compile a list of all papers related to damage agents in Australian forests. This journal has for a long time been the main repository for research and management of Australian forests. The journal is the most complete repository of the research effort that has produced the bulk of the contemporary knowledge and procedures for managing the main damage agents of Australia's wood production forests. This longevity of record spans the era when the ownership and management of the production forestry sector has undergone considerable change. For this reason, the record is used to examine the types of institutions contributing to the acquisition of knowledge and development of procedures for managing damage agents and track how the level of their contribution has changed over time. For each paper located the following information was collected and collated: the year and decade of publication; the type of institution (state government, CSIRO, commonwealth government, university, private) to which the senior author was affiliated; and, the subject area of the publication (as listed previously).

For each institution type the total published paper output for each decade was tallied, plotted and examined to describe decadal trends over four decades (1980-2018). The contribution of each institution type to total pool of published papers in each subject area was calculated (as a proportion of total), plotted and described.

6.2.3. Demographics of researchers contributing to myrtle rust publications

The incursion, attempted eradication and transition to management of myrtle rust (*Austropuccinia psidii*) in Australia is the most recent example of a priority pest species becoming established in Australia. The incursion and establishment provide the most complete contemporary evidence of Australia's research capacity for acquiring knowledge and developing procedures for managing a new forest damage agent. Google scholar searches were done to locate publications in peer-reviewed journals and reports to responsible agencies for the period 2010-2019 related to the Australian myrtle rust establishment. All authors contributing to each publication and their host institutions were collated. The host institutions were then classified as one of the following: state government – forest science, state government – biosecurity, state government – herbaria, state government – other, commonwealth government – research, commonwealth government – biosecurity, Australian university, Australian private consultant, International university, International government, International consultancy.

The number of publications contributed by individual researchers were tallied and classified in five publication output classes as follows: 1 publication, 2-3 publications, 4-5 publications, 6-9 publications, 10 or more publications. A frequency histogram of number of researchers in each of the five publication output classes was generated. Eighty nine percent of the authors belonged to six host institution types (state government – forest science, state government – biosecurity, commonwealth government research, Australian university, International university, International government). Further analysis to examine the demographics of the author's host institutions were limited to those six institution types. Cross-tabulations were done of the number of researchers by publication output class and host institution type. A chi-squared test was done to test for independent assortment of publication output class and host institution type.

6.3. Results

6.3.1. Changes in research activity 2008-18

A total of 584 published works involving Australian researchers and relevant to forest damage agents in Australian production forests were located. There was a moderate downward trend in publication output across the period 2008-18 (Figure 1a). However, that trend was unequally spread across the subject areas. Publication outputs increased during the latter half of the 11-year period in four of the subject areas – entomology, fire / storm, climate and tree physiology (Figure 1b). The remaining subject areas showed declines in output in the latter half of the period, with the decline in output greatest for the more management focussed areas – impact and detection / surveillance.

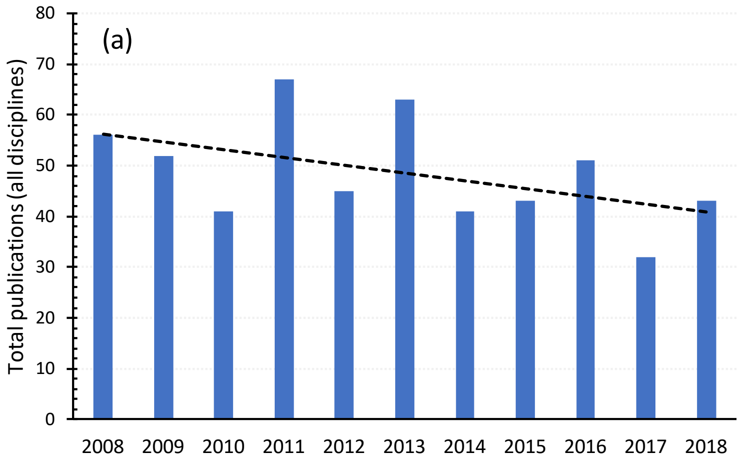

Figure 5. The annual number of publications between 2008-18 involving Australian authors that are relevant to forest damage agents in Australian production forests.

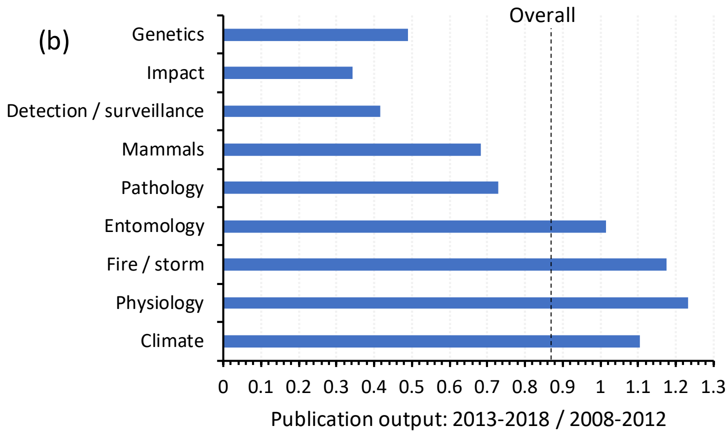

Figure 6. Fraction of the publication output done in the last five years (2013-18) relative to the first five years of the decade for each of nine subject areas. Source data as for Figure 5.

6.3.2. Changes in institutions conducting research

A total of 289 papers related to forest damage agents and their management have been published in *Australian Forestry* since 1980. Publication output increased steadily for three decades and then declined sharply over the last (Figure 7). State-based forestry agencies have been dominant contributors to published output over the four decades (Figure 8). However, there has been a decade by decade rise in the contribution from universities to become the dominant contributor to published output in the last decade (Figure 8). CSIRO has made a smaller but stable contribution to publication output across the four decades.

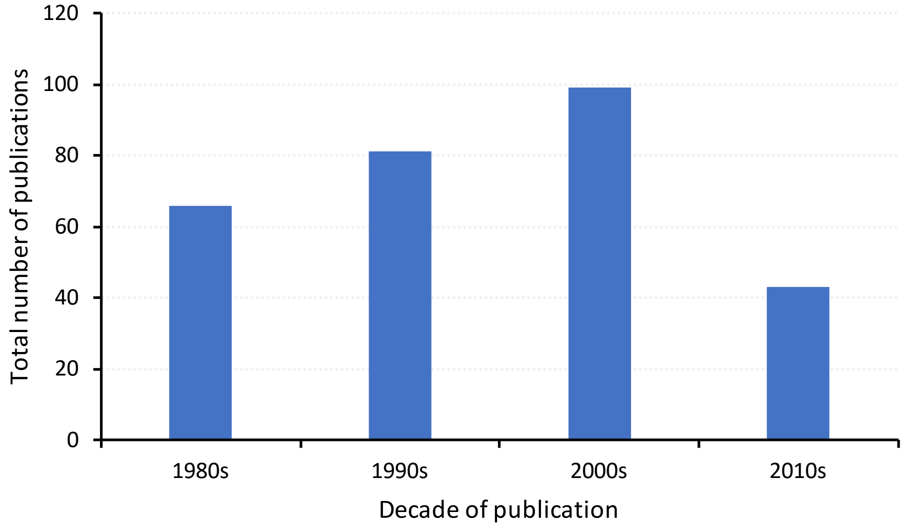

FIGURE 7. NUMBER OF PAPERS RELATED TO FOREST DAMAGE AGENTS PUBLISHED IN AUSTRALIAN FORESTRY OVER THE PAST FOUR DECADES.

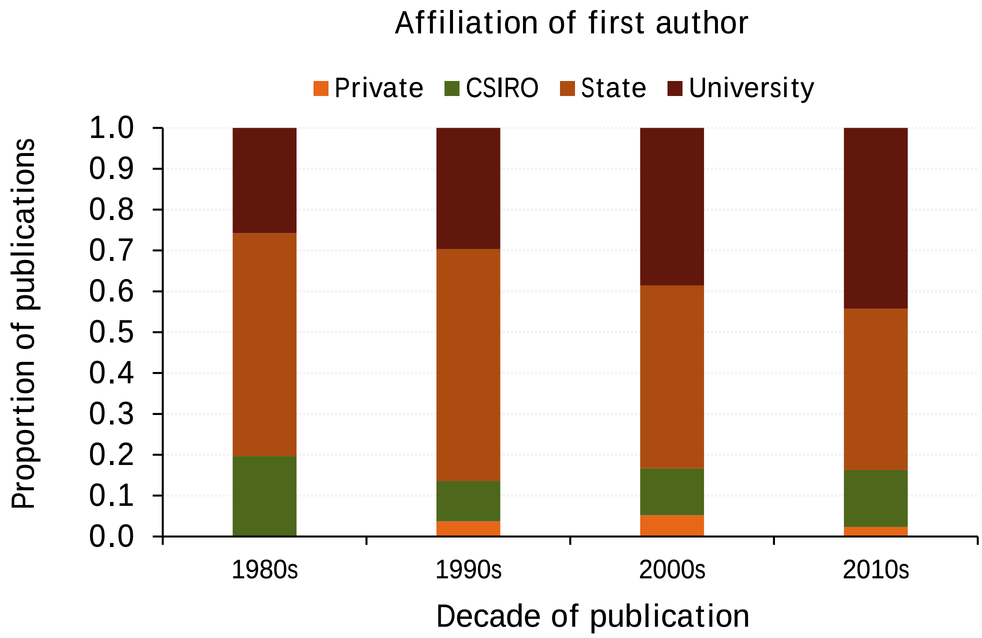

FIGURE 8. INSTITUTIONAL AFFILIATION OF THE SENIOR AUTHOR IN *AUSTRALIAN FORESTRY* PAPERS RELATED TO FOREST DAMAGE AGENTS PUBLISHED OVER THE PAST FOUR DECADES.

6.3.3. Demographics of researchers contributing to myrtle rust publications

Sixty published papers and reports documenting the myrtle rust incursion and establishment in Australia were located. A total of 154 individuals contributed to those published works with the great majority

(70%) contributing to a single published work (Figure 9). Five individuals (3%) contributed to six or more published works.

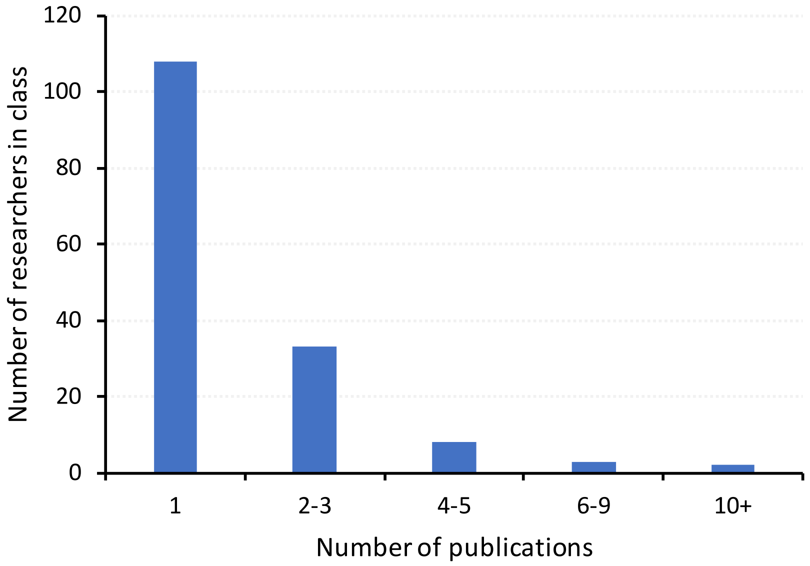

FIGURE 9. CONTRIBUTION OF INDIVIDUAL RESEARCHERS TO AUSTRALIAN MYRTLE RUST PUBLICATIONS released between 2010-2019.

There were significant differences ($\chi^2_{20} = 58.5, P < 0.001$) between the institution types in the contribution made by individuals to the body of published work. A small number of individuals (two) from state agencies with a forest science focus contributed to 10 or more published works (Figure 10a). The large contribution by this small number of individuals from state agencies with a forest focus was the most significant factor explaining differences between institutions in the contribution of individuals to the body of published works chronicling the establishment of myrtle rust in Australia (Figure 10b).

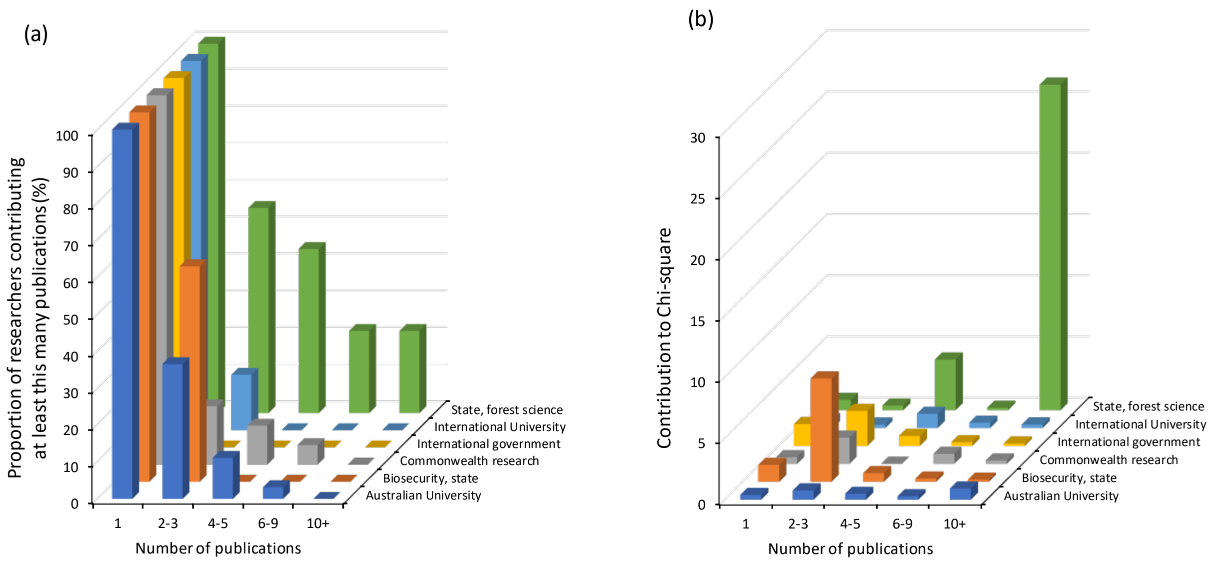

FIGURE 10. AUSTRALIAN MYRTLE RUST PUBLICATIONS BETWEEN 2010-19 shown as: (a) the number of publications contributed by individual researchers grouped according to the type of institution in which they work; (b) contribution of the total chi-square value of the test for independent assortment of the

number of publications by individual researchers and the the type of institution in which the researchers work.

6.4. Discussion and conclusions

Based on the evidence presented here, Australia is maintaining its capacity to undertake research into forest damage agents. Over the period 2008-18 there was a downward trend in publication output during the past decade. This decline was particularly sharp in Australian Forestry but less pronounced across all journals. This likely reflects a decreasing role of the forestry profession contributing to the research effort and in its place a greater contribution made by university researchers from non-forestry backgrounds. Although a decline in published output has taken place, it has not been as sharp as the decline in the number of non-university scientists documented by Turner and Lambert (2012), or the decline in the number of forest health specialists documented by Carnegie et al. (2018a).

An important consideration for research capacity in the biosecurity context is the capacity to rapidly acquire new knowledge during emergency responses following new incursions. The capacity to rapidly develop and undertake a program of research to support responses following a new incursion was tested during the past decade as part of the national response to the establishment of myrtle rust in Australia. Sixty published papers and reports documenting the acquisition of new knowledge were produced in less than a decade since the pathogen was first detected in 2010. This level of publication output was double that for *Essigella californica* in Australia over the 20 years following its detection and subsequent establishment in 1998.

The shifting focus of research output over the latter half of the last decade towards climate, and physiology mirrors the major RDE priorities that arose from the August 2018 workshop. However, research alone will not address the priorities developed from the expert workshop. FWPA invested in research into managing risks associated with drought and climate change during the past decade (Pinkard et al. 2014, Battaglia et al. 2015, Battaglia and Bruce 2019). In each case the lack of observations was a limiting factor in achieving the anticipated outcomes from the research. Forest surveillance will be needed to address this.

Industry capacity in surveillance is limited to a small number of large estate managers, mostly of publicly-owned plantations (Carnegie et al. 2018a). This is the area that of forest health management that has had one of the sharpest declines in research activity over the past decade. This investment plan proposes several actions to develop or adapt tools and systems to support forest surveillance. Importantly, there is a strong focus on having those tools and systems operate at the national-level and thus make surveillance accessible to growers in regions that may not have dedicated surveillance personnel.

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Appendix 1: Stakeholders consulted

Name	Organisation	Purpose
Don Aurik	Timberlands	Initial workshop
Rohan Burgess	Plant Health Australia	Initial workshop
Angus Carnegie	NSW DPI	Initial workshop, review of management issues, review of research
Ian Dumbrell	WAPRES - IPMG	Initial workshop, review of management issues
Stephen Elms	HVPlantations	Initial workshop, review of management issues
Natalie Heazelwood	AFPA	Initial workshop
Phil Lacey	PF Olsen	Initial workshop
Ian Last	HQPlantations	Initial workshop
Simon Lawson	Uni Sunshine Coast	Initial workshop, review of research
Jodie Mason	FWPA	Initial workshop
Helen Nahrung	Uni Sunshine Coast	Initial workshop, review of research
Jim O'Heir	Uni South Australia	Initial workshop
Geoff Pegg	Queensland Dept. Agric. and Fisheries	Initial workshop, review of research
Islay Robertson	HQPlantations	Initial workshop
Louise Shuey	Queensland Dept. Agric. and Fisheries	Initial workshop
David Smith	Dept. Economic Dev. Jobs, Transport & Resources	Initial workshop
Christine Stone	NSW DPI	Initial workshop, review of research
Sharyn Taylor	Plant Health Australia	Initial workshop
Francisco (Paco) Tovar	Plant Health Australia	Initial workshop, review of management issues, review of research
Suzette Weeding	Sustainable Timber Tasmania	Initial workshop
Dean Williams	Sustainable Timber Tasmania	Initial workshop
Karl Wotherspoon	Sustainable Timber Tasmania	Initial workshop, review of management issues
Andrew Jacobs	Forico	Review of management issues
Jim Wilson	Forico	Review of management issues
Brad Potts	University of Tasmania	Review of management issues
Greg Dutkowski	STBA	Review of management issues
Mike Battaglia	CSIRO	Review of research
Libby Pinkard	CSIRO	Review of research
Tony O'Grady	CSIRO	Review of research
Patrick Mitchell	CSIRO	Review of research
Tim Brodribb	University of Tasmania	Review of research
Julianne O'Reilley-Wapstra	University of Tasmania	Review of research
Jon Osborne	University of Tasmania	Review of research
Arko Lucieer	University of Tasmania	Review of research

Beryl Morris	Terrestrial Ecosystem Research Network	Review of management issues, review of research
Mark Grant	Terrestrial Ecosystem Research Network	Review of management issues, review of research
Peter Bailey	Terrestrial Ecosystem Research Network	Review of management issues, review of research

Appendix 2: Initial workshop

Park Royal Hotel, Melbourne Airport, Vic, August 29-30

Attendees:

Don Aurik[FHaB] (Timberlands), Rohan Burgess (Plant Health Australia), Angus Carnegie[FHaB] (NSW DPI), Ian Dumbrell[FHaB] (WAPRES / IPMG), Stephen Elms[FHaB] (Hancock Victoria Plantations), Natalie Heazelwood (AFPA), Phil Lacey[FHaB] (PF Ohlsen), Ian Last[FHaB] (Hancock Q'ld Plantations), Simon Lawson[FHaB] (University of the Sunshine Coast), Jodie Mason (FWPA), Helen Nahrung (University of the Sunshine Coast), Jim O'Heir (University of South Aust.), Geoff Pegg[FHaB] (Q'ld Dept.Agric.&Fisheries), Islay Robertson[FHaB] (Hancock Q'ld Plantations), Louise Shuey (Dept.Agric.&Fisheries, Q'ld), David Smith[FHaB] (DEDJTR Victoria), Christine Stone[FHaB] (NSW DPI), Sharyn Taylor (Plant Health Australia), Francisco (Paco) Tovar[FHaB] (Plant Health Australia), Tim Wardlaw[FHaB] (Uni. Tas.), Suzette Weeding (Sustainable Timber Tas.), Dean Williams (Sustainable Timber Tas.), Douglas Wilson (Dept. Agriculture & Water Resources, Forestry Branch), Karl Wotherspoon (Sustainable Timber Tas.)

Agenda

DAY 1 – WEDNESDAY 29 AUGUST		
8.30-9.00	Welcome Coffee, Tea & snacks	
9.00 – 10.30	Session 1 – Forest Health and Biosecurity across Australia	
	Welcome and introduction	Phil Lacy
	SNAP-SHOT PRESENTATIONS – 2 slides, 5 min per speaker What are you up to in forest health and biosecurity?	Various
10.30 – 11.00	Morning Tea	
11.00 – 12.00	Session 2 – Biosecurity Surveillance Implementation Plan	
	Forest Biosecurity Surveillance Implementation Plan – Context & Summary	Paco Tovar
	Q&A session, general discussion	ALL
12:00 – 13:00	Lunch	
13.00 – 15:00	BREAK-OUT GROUPS DISCUSSION Discuss Actions and Tasks in the Implementation Plan particularly: Is the project still necessary? What needs to happen? Estimate duration and budget?	ALL
15:00 – 15:30	Afternoon Tea	
15:30 – 17:00	BREAK-OUT GROUPS FEEDBACK Groups to report back to meeting	ALL
DAY 2 - THURSDAY 30 AUGUST		
8.30-9.00	Welcome Coffee, Tea & snacks	
9.00 – 10.30	Session 3 - FWPA R&D Priorities for forest threats	

	Investment plans to support GRAC vision	Jodie Mason
	Scope for investment plans	Tim Wardlaw
	How can we quantify impacts (production / value) from threats and losses averted from managing those threats?	Tim Wardlaw
10.30 – 11.00	Morning Tea	
11.00 – 12.00	BREAK OUT GROUPS DISCUSSION Discuss threat and management activity rankings (sent prior to workshop). Consider: Ranking of threats according to impacts Ranking of management activities in averting losses Trends, threats and opportunities	ALL
12:00 – 13:00	Lunch	
13:00 – 15:00	BREAK-OUT GROUPS FEEDBACK Groups to report back to meeting	ALL
	WORKSHOP SYNTHESIS Can we integrate Forest Biosecurity Surveillance Implementation Plan into the same investment framework as Forest Threats?	
15:00 – 15:30	Afternoon Tea – WORKSHOP END	

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Appendix 3: Detailed evaluation of identified issues for the shortlisted damage agents

1. Damage agents of temperate softwood plantations

1.1. Sirex

Issues identified	Status of issue	Investment priority
Levels of Kamona strain remain low in nematode population – reduced infectivity → increased intensity of inoculation → cost to maintain low Sirex population	PhD study (FABI – Bernard Slippers lab) investigating issue. Helen Nahrung is Australian collaborator (co-ordinating Australian collections of nematodes etc. for study).	Y (1.3.1)
Effectiveness of control in sub-tropics	Initial study by Nahrung et al. (2016a). *Ips* disruption of trap trees – considered a minor issue. Low nematode parasitism levels – will be informed through project 1a.	Y (1.3.1)
Ips disruption of trap trees	Temperate softwoods: addressed by study of Clarke et al. (2016)	N

1.2. Drought induced damage

Current routine management	Site-specific deployment of management (silviculture / genetics) based on drought-risk required but not possible to deliver currently.

Issues identified	Status of issue	Investment priority
Site-risk predictive model	Lack of observational data constraining development of predictive model (Battaglia and Bruce 2015). Develop tools and systems to support forest surveillance nationally. New observational data arising from surveillance updating predictive risk models / mapping. Benefit of accurate site-risk predictive model would be provided through more effective deployment of management (e.g. timing of	Y 1.1

	thinning). Cumulative value depends on recurrence of mortality events – this is one of the key outcomes from increasing observational data.	
Quantifying the impact - incipient versus obvious drought damage as trigger for silvicultural options	Recent advances in methods to detect permanent injury thresholds of water stress (Choat et al. 2018) but not applied yet to *P. radiata*. Observations from enhanced support for surveillance (project 2.2a) will help deal with quantifying injury thresholds. Benefit of accurate predictive injury threshold model would be provided through more effective deployment of management (e.g. timing of thinning). Cumulative value depends on recurrence of events above important injury threshold– this is one of the key outcomes from increasing observational data.	Y 1.1
Interactions with biotic agents	Surveillance data shows strong amplification in the activity of serious pests with drought (Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee 2018) but little understanding of process. Observations from enhanced support for surveillance (project 2.2a) will help inform biotic interactions. Benefit of clearer understanding of biotic interaction would be provided through more effective deployment of management (e.g. timing of thinning). Cumulative value depends on recurrence of events above important injury threshold– this is one of the key outcomes from increasing observational data.	Y 1.1
Site-silviculture options	Options well understood but deployment depends on comprehensive site-level drought-risk identification (Stone et al. 2012)	N
Genetics	Redefine site-genotype matching from findings of FWPA project (Ivkovich et al. 2015)	N

1.3. Vertebrate pests

Issues identified	Status of issue	Investment priority
Genetics	ARC linkage project in progress. Review outcomes upon completion	N (but see 1.3.4)
Crop protection versus population management?	Blue-sky thinking for whole of landscape approach. May be picked up in re-bid by UTas for ARC Training Centre	N

1.4. Essigella

Issues identified	Status of issue	Investment priority
Effectiveness of the biological control?	Ongoing monitoring of the spread of *Diaeretus* via annual surveillance in NSW, Vic. & SA	N
Contribution of local predators to control?	Not investigated	N
Risk maps to guide other management options e.g. nutrition management?	Stone et al. (2013) provided guidelines for risk-based management. Strong climate amplification of (drought and non-heatwave conditions) suggest site drought-risk predictions will be critical.	Y 1.1
Why doesn't it establish in subtropics?	Not investigated	N

1.5. Ips

Issues identified	Status of issue	Investment priority
Trapping to help manage damage events (push-pull strategy)	Semio-chemicals useful for managing bark beetles reviewed by (Gitau et al. 2013).	N
Risk profiling following damage event to assist salvage decisions	Not investigated.	N

1.6. Dothistroma

Unmanaged losses	Not quantified
Current routine management	*Dothistroma*-resistant material is available for deployment

Drying climate in Southern Hemisphere is becoming less favourable for epidemic disease (Woods et al. 2016)

Issues identified	Status of issue	Investment priority
Genomics	*Dothistroma*-resistant selections available through STBA (Stephen Elms pers comm)	N

2. Damage agents of temperate hardwood plantations

2.1. Drought induced damage

Issues identified	Status of issue	Investment priority
Detect stress / predict at-risk stands for early intervention	Lack of observational data limiting model development (Battaglia and Bruce 2019). Develop tools and systems to support forest surveillance nationally. New observational data arising from surveillance updating predictive risk models / mapping.	Y 1.1
Species selection for drought tolerance	Study by Dutkowski and Potts (2012) showed strong race-level differences in drought resistance in *E. globulus*.	N

2.2. Defoliating insects

Issues identified	Status of issue			Investment priority
Regulatory changes to chemicals / application are potential threats	APVMA move to AgDisp modelling to determine with of buffers on streams. That current model when applied to operational aerial spraying with α-cypermethrin would require buffer on smallest streams to increase from 50m to 300m (small streams have low water volume therefore a given amount of insecticide entering via drift would be greater than larger streams). This would dramatically decrease the proportion of the plantation areas that could be sprayed – 54% and 72% for 200 and 300m buffers, respectively when applied to a typical plantation estate in Tasmania. Forest Pest Management Research Consortium doing wind-tunnel studies to refine drift parameters in AgDisp Model. Plan to extend to include effect of canopy permeability (as smaller streams typically are fully covered by canopy).			Y 1.3.2
	Anticipated benefit (in averted losses from spraying) of parameterising AgDisp model for canopy permeability (assume model predicts current buffer widths).			
Biocontrol where appropriate	Current FWPA project (VNC418-1617) is using *Gonipterus* as a case-study for deploying more effective protocols for selecting biological controls by more accurately resolving (taxonomically and climatically) pest taxon and its associated natural enemies. The end-point is expected to be a climatically-matched biotype of the most commonly occurring natural enemy (probably *Anaphes nitens*) of *G. platensis* and *G.* sp. 2. Mass-rearing and release of the parasitoide will be the			Y 1.3.3

	next step in the development of a more targeted biocontrol.		
	Anticipated benefit in reduced management cost compared with current insecticide program	2-4 x based on findings of (Valente et al. 2018)	
Breeding for resilience	Ongoing opportunity to capture observations of resilience when genetic trials are harvested at end of rotation (Brad Potts and Greg Dutkowski pers comm).		N

2.3. Teratosphaeria spp.

Issues identified	Status of issue	Investment priority
Knowledge has not been reviewed and applied	Review current knowledge: taxonomy, quantification of impacts; management options (including tree breeding), forecasting/modelling hazard; surveillance for early detection and response	Y 1.3.5

2.4. Vertebrate browsers

Issues identified	Status of issue		Investment priority
Maintaining social license for lethal control	High intensity of population control (culling by shooting or trapping) used routinely. Past research (Bulinski 1999, Walsh and Wardlaw 2011) has shown a large proportion of plantations, nearly 60% in Walsh and Wardlaw (2011) had low browsing pressure and could be established with lower intensity of management. However, attempts to develop browsing risk model have had limited success because of low number of observations. Opportunity to make more use of operational browsing monitoring / management data in a similar way that was successfully used for developing a model to predict risk of high leaf beetle populations (Wardlaw et al. 2018). At least two forest management companies maintain operational browsing monitoring data - Forico for their hardwood and softwood plantations (Jim Wilson pers. comm.) and Timberlands for their softwood plantations (Don Aurik pers. comm.)		Y 1.3.4
	Risk-based management: 50% reduction in amount spent on browsing management in 50% of plantations predicted to be low browsing risk.		
	Anticipated annual benefit of risk-based management (Tasmania 10,000 ha per annum planting program)		

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3. Damage agents of tropical softwood plantations

3.1. Cyclones

Unmanaged losses	>30,000 ha from cyclones Yasi & Marcia (Geddes 2016). Financial losses are not well documented but (Skelton 2007) reported 100,000 m^3 volume loss from Cyclone Larry
Current routine management	

Issues identified	Status of issue	Investment priority
Have refinements to management been effective?	Refinements to management have been done in response to recent cyclone. Need to wait to see if measures developed and introduced have been successful	N

3.2. Blue stain & associated insects

Unmanaged losses	Not reported
Current routine management	

<table>
<tr><th>Issues identified</th><th>Status of issue</th><th>Investment priority</th></tr>
<tr><td>Handling damage, delays to processor</td><td rowspan="5">This damage agent and suite of issues was not investigated. Niche, high-value product with very specific and potentially expensive management solutions. Would require a detailed analysis before the costs and benefits of RDE investment could be attempted.
Note though there are well-established procedures for managing Ips and associated blue stain that evolved from research and monitoring done during the salvage of plantations burnt during the 1994 Beerburrum fire (Hood and Ramsden 1997, Wylie et al. 1999).</td><td rowspan="5">N</td></tr>
<tr><td>Capital-intensive solutions therefore need to analyse options</td></tr>
<tr><td>Management issue (seasonality, bark/debarked)</td></tr>
<tr><td>Treatment - changes to regulations</td></tr>
<tr><td>Training</td></tr>
</table>

3.3. Sirex

Unmanaged losses	Not reported (field behaviour still being determined)
Current routine management	To be determined once field behaviour is understood

Issues identified	Status of issue	Investment priority
Introducing nematode - need to know if it has been successful	Initial study by Nahrung et al. (2016a). Low nematode parasitism levels – will be informed through FABI PhD project that Australia is participating in via Helen Nahrung. Ongoing monitoring of field behaviour as Sirex and its biological control ecosystem becomes established in the tropical pine estatses	Y 1.3.1
Behaviour in different pine species	Known lower performance of nematode on hybrid pines due to less favourable growing environment for the fungus *Amylostereum* (Nahrung et al. 2016b), but suitability to host *Sirex* also lower. *Sirex* recently arrived in area contiguous with hybrid plantation. Feld monitoring commence this season (H. Nahrung pers. comm.).	Y 1.3.2

3.4. Drought-induced damage

Unmanaged losses	Not reported
Current routine management	None

Issues identified	Status of issue	Investment priority
Develop a more systematic plantation health surveillance system	Develop tools and systems to support forest surveillance nationally. New observational data arising from surveillance updating predictive risk models / mapping.	Y 1.1
Making use of available data: benefits extend beyond drought		Y 1.1
Better information to minimise risk		Y 1.1

4. Damage agents of temperate native forests

4.1. Heatwave

Unmanaged losses	331,000 m^3
Current routine management	None
[1.] (Wardlaw 2018)	

Issues identified	Status of issue	Investment priority
Mechanism causing temperature sensitivity not known	This is a new discovery and is globally-significant, therefore very prospective study academically. Clear experimental pathway using well-developed methods.	Y 1.2
Extent and degree of temperature sensitivity not known	Sensitivity extends from Sth Tas to Central Victoria. Only measured in ash forests but the extent includes main provenances of E. nitens and E. globulus. None of the physiological studies done on these two species can inform on temperature sensitivity (Libby Pinkard pers.comm.)	Y 1.2
No method to measure temperature sensitivity	Will flow from studies to determine mechanism. Until a method is developed we will not know the geographic, taxonomic and forest-age extent of susceptibility and therefore will be unable to account for impact (e.g. future yields). Until a method is developed we will be unable to determine if adaptation measures are working.	Y 1.2

4.2. Drought

Issues identified	Status of issue	Investment priority
Detect stress / predict at-risk stands for early intervention	Develop tools and systems to support forest surveillance nationally. New observational data arising from surveillance updating predictive risk models / mapping.	Y 1.1
Interactions with biotic agents		Y 1.1
Site-silviculture options	Future thinning of forests at Tumbarumba flux site will provide excellent data on the magnitude of soil moisture stress amelioration	N