Resources

Evaluating the costs and benefits of managing new and existing biosecurity threats to Australia's plantation industry

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Forest & Wood Products Australia

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Prepared for

Forest & Wood Products Australia

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Executive Summary

Australia's forest and wood products industry faces a significant challenge in mitigating biosecurity threats to plantation forest productivity. The term 'biosecurity threats' is defined here in its widest sense to encompass endemic and established exotic pests as well as pests not yet present in Australia.

Forest management planning must factor-in the costs incurred by ongoing monitoring and control that is essential for both native and established exotic pests. There is also the constant threat of invasive exotic pests that could add to these costs in future; a risk demonstrated recently with an incursion by the Giant Pine Scale (*Marchalina hellenica*).

Previously, industry was not able to make informed decisions about prioritising research funding for managing biosecurity threats because there were few, if any, cost-benefit analyses to provide a benchmark for Australia. This project addresses this need directly by:

- Analysing the risk posed by exotic pests to the Australian plantation forest industry.
- Benchmarking current forest health surveillance and biosecurity activities in Australia.
- Presenting three case studies on the costs and benefits of managing forest pests. Two, focus on pests that are already established — an endemic, native defoliating pest (chrysomelid leaf beetle) of Tasmanian hardwood plantations and an established exotic pest (Sirex woodwasp) causing mortality in *Pinus* plantations. The third is a scenario for an exotic pest incursion into a Queensland pine plantation estate (Japanese pine sawyer beetle carrying pinewood nematode).

We found that the risk of exotic pest incursions is increasing, despite international regulations regarding some high-risk pathways (e.g. wood packaging) as well as pre-border and border inspections programs. Over the last 15 years, pest interceptions at the border have been increasing, associated with a simultaneous, rapid expansion in the quantity of imported material and travellers (potential pest vectors) arriving in Australia.

Our benchmarking found that investment in forest biosecurity has not kept pace with the escalating risk. We identified shortfalls in both post-border surveillance (relating to forestry) and plantation surveillance; this is despite significant improvements in biosecurity response procedures after industry signed the Emergency Plant Pest Response Deed.

We also identified a number of gaps in Australia's ability to manage threats from exotic pests and diseases. Many of these gaps are now being addressed through the National Forest Biosecurity Surveillance Strategy (NFBSS) and associated Implementation Plan under the Federal Government's 2015 Agricultural Competitiveness White Paper. Three authors of this report — Angus Carnegie, Simon Lawson and Tim Wardlaw — were involved in this process.

The two case studies of established pests both found considerable financial benefit from applying management practices that arose from research. Both case studies highlighted the importance of co-ordinating the research and adoption of the resultant management practices. No management, or sub-optimal management conducted before research has been completed, each incur a large cost burden. Long delays between conducting research and implementing the resultant management practices also incur a considerable cost burden. Structural arrangements that allow research to be centralised and resultant management practices available to all affected plantation owners is likely to provide the best financial outcome.

In the invasive pest scenario, there are substantial returns on investment when forest biosecurity programs focus on preventing establishment, even of a single pest in one plantation estate. This suggests even bigger returns on programs that target many pests across the national plantation estate. Such programs are now under consideration by the NFBSS.

The outcomes reported here will give the industry greater certainty that future investments in forest biosecurity and preparedness RD&E are cost effective and will deliver genuine, long-term benefits.

A high priority for industry is early investment in research guiding management or control against key pests; a current example is Giant Pine Scale. In addition, greater investment in a national forest biosecurity program is an effective way to minimise future risk to the national forest estate.

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Introduction

Endemic and established exotic pests and pathogens create significant risks for the forest industry in Australia. These risks range from reductions in productivity through to complete plantation failure. The industry also faces a range of exotic biosecurity threats that, if they were to become established in Australia, may have severe effects on plantation productivity and viability. A significant impediment to ongoing industry investment in forest health and biosecurity R,D&E has been the high level of uncertainty surrounding the benefits of the research that addresses these issues and their application and deployment operationally.

Since the publication of the Forest Biosecurity and Preparedness Investment Plan in 2013, FWPA has funded as its highest priorities a revision to the Plantation Timber Industry Biosecurity Plan (2013) and production of the Biosecurity Manual for the Plantation Timber Industry (2015), in line with other plant industries. These projects have provided the industry with somewhat better preparedness in regard to managing the risks posed by exotic pests and pathogens. However, the industry does not presently have a good handle on the likely benefits from investment in forest biosecurity. This may be contrasted with weed management research (FWPA Herbicide Consortium) which has convinced its funding providers of the benefits of R&D and now has an ongoing funding stream. The effects of pests and diseases are not always clear unless there is a severe outbreak that may result in multiple tree deaths. This is due to the interplay between the pest, its host tree and environmental conditions. The historically reactive approach to pest and disease management in Australia (and overseas) often means that funding only becomes available when a problem emerges.

Over the last 100 years the Australian plantation industry has developed increasing confidence regarding the costs and benefits associated with a range of plantation investment inputs. Examples include:

- Genetic improvement: Clear gains in productivity have been made in exotic conifers and in the blue gum industries in Australia.
- Fertilisation: Optimum composition, use and timing of fertiliser application matched to site, soil and tree taxa. While there is less emphasis now on this research, most companies still maintain internal expertise and have the capability to address issues as they arise.
- Weed control: Effective weed management and ongoing research into the cost-effective use of herbicides has been supported by a Herbicide Consortium funded directly by industry (forestry and chemical companies), AFPA and FWPA.
- Silviculture: Optimised silviculture (thinning and pruning regimes, species-site matching etc.) has had a considerable historical research input and still attracts funding but mainly for fine-tuning under changing economic circumstances.
- Harvesting and operations: Efficiencies in harvesting trees and transporting them to processing facilities can deliver considerable economic advantages for minimal outlays. This has been recognised by the ongoing funding by industry and FWPA of the Australian Forest Operations Research Alliance (AFORA).

The above examples contrast with the relatively poor current state of confidence in Australia with regard to the benefits of managing already established pests and diseases in plantations, and even less so in regard to pre-border biosecurity threats, although recent interceptions (e.g. Japanese pine sawyer beetle and Asian longicorn beetle) and incursions (e.g. Myrtle Rust and Giant Pine Scale) are beginning to bring these to the fore in regards to risk management obligations of managers to their investors.

Two recent reviews commissioned by FWPA into Forest Biosecurity and Preparedness both made similar recommendations based on extensive consultation with industry and researchers. Recommendation 2 in Mohammed et al. (2011) was to conduct Benefit-Cost Analysis (BCA) to engage industry and demonstrate the benefits of how biosecurity must be carried out (with a favourable comparison made to how this is successfully undertaken in New Zealand), and with a further recommendation that this be funded by FWPA. FWPA commissioned a second review into Forest Biosecurity and Preparedness, which drew on the outcomes of Mohammed et al. (2011) and set the framework for the 2012 Investment Plan for Forest Biosecurity and Preparedness (Bailey 2012). This plan also emphasised that a comprehensive BCA be performed to illustrate the impact of pests and their control on economic returns from timber production (Funding Priority 3).

To directly address the need for a rigorous examination of the cost-benefits (B:C) of R,D&E in forest health and biosecurity, we designed and carried out five sub-studies. These are presented here as:

- Chapter 1: An analysis of the risk posed by exotic pests to the Australian forest industry
- Chapter 2: Benchmarking current forest health surveillance and biosecurity activities in Australia

These chapters are followed by two case studies on the benefits and costs of managing:

- Chapter 3: An endemic native pest (chrysomelid leaf beetles in Tasmania)
- Chapter 4: An established exotic pest (Sirex woodwasp)

And

- Chapter 5: An exotic pest incursion scenario for Japanese pine sawyer beetle carrying pinewood nematode into a pine plantation estate.

Outcomes from the studies presented here will assist industry in making better-informed decisions on the level and types of future investments in forest biosecurity and preparedness R,D&E and provide confidence that these problems can be effectively managed into the future.

1. The risk of exotic pests to the Australian forest industry

Summary

This chapter establishes that there is a clear — and ongoing and increasing — threat of exotic forest pests arriving into Australia. Specifically, we report that:

- There are a number of control activities across the biosecurity continuum already in place that aim to reduce the chance of these pests entering and spreading into Australia, and we describe these biosecurity processes.
- Analysis of Australian interception data for forest pests showed a general trend in increased numbers of intercepts over time of total pests, including high priority pests, with an especially rapid increase in numbers of intercepts since 2010.
- We present data on trade and pathways that show the major pathways that these pests are moving and how these are changing over time. Rapid increase in world trade is the major driver of increased interceptions.
- Only a small proportion of the total number of pests identified in pest lists appear to be moving on the various pathways into Australia.
- A high proportion of Australian intercepts are listed on the Plantation Forest Industry Biosecurity Plan High Priority Pest list (9 of the 13 listed insect pests were intercepted between 2000 and 2015) and a high proportion of all forest pest intercepts also have *Pinus* spp. as recorded hosts.
- Numbers of intercepts of beetles in the family Cerambycidae (longicorn beetles) formed both the major proportion of intercepts and the group showing the sharpest increase in intercepts since 2011. This raises questions on the effectiveness of ISPM 15, which was especially designed to regulate the wood packaging material pathway, a major source of entry for this important group of forest pests.
- We highlight recent programs run by the Federal Government Department of Agriculture and Water Resources that illustrate the potential cost-effectiveness of pre-border interventions in reducing numbers of pests arriving at the border.

Introduction

The forest, wood and paper products industry is a highly significant contributor to the Australian economy, ranking as the eighth largest manufacturing sector, and with gross value of sales in excess of $20 billion and an industry value-add of $7 billion in 2012-13 (ABARES 2014). As an individual sector, this ranks it higher than, for example, horticulture at $9 billion gross value of production (vegetables, fruit, nuts, etc.), wheat ($7.1 billion) and cattle ($7.1 billion) (ABARES, Australian Commodities 2015). Additionally, the industry directly employs over 75,000 people (ABARES 2014), with many of these jobs based in rural and regional Australia.

As with other agricultural industries, this production is under constant risk of the introduction of exotic pests and diseases that could impact negatively on industry productivity. Australia's softwood industry, which contributes about 75% to the value of overall production, is at particular risk given that it is based on exotic *Pinus* species which have a plethora of insects and pathogens associated with them in their native overseas ranges. In addition, novel host associations are also a threat to exotic species in Australia with *Sirex noctilio* woodwasp and *Ips grandicollis* bark beetle becoming pests of *Pinus radiata*. These associations are not found within either of the two pest's native ranges. While Australia has one of the strongest and strictest quarantine systems in the world it is not immune to these threats, as recent establishments such as myrtle rust (*Austropuccinia psidii*), and giant pine scale (*Marchalina hellenica*) demonstrate.

In this chapter we use the terms 'threat' and 'risk' with the following definitions. Threat: a factor that generally cannot be controlled. Threats need to be identified, but they often remain outside of your control. Risk: A factor that can be mitigated c.f. threat.

Forest Biosecurity Threats & Risk Assessment

To accurately gauge the risk that exotic pest threats pose to the Australian forest industry we need to understand the various components that together make-up their likelihood of entry and establishment. These components are (1) the suite of exotic pests that may threaten Australian forests (2) the likelihood of entry into Australia (pathways) of these exotic pests, and then into production areas or native forest (establishment), and (3) what control activities are in place to stop (or reduce the chance of) this entry and establishment (Figure 1).

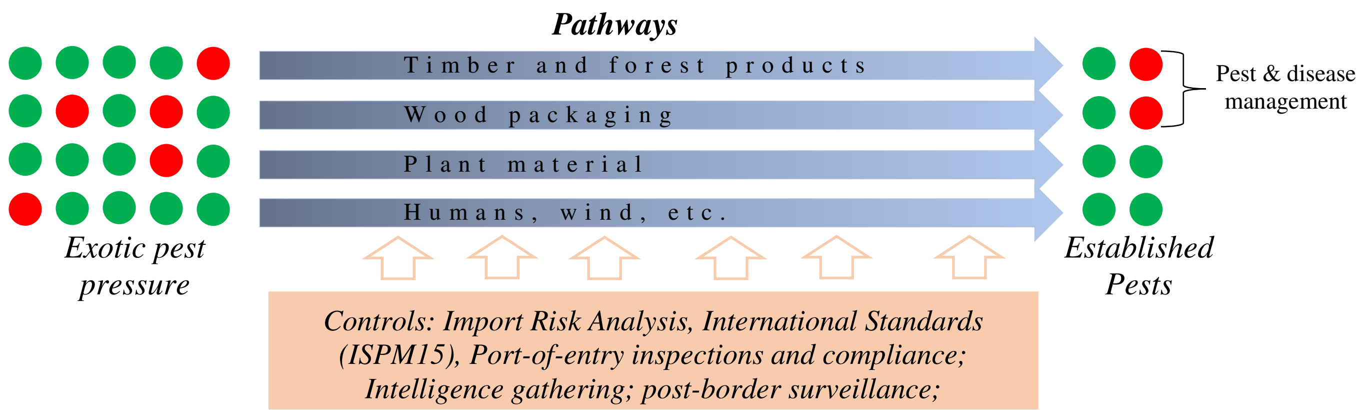


Figure 1: Stylised diagram illustrating pest pressure (potential pests that can enter and establish in Australia, including both quarantine pests [red] and non-significant pests [green]), various pathways of entry (e.g. imports), and control activities to reduce the chance of entry and establishment. Note that despite control activities, some pests still establish and result in ongoing management costs.

Pests

The first component we need to understand is what are the exotic pests that may threaten our forest industry if they arrive and establish. Here we use the broad term *pest* to encompass insect pests, fungal pathogens and nematodes. Various lists of exotic pests have been produced that we can draw on to identify the full suite of pests around the globe that may threaten Australia's forest industry.

The Subcommittee on National Forest Health (SNFH[1]) began defining a new comprehensive pest list by developing a 'Global Pest List' of exotic forest pests and pathogens, from which expert opinion was used to select a *Priority Pest List* for further evaluation, with the aim of updating the High Priority Pest list for Australia, but this work was not finalised before the disbanding of SNFH in 2014.

Other large lists have also been developed for forest pests, particularly for bark beetle and cerambycid pest groups (see Brockerhoff et al. (2014) and Leung et al. [2014]). Haack & Rabaglia (2013) estimate that there are in total 6,000 scolytines worldwide, including 1800 ambrosia beetles, that serve as a poll for potential movements of this highly significant pest family that is of particular importance for conifer species.

In the Australian Plantation Forest Industry Biosecurity Plan (PFIBP, Plant Health Australia 2013) twenty high priority exotic pests were identified. The PFIBP also includes a more extensive list in Appendix 1 (Plantation forest industry threat summary tables) which lists 24 invertebrate pests (including the 13 high priority pests) and 20 pathogens (including the 7 classified as high priority). This list was updated from the original 2007 Plantation Timber Industry Biosecurity Plan list using expert opinion and some new information on significant intercepts (e.g. Burning Moth, *Hylesia nigricans*), but the process was informal and not extensive. These lists included in the PFIBP were based heavily on a more extensive list compiled as part of a Federal Government commissioned "Import Risk Analysis for Sawn Coniferous Timber from Canada, New Zealand and the United States", which categorised pests of coniferous timber in those source countries by their presence or absence in Australia (DAFF 2004), including a total of 395 arthropod species alone. A new, formal pest risk analysis is therefore required to update and improve the overall pest list for Australia, including pathway analysis, analysis of interception records, likelihood of establishment and impact, etc. The abovementioned studies could serve as the basis for this revision, informed by the recently obtained interception data as first reported here.

Other countries have also developed similar lists. New Zealand, because of its proximity and common reliance on *P. radiata* for its softwood industry is particularly relevant. Sopow et al. (2010) identified 997 pest records on conifers from the literature, of which 583 had been recorded on *Pinus radiata*, with the vast majority of these not established in New Zealand (or Australia). For the New Zealand list, expert opinion was used to select 32 pests for further evaluation and risk rating to end up with a list of 12 High Priority Pest of conifers for New Zealand. This list includes several pests that were not included in the PFIBP priority list. Only a small proportion of these pests, however, are likely to be a significant threat if they established in production areas in Australia. Unfortunately, not all pests are identified as significant pests prior to their arrival. Sirex wood wasp (*Sirex noctilio*), Ips bark beetle and its

[1] Now disbanded, and "replaced" with the Forest Health and Biosecurity Subcommittee.

associated blue stain fungus (*Ips grandicollis* and *Ophiostoma ips*), Dothistroma needle blight (*Dothistroma septosporum*) and Myrtle rust (*Austropuccinia psidii*) were all known to be serious pests elsewhere before their arrival in Australia. However, Monterey pine aphid (*Essigella californica*) and Giant pine scale (*Marchalina hellenica*), for example, were not on any lists of potential exotic threats to Australia prior to their arrival. So, although pest lists can be useful to focus some biosecurity activities (e.g. surveillance for Gypsy moth, *Lymantria dispar*), they are not foolproof.

Trends in Risks

To gain insight into the threat that exotic pests and diseases pose to the Australian forest industry it is first essential to review what is happening globally, since Australia is tightly interwoven into the system of globalised and expanding world trade which is regarded as the primary driving force in the movement of forest (and other) invasive species around the world (Roques 2010; Roy et al. 2014; Wingfield et al. 2015). For forest pests, some of the best data on the rate of new introductions and their impacts that has been generated has come from the experience in North America and New Zealand, where good interception data has been married with data on incursions and establishments.

In forest biosecurity internationally there has been a focus on wood and bark boring insects, which include some of the most devastating forest pests globally and for which we have better data on interceptions and establishments than any other forest pest group. For example, Haack (2006) reported 25 new bark and wood boring Coleoptera that became established in the USA in the twenty years between 1985 and 2005, with more than one new species establishing per year. Most of these (18) were bark beetles (Coleoptera: Curculionidae: Scolytinae), a group that contains some of the most consistently destructive forest pests in the world. Of these beetle pests that established in the USA around that time, the emerald ash borer, *Agrilus planipennis*, is now devastating native ash in forests across the continental USA, and is likely to permanently alter the composition of many of these forest types (Herms & McCullough 2014). These trends have been repeated elsewhere in the world for other pests and pathogens (Humble & Allen 2006; Kenis et al. 2008; Roy et al. 2014). For example, Sudden oak death (*Phytophthora ramorum*) is also having permanent effects on oak forests in the USA (Swiecki et al.2016) while pine wilt disease (caused by the nematode *Bursaphelenchus xylophilus*) is having severe impacts on *Pinus* forests in north Asia and more recently in Portugal and Spain (Naves et al. 2016).

When looked at over longer time periods cumulative introductions for forest, agricultural and horticultural pests look remarkably similar, with a relatively steady linear trend up to around the early 1990's followed by an almost exponential increase in accumulations of exotic pests thereafter. The movement of Australian-origin pests is a typical example, as shown in Fig. 2 below, adapted from Hurley et al. (2016). This trend is likely to continue given the continued expansion in world trade, notwithstanding the ongoing effects of the Global Financial Crisis of 2008 on world trade.

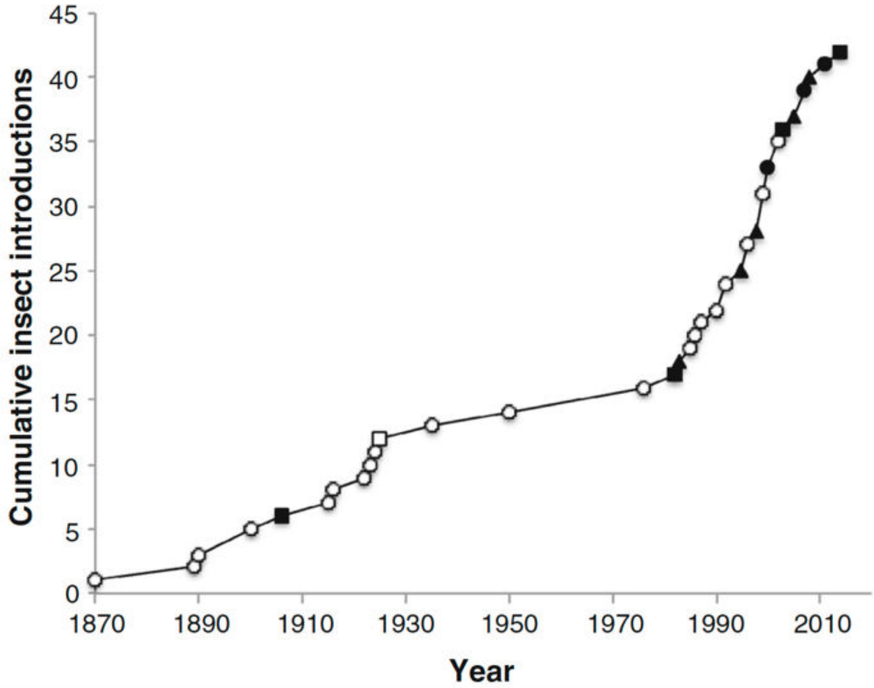


Figure 2: Cumulative introduction of insect pests feeding on eucalypts outside their native range in Australasia. Adapted from Hurley et al. 2016

To illustrate that the risk of establishment of these exotic pests is also real for Australia, we provide data on exotic pests and pathogens that have established in Australia over the past century (Figures 3 & 4). Over 90 pests and pathogens of arborescent hosts (including *Pinus, Eucalyptus, Salix* etc.) have established in Australia since detailed records began (this data is based largely from the Australian Plant Pest Database [www.planthealthaustralia.com.au], but also from published literature: Table 1 in Appendix 1 lists these pests and pathogens). Approximately 20 of these have caused serious damage to plantations, conservation forests and amenity trees (e.g. Sirex woodwasp, Dothistroma needle blight, Diplodia canker, Ips bark beetle (and its associated blue stain fungus), myrtle rust, poplar rust, etc.).

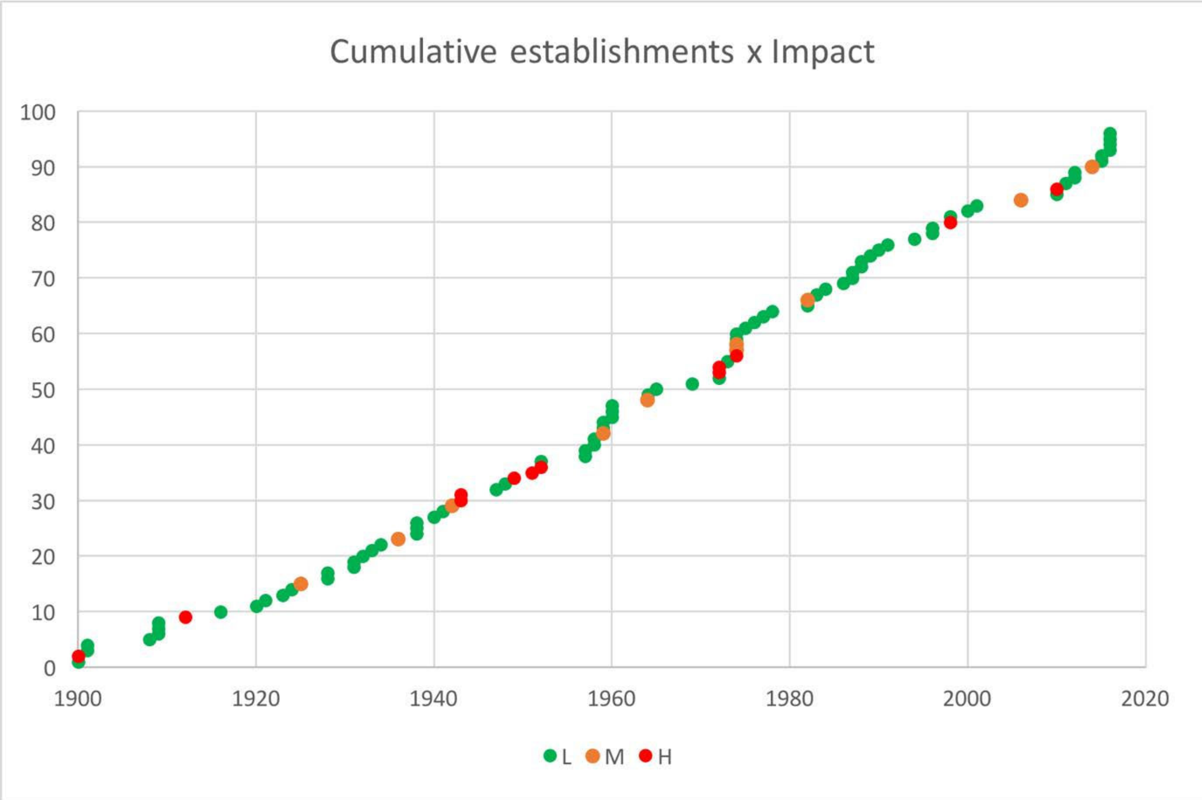


Figure 3: Incursion of exotic pests and pathogens on arborescent hosts (*Pinus* and "other" tree genera). Green = Low Impact; Orange = Medium Impact; Red = High Impact.

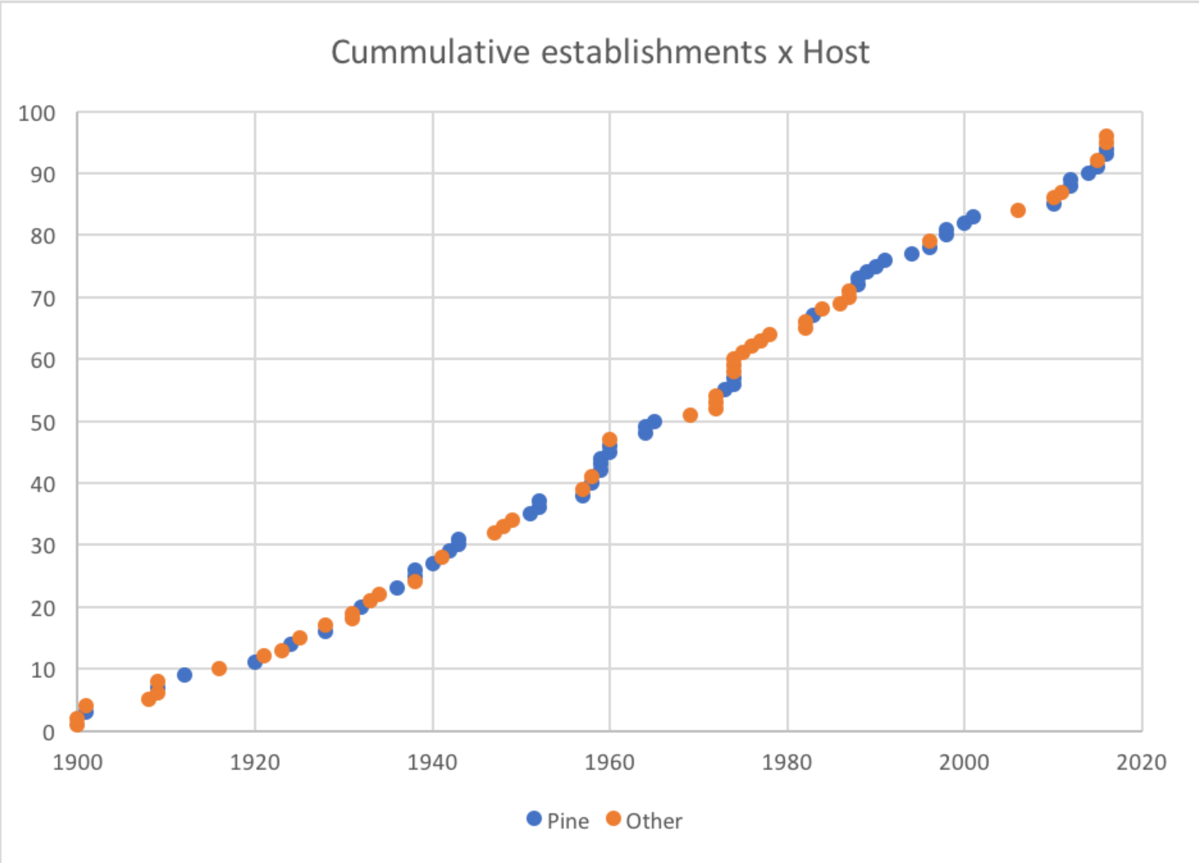


Figure 4: Incursion of exotic pests and pathogens on arborescent hosts (*Pinus* and "other" tree genera).

What can be noted from the comparison between Fig. 2 and Figs 3 and 4 is the lack of a rapid increase in establishments in the period following 1990 for Australia compared to the general world trend. The reasons for this are somewhat unclear, but may relate to the more stringent quarantine regulations that Australia has imposed on imports over an extended period, as well as Australia's isolation as an island continent with less porous borders in regards to movement of goods compared to Europe, Africa, Asia and North and South America. Other potential reasons are the high level of endemism in Australia's native forests and hardwood plantations and lack of seasonal synchrony makes it harder for exotic pests to establish than for species moving from Europe to North America, for example. This is one reason why Australia's plantations of exotic pine species are at particular risk. We show later in this chapter that the risk of introductions of more exotic biosecurity threats continues to increase due to increased movements of containers, pallets, dunnage and other high-risk material into the country, as well as increased numbers of interceptions of pests on this material over the last 15 years.

Pathway analysis of the likelihood of entry of pests into Australia

There are a large number of potential pests worldwide, only a relatively small number of which are likely to cause significant impact; *but how will they arrive here*? There are many pathways for these exotic pests to reach Australia, including, as outlined above, importation of goods in wood packaging, importation of live plant material, importation of timber and forest products, via international travellers or mail, and natural spread (wind). We can look at these potential pathways to further understand the risk of entry and establishment of exotic pests.

Pathways

As stated above, pest lists by themselves are of limited usefulness in that while some pests that are listed are consistent risks (e.g. gypsy moth) many that do establish and become pests were not on pest lists or would not have been included on a pest lists had they been developed at the time. This has led to an approach to attempt to prevent exotic pest movements based on managing and regulating the pathways on which pests travel, of which there are two major recognised pathways for forest pests (Roy et al. 2014).

Wood Packaging Material

Wood packaging material (WPM) is a well-known pathway on which many serious exotic pests have been able to travel around the world. In Australia, *Sirex noctilio* wood wasp and the five-spined bark beetle *Ips grandicollis* are good examples of pests which have most likely entered and established in Australia on this pathway. To regulate this pathway internationally, the International Plant Protection Convention (IPPC) developed the International Sanitary and Phytosanitary Measure (ISPM) 15 which began to be implemented widely in 2006. ISPM 15 mandates treatment measures (currently fumigation, heat treatment or microwave radiated) that reduces the risk that wood packaging material (pallets and dunnage in particular) can harbour live insects or pathogens. Treatment operators must be registered and the products stamped with the approved ISPM 15 logo, treatment type and registered treatment operator number.

A comparison of the numbers of forest and timber pest interceptions pre- and post-implementation of ISPM15 revealed that this phytosanitary standard reduced infestation rates on imported wood packaging 36-52% of pre-treatment articles (Haack et al. 2014). This was far below the original stated goal of ISPM15, and highlights the ongoing risk of this commodity to the forest industry in Australia. More positive was that compliance rates (a major issue with the implementation of ISPM 15) improved from 72.4 % in 2005 (the year the USA implemented ISPM 15) to 97.7 % in 2009 (issues of non-compliance are still being recorded in Australia). Pests of quarantine concern associated with wood packaging material were intercepted on just 0.14% of consignments in the USA. This relatively low figure needs to be considered in terms of the total number of sea containers entering the United States; 25 million at the time, of which approximately 52% are thought to contain wood packaging material. On this basis Haack et al. (2014) estimated that this still meant that around 13,000 containers entering the USA annually were infested with live wood pests.
Brockerhoff et al. (2006) further highlight the risk of wood packaging material, with 73% of interceptions of timber pests (bark and ambrosia beetle - Scolytinae) into New Zealand associated with dunnage, crating and pallets. They also show the origin of risk of infestation on such goods is not uniform, with the majority of interceptions originating from Europe (31.3%), Australasia (19.8%), northern Asia (14.5%) and North America (14.2%). Interceptions from China increased significantly in the last decade of data (1990-2000), indicating a large increase in trade with this country (see the by-country analysis of Australian intercepts below for comparison).

In a review of risks associated with the importation of forest products AQIS (1999) reported over 13,000 interceptions of pests on imports of timber and wood products in the period 1986 to 1998. Interceptions included significant pests of living trees (e.g. Cerambycidae, Siricidae, Buprestidae, Curculionidae) and timber-in-service pests (e.g. Bostrichidae, Isoptera, Anobiidae). These were intercepted on a wide variety of products from a wide range of importing countries. Less than half of these interceptions were identified to genus level, and even less (30%) to species level, so it is difficult to gauge what proportion of these were actually "quarantine pests" (i.e. high priority pest or on the *Priority Pest List*). However, over 3,000 of these interceptions were not present in Australia, and therefore of potential quarantine concern. Furthermore, during 1997–1998 alone, AQIS intercepted 441 insects on wooden packaging, 50% of which were known exotic timber borers or potential timber borers (Biosecurity Australia 2001b). Moreover, a detailed study in 1999 of imported green bulk timber from Canada and USA indicated that the then current inspection methods (external inspection only) would have missed 30% of bundles that actually contained quarantine pests (Biosecurity Australia 2001a).

A survey of 3001 sea containers in Brisbane identified that 3.5% of these were infested with at least one species of forest and timber pests (in the families Bostrichidae, Curculionidae [Scolytinae], Cerambycidae and Siricidae), including key exotic pests such as *Urocerus gigas, Sirex juvencus, Heterobostrychus aequalis,* and species of *Arhopalus* (Stanaway et al. 2001). Of wood item consignments inspected by the former Australian Quarantine Inspection Service (AQIS) at Australian ports, 0.51–0.65% were infested with live insects (Salvage (1999), cited in Haack et al. [2014]). Note that 3.5 million shipping containers now arrive in Australia annually, so even these small percentages also represent large numbers of containers infested with forest and timber pests. Using these figures this would represent almost half a million containers (490,000) entering Australia annually with potential forest pests.

In 2006, Biosecurity Australia (2006) published updated data of exotic pests intercepted during port-of-entry inspections from 1975 to 2003, with over 5,500 exotic insects detected on wood packaging materials alone (i.e. this does not include pests intercepted on break bulk timber imports etc.). These included pests identified as forest industry High Priority Pests, such as *Monochamus alternatus* (Japanese pine sawyer beetle), *Urocerus gigas* (giant woodwasp), as well as many Scolytidae (bark beetles) and Cerambycidae (longicorn beetles) not identified to genus that could well have been quarantine pests.

To put this into perspective, as part of an inquiry into environmental biosecurity, the Australian Government provided data on interceptions across all plant industries for the period 2009–2014, with 16,100–18,700 pests detected annually (Department of Agriculture & Department of Environment 2014). The largest number of interceptions were at "quarantine intervention points" (approximately 15,000 per annum), with approximately 1,500 per annum at "post quarantine detection" points (i.e. almost 10 % post quarantine). The bulk of detections arrived either by air or sea.

Using interception data for 2000–2015, we provide an update below that confirms the increasing and serious threat posed by exotic pests reaching Australia's borders.

Plants for Planting

Movement of pests on live plant material is another major pathway for forest pests worldwide, with Liebhold et al. (2012) estimating that 70% of all pest and pathogen establishments between 1860 and 2006 in the USA likely entered on live plants. They comment specifically on four important forest pests and pathogens in the USA that have moved on this pathway (White pine blister rust (*Cronartium ribicola*), Sudden oak death (*Phytophthora ramorum*), Citrus longhorned beetle (*Anoplophora chinensis*) and Light brown apple moth (*Epiphyas postvittana*) [an Australian-origin pest]. A number of other studies have also identified the importance of this pathway (Brasier 2008; Wingfield et al. 2015). The situation surrounding live plant imports was serious enough for more than 70 plant pathologists in 2011 to prepare the Montesclaros Declaration that stated *"As scientists studying diseases of forest trees, we recognize that the international trade of plant material is increasing the risks to forest health worldwide. The evidence for this view is based on the recent, unprecedented rise in numbers of alien pathogens and pests emerging in natural and planted forest ecosystems in all parts of the globe. We thus propose a phasing out of all trade in plants and plant products determined to be of high risk to forested ecosystems but low overall economic benefit"*. The stated goal is not likely to be achieved, but work has progressed through the IPPC and other plant protection organisations to develop a standard, ISPM 36 "Integrated measures for plants for planting", that should reduce risk along this pathway. ISPM 36 was adopted in 2012 and the standard published in 2016 (see: https://www.ippc.int/static/media/files/publication/en/2016/01/ISPM_36_2012_En_2015-12-22_PostCPM10_InkAmReformatted.pdf).

This pathway is less problematic for Australia as long as the strong quarantine restrictions currently in place for live plant material are maintained. For example, importation of *Pinus* spp. nursery stock is completely prohibited from most countries of origin, while tissue culture stock of species other than *P. radiata* is permitted under stringent conditions, including being grown in a post-entry quarantine facility for a minimum of two years for disease screening (BICON database: https://bicon.agriculture.gov.au/BiconWeb4.0). Import of nursery stock and tissue culture of *Eucalyptus* is currently completely prohibited. New Zealand and Australia are widely recognised as having the strictest phytosanitary regulations in the world pertaining to plants for planting, while Europe has the least stringent amongst developed countries, with these imports generally authorised across all EU borders (Eschen et al. 2015). Due to the lower risk of this pathway for Australia compared to other parts of the world, we have concentrated in this chapter on analysing risks created to the Australian forest industry by the wood packaging pathway, although we cannot discount movements on this pathway through illegal importation of live plant material.

How are exotic pests and diseases getting to Australia?

Every year Australia allows people and imported commodities into the country that bring with them the risk of exotic pests and pathogens. Figure 5 shows the common transmission pathways for these pests and pathogens.

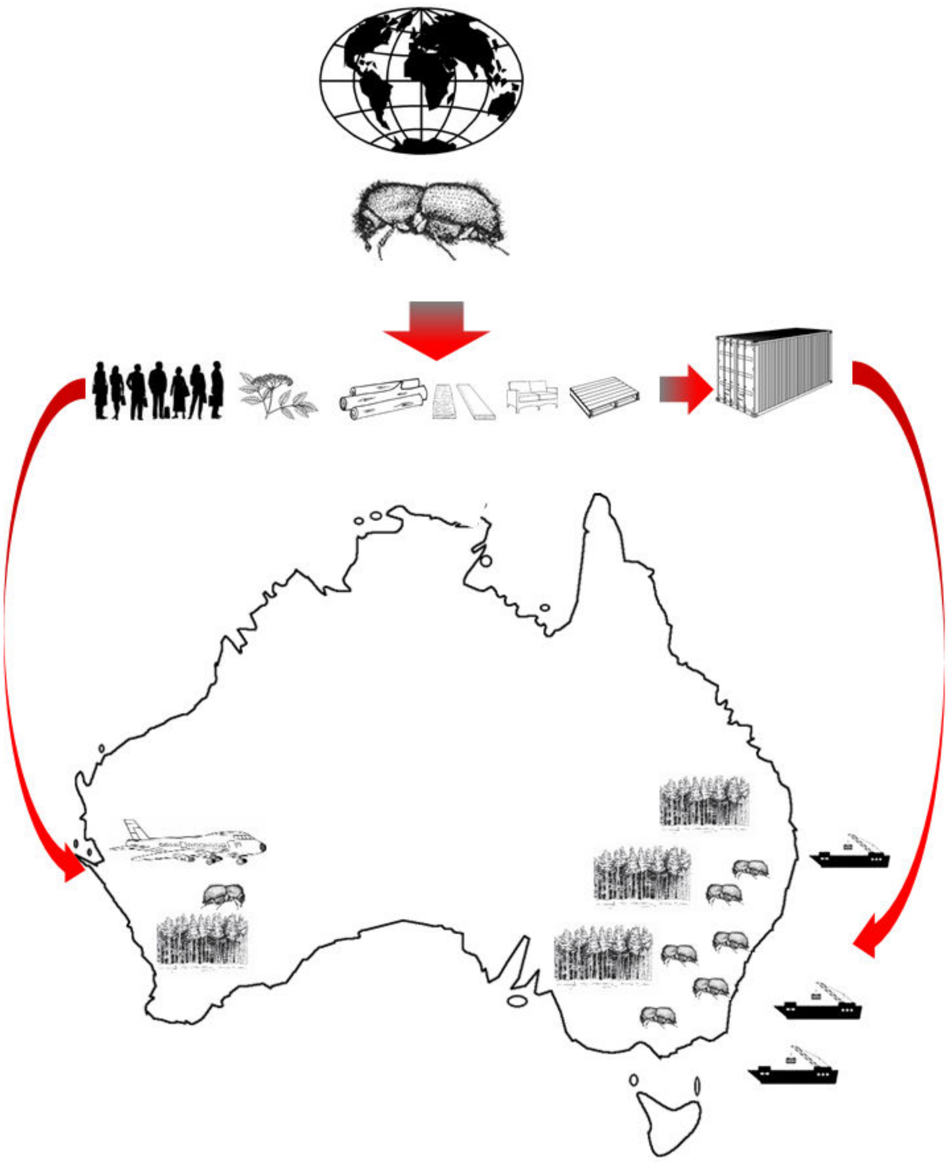


Figure 5: Common pathways for the transmission of exotic forestry insect pests and pathogens

To assist this project in improving our knowledge of the situation regarding movement of forest pests on pathways into Australia, the Federal Department of Agriculture and Water Resources (DAWR) provided the project with intercept data from 2000 to 2015 from their 'Incidents' database. DAWR have advised that interpretation of this data should be treated with caution, as is the case for data of this type collected by similar agencies overseas (e.g. USDA APHIS, MAFF New Zealand) since factors such as effort and access to diagnostic expertise etc. inevitably change over time in an operational environment. Nonetheless, a number of studies have shown the value of this data in monitoring trends in pest movements around the world and in assessing threats, and intercept data also remains our best estimate of propagule pressure (frequency and numbers of pests occurring at the border - Brockerhoff (2009); Brockerhoff et al. (2006); Brockerhoff et al. (2014); Burnip et al. (2010); Haack et al. (2014); Haack & Rabaglia (2013); Humble (2010); Zahid et al. (2008)). Data for the most part is of adult insect intercepts, and so because larval intercepts have not been included, total intercepts may be underestimated. The results presented here should only be considered a preliminary analysis of this information – a more thorough analysis of this data, including further guidance in its interpretation from experienced DAWR biosecurity staff will be provided in a scientific paper to be generated from this work.

Using these pest interception records (n= 963) as a guide shows us that shipping was the primary pathway for exotic pest movement into Australia. Between 2000 and 2016 shipping accounted for 92% of all exotic insect interventions with the balance associated with aircraft, international mail and other unknown sources (Fig. 6).

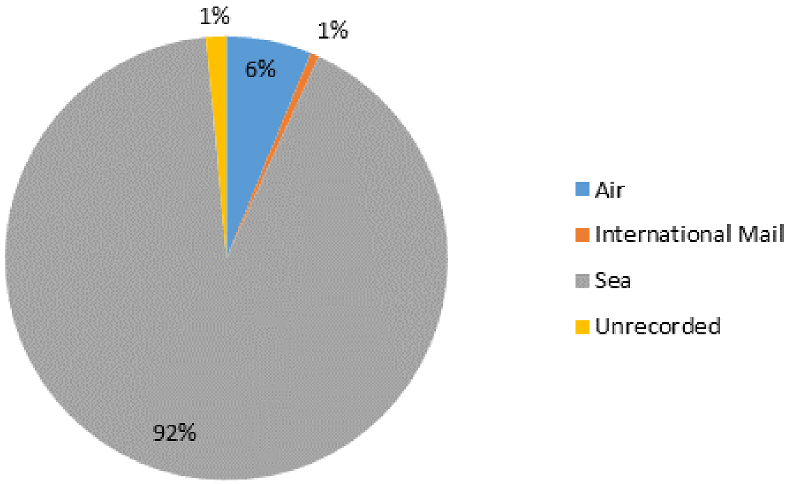


Figure 6: Arrival mode of intercepted imported exotic insects

To put the scale of the shipping pathway into context, in 2013-14 3.5 million shipping containers were imported to Australia with only a very small percentage subject to biosecurity inspection. These containers arrived at 16 seaports with 62% of all containers arriving at the ports of Sydney and Melbourne (Fig. 7).

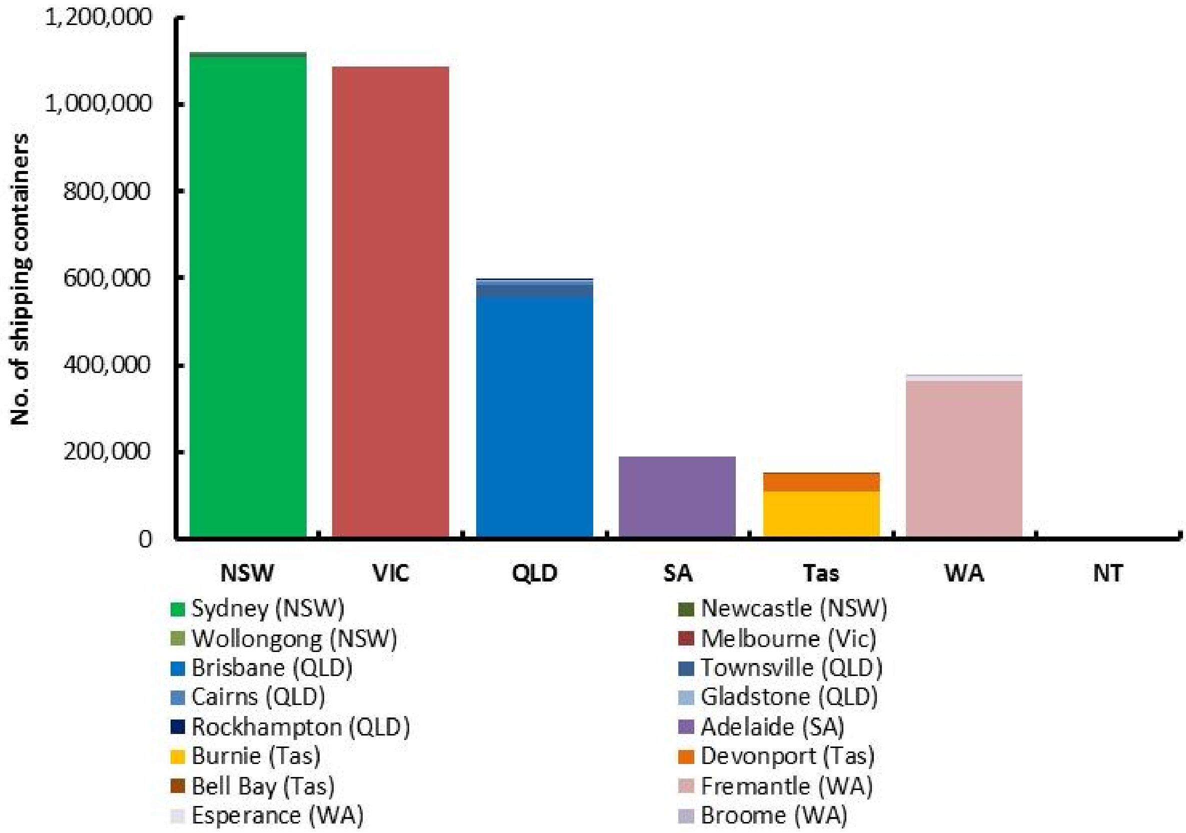


Figure 7: Total number of shipping containers (TEU*) imported to Australia in 2013-14 by State and locality. Data source: http://www.portsaustralia.com.au/aus-ports-industry/trade-statistics/ & http://www.cbfca.com.au/documents/TBMTS_Data_April_2015.pdf. * TEU - Twenty-foot equivalent shipping container unit

Although much less significant than shipping, air travel is also a recognised pathway for the introduction of exotic pests. In 2014 Australia had 6.36 million international visitors from over 23 different countries. The vast majority of these visitors arrived by air. In 2014 New Zealand and China accounted for 30% of the total visitors (Fig. 8).

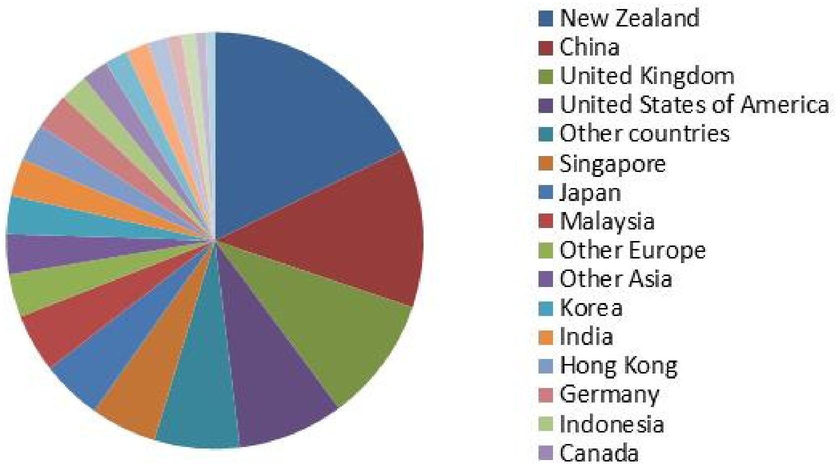


Figure 8: International visitors to Australia in 2014 by country of origin. Data source: Austrade Tourism Research Australia

How many potential pests and diseases are making it to Australia's border?

Over the past 16 years (July 2000–February 2016) DAWR Biosecurity has recorded close to one thousand incidents (n=963) involving the interception of exotic forest pests. Analysis of these incidents reveals that 68% (n=650) are known or likely exotic insect pests with 31% of these (n=250) priority listed as a serious threat (high risk). Of the remaining incidents (n=313), 16% (n=157) involved insects that were classified as low risk and 16% (n=156) were classified as having an unknown risk status (Fig. 9).

Figure 9: Incidents involving the interception of exotic insect species by risk category (July 2000 to Feb 2016). Data source: Commonwealth Department of Agriculture & Water Resources – Compliance Division

Much less is known about the importation of exotic forestry pathogens as there is no easy procedure or mechanism for monitoring their arrival. Examples of existing exotic forestry pathogens include Dothistroma Needle Blight and Phytophthora Root Rot. How these pathogens arrived in Australia has never been clearly resolved.

What hosts do exotic pests use to get to Australia?

Exotic insect pests utilise a broad variety of hosts to enable their spread. Australian Border Security records show that nearly half of all interception incidents are associated with wood products and wood packaging (Fig. 10).

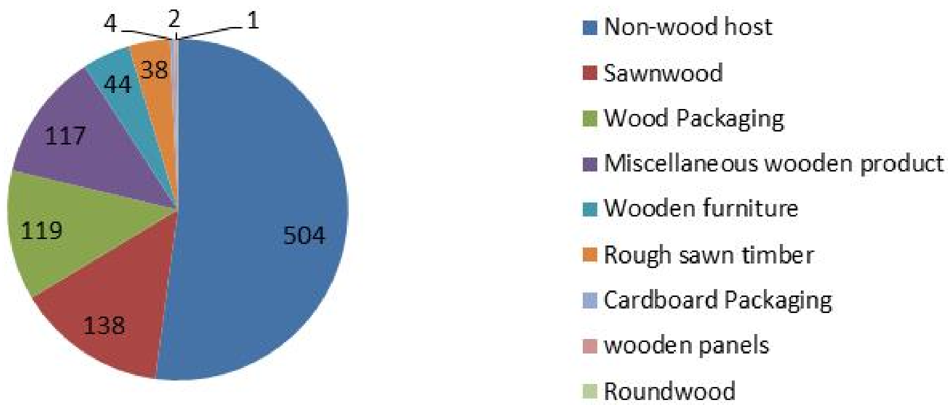


Figure 10: Number of exotic insect interception incidents (n=963) at the Australian border by host type (July 2000 to Feb 2016).

Analysis of non-wood hosts shows that over half of all exotic insect interceptions occur on shipping vessels. Generic goods ("Goods Other") and shipping containers are the next most common host (Fig. 11).

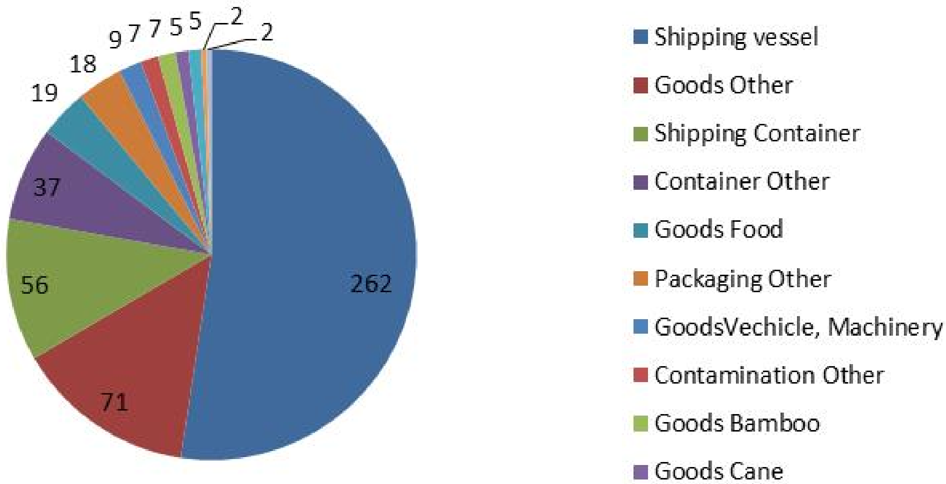


Figure 11: Number of exotic insect interception incidents (n=963) at the Australian border by 'Non-wood' host type (July 2000 to Feb 2016).

Where are the exotic pests coming from?

DAWR Biosecurity intervention records show that over the last 16 years exotic pests have originated from 52 different countries. However, 90% of all incidents are attributable to 16 countries and over 60% may be attributable just to New Zealand and China (Fig. 12).

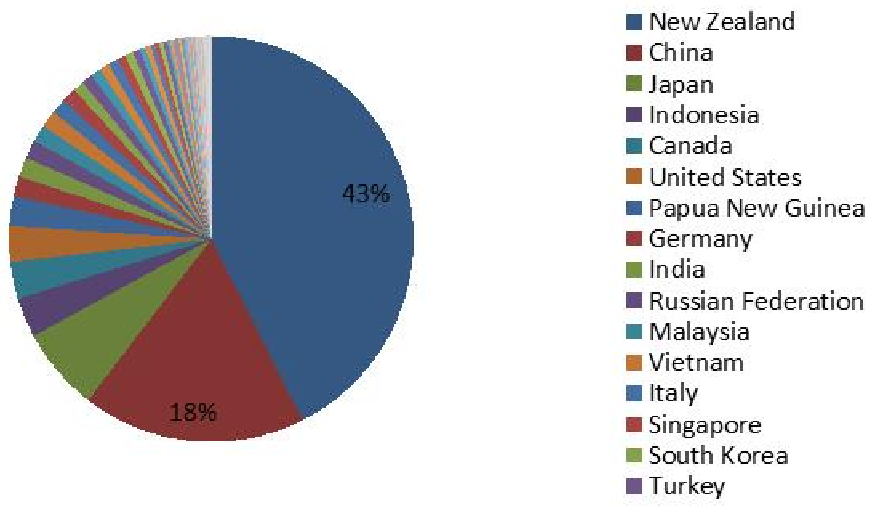


Figure 12: Number of exotic insect interception incidents (n=844) at the Australian border by country of insect origin (July 2000 to Feb 2016)

Closer examination of the interception records reveals that a single pest species, Burnt Pine Longicorn (*Arhopalus ferus*), has been responsible for 45% (n=383) of all incidents. This pest, which is regarded as having a medium risk rating in the PFIBP, is easily detected and periodically turns up in large numbers at shipping port facilities primarily originating from New Zealand. Figure 13 shows the effect of excluding this pest from the data.

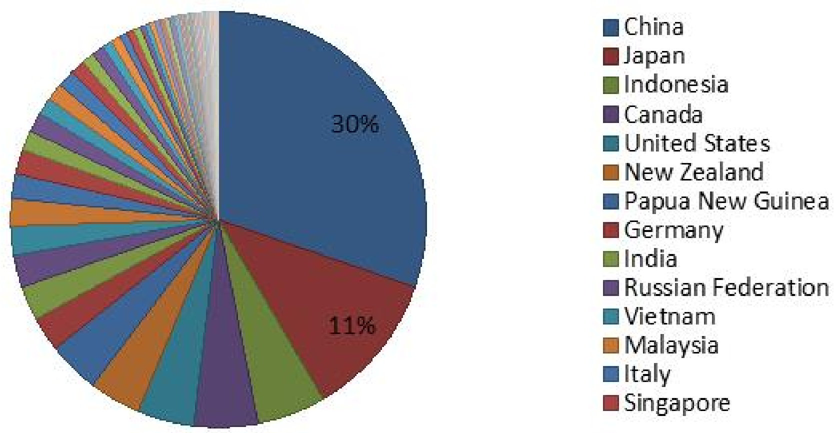


Figure 13: Number of exotic insect interception incidents (n=522) at the Australian border by country of pest origin with Burnt Pine Longicorn records excluded (July 2000 to Feb 2016)

When Burnt Pine Longicorn records are ignored the significance of North and South East Asian nations as a source of exotic pests is raised and the ranking of New Zealand drops from first to sixth. China, Japan, and Indonesia become the top three sources of exotic insect pests and Papua New Guinea, India, Vietnam and Malaysia fall within the top dozen.

As wood products and wood packaging are associated with roughly half of all exotic insect pest incursion records it is appropriate to examine their origin. For sawn wood there are 28 countries that supply sawn wood to Australia (Fig. 14). New Zealand is by far the largest supplier exporting 241,000m^3 to Australia in F2015 which constituted 25% of the market. The Czech Republic is the second largest supplier at 113,000m^3 which represents 12% of the imported sawn wood market.

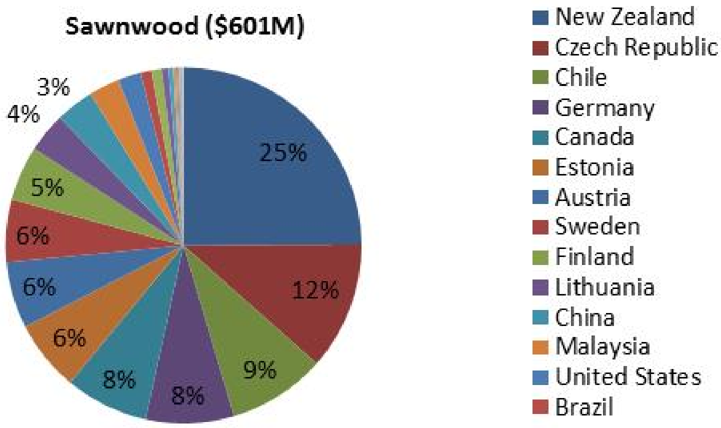
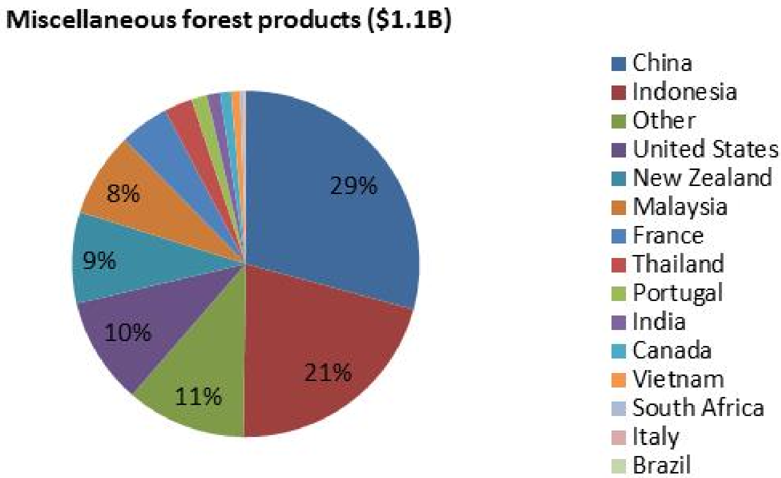


Figure 14: Value of sawn wood imported to Australia in 2014-15 by country of origin

In relation to miscellaneous wood products and wooden furniture, North and South East Asian countries are the primary suppliers with China being the largest (Fig. 15).



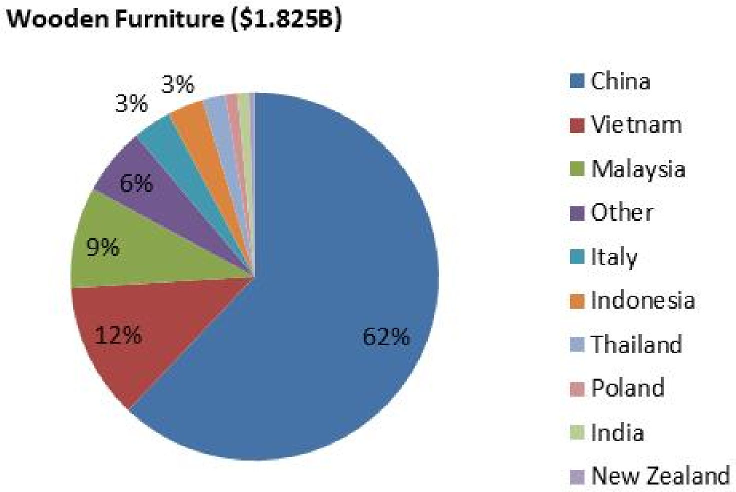


Figure 15: Value of miscellaneous forest products and wood furniture imported to Australia in 2014-15 by country of origin. Note *: The value of wooden furniture is not directly related to its wood content.

Is the risk of exotic pest incursions changing?

There are several ways to assess whether the risk of exotic pest incursions is growing. One method is to examine the change in the number of pests intercepted by DAWR Biosecurity over time (Fig. 16). These records show that there has been an increase in both the total number of pests intercepted and the number of priority pests (high risk) intercepted. In the absence of detailed knowledge of DAWR resourcing, training and surveillance techniques, caution should be exercised when forming a view on these trends.

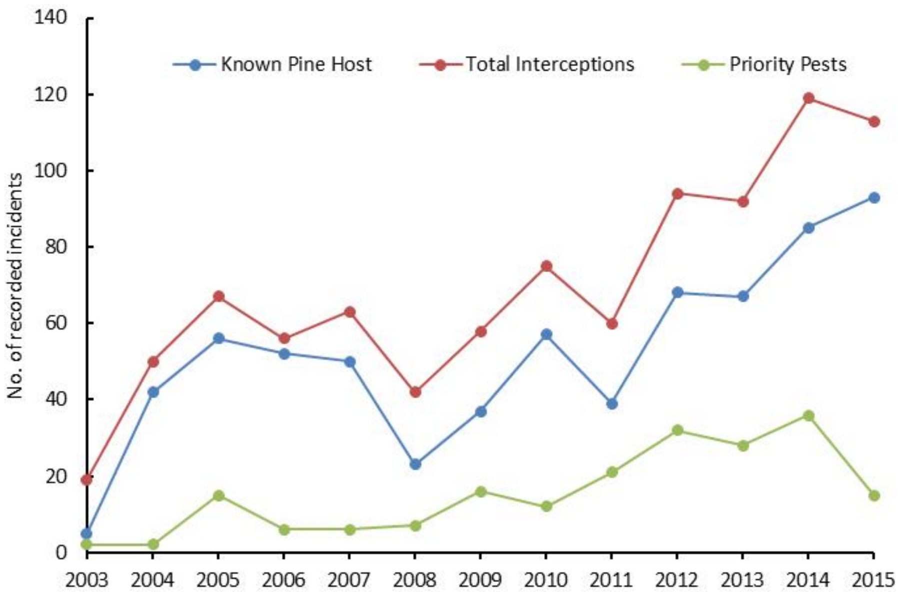


Figure 16: Forest pest interceptions (2000-2015) by Australian Border Security.

A less direct but more independent way to assess changing risk is to assess the changing quantum of pest host commodities that are being imported to Australia. Figure 17 and 18 respectively reveal that the amount of imported wood product and wood packaging have both grown rapidly over the last 15 years. From these trends it may be assumed that there has been a comparable increase in the risk of exotic pests (assuming no change in biosecurity practice) invading our shoreline. Due to the lag time between a pest's incursion and its establishment in the field it is likely to be some years before it becomes apparent whether the increased risk is translating into a material threat to forest industry biosecurity.

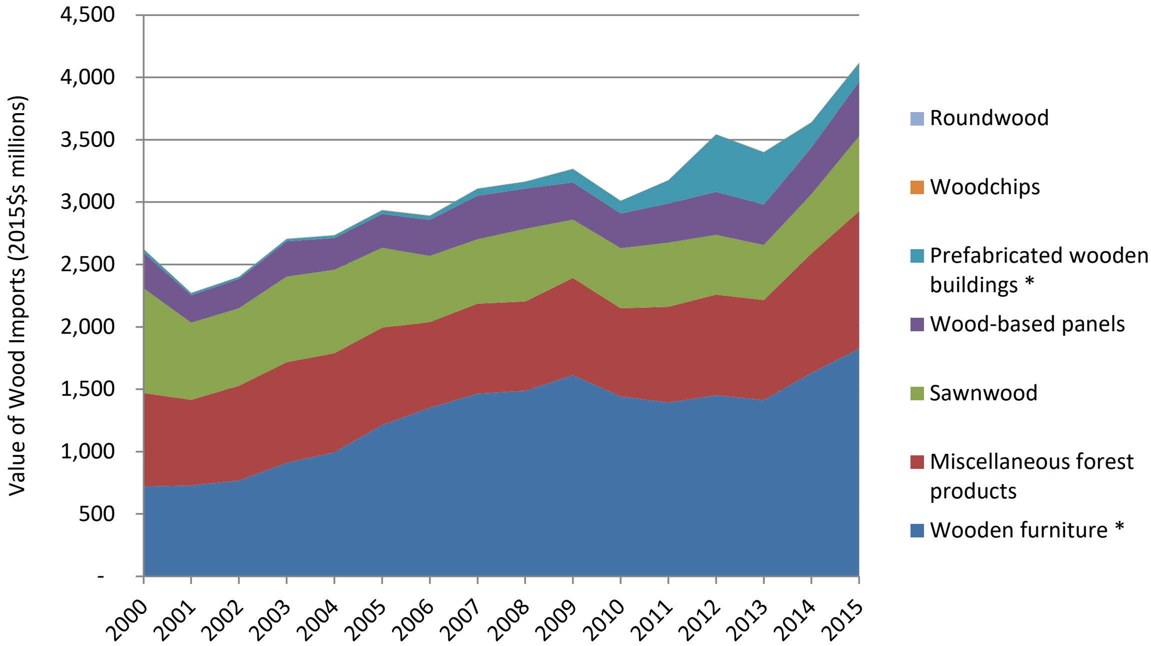


Figure 17: Value of Australian imported wood products by year (2000-2015) inflation adjusted to 2015$s. Data source: ABARES (2015) AFWPS Imports quarterly index. Note *: The value of wooden furniture and prefabricated wooden buildings is not directly related to their wood content.

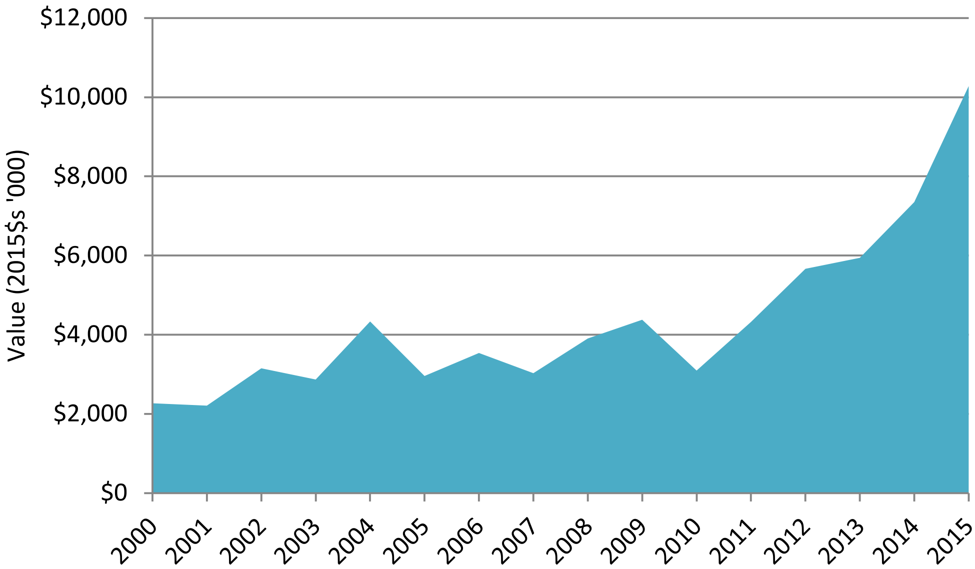


Figure 18: Value of Australian imported packing cases, boxes, crates and drums by year (2000-2015) inflation adjusted to 2015$s. Data source: ABARES (2015) AFWPS Imports quarterly index

Priority Pest	Number of Interceptions	% Total Intercepts
Dendroctonus spp.	1	0.1
Ips typographus	0	0.0
Monochamus spp.	35	3.6
Tomicus piniperda	1	0.1
Coptotermes formosanus	22	2.3
Coptotermes gestroi	31	3.2
Urocerus gigas	10	1.0
Hylesia nigricans	4	0.4
Lymantria dispar	75	7.8
Lymantria monacha	0	0.0
Orgyia thyellina	0	0.0
Bursaphelenchus spp.	4	0.4
Total High Priority Intercepts	**183**	**19.0**
Lymantria dispar as % of priority intercepts		41.0
TOTAL Intercepts	963	100

Table 1: Summary of numbers and proportion of intercepts of the twelve high priority invertebrate pests that were intercepted during the period 2000–2015.

Trends in Specific Pest Intercepts

Intercepts of High Priority Pests

DAWR provided the project intercept data from 2000 - 2015 for the key insect families, genera and species that are listed in the Plantation Forest Industry Biosecurity Plan (PFIBP). Data on intercepts of the seven high priority pathogens was not available for this chapter. It should be noted that not all containers/consignments arriving are inspected. Under risk-based inspection regimes, only samples of consignments are inspected and interceptions are made when a consignment is inspected. There can be additional entry of exotics through those uninspected, even though at a reduced rate. Table 1 summarises these intercepts for the high priority invertebrate pests.

Of the twelve high priority invertebrate (insects and nematodes) pests listed in the PFIBP, Table 1 shows that nine were intercepted in the period 2000–2015 and these formed around 20% of all intercepts in the DAWR database during that time period. These intercepts were dominated by a few common specific intercepts. In particular, gypsy moth (*Lymantria dispar*) formed approximately 40% of intercepts of high priority pests. In contrast, for high priority bark beetles there was only one intercept of *Dendroctonus* spp., no intercepts of *Ips typographus* and only one intercept of *Tomicus piniperda*. More common were intercepts of the two termite species on the list (*Coptotermes formosanus* and *Coptotermes gestroi*) and the giant woodwasp *Urocerus gigas*.

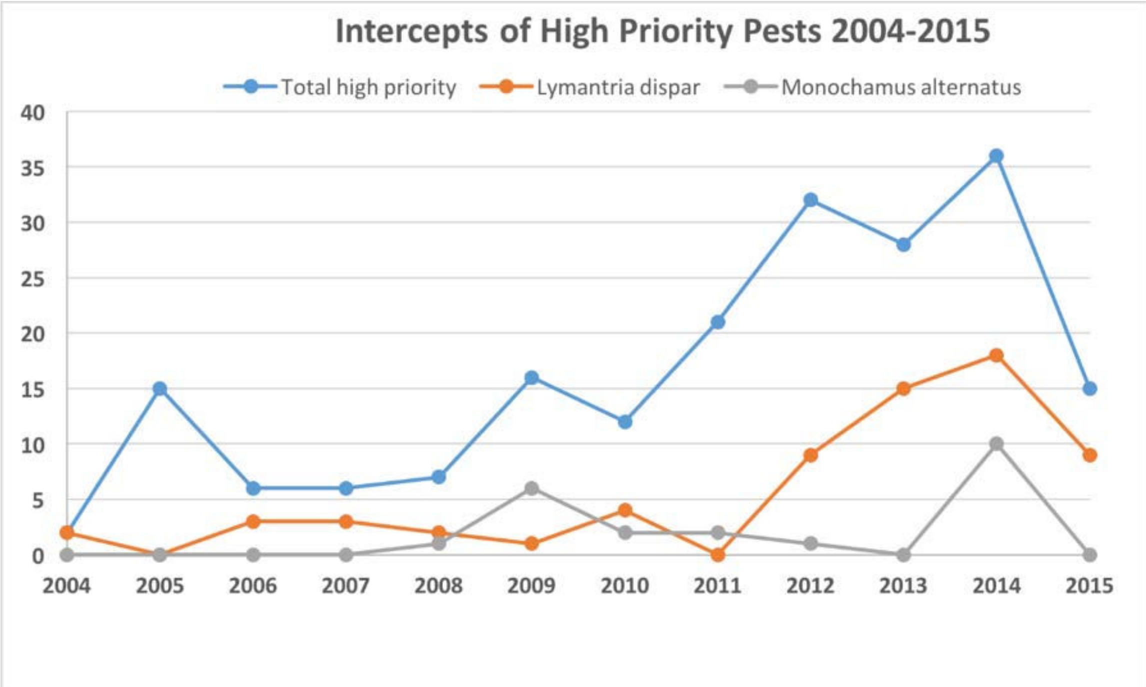


Figure 19: Total numbers of intercepts of the 12 invertebrate high priority pests in the Plantation Forest Industry Biosecurity Plan, together with gypsy moth (*Lymantria dispar*) and Japanese pine sawyer (*Monochamus* alternatus) interceptions, between 2000 and 2015.

The trend in total intercepts of the 12 high priority pests in the PFIBP over the last 15 years shows a large increase, particularly since 2010 (Fig. 19). There also appears to be a strong correlation between the variation in intercepts of high priority pests and a single pest, the gypsy moth *Lymantria dispar*. This is a concerning trend, since *L. dispar* is one of the most devastating pests that could be introduced into Australia given its potential economic impacts on a large number of industries including production forestry, as well as native forest ecosystems (Matsuki et al. 2001). Another serious pest, the Japanese pine sawyer beetle, *Monochamus alternatus*, vector of *Bursaphelenchus xylophilus* the cause of pine wilt disease, showed no clear trend in increased numbers of intercepts since 2010, excepting the serious interception in pallets across several states in 2014.

Intercepts of all 24 invertebrate pests ('known pests') on the threat summary tables of the PFIBP also showed an increasing trend in interceptions since 2010 (Fig. 20).

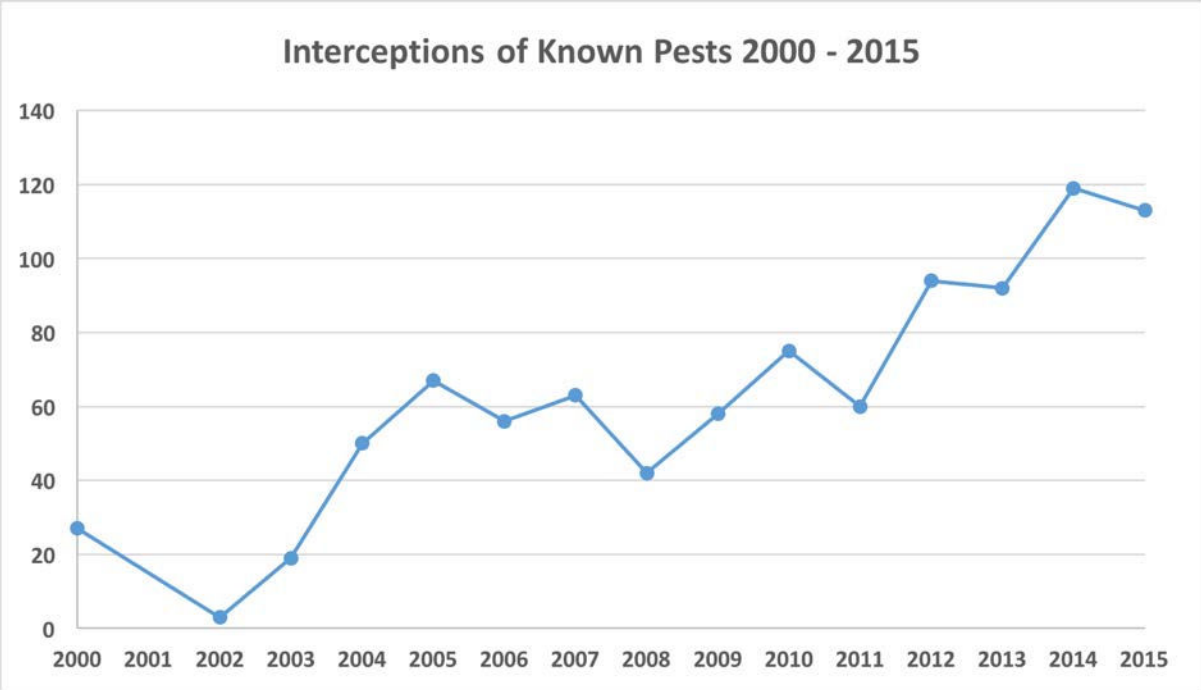


Figure 20: Total numbers of intercepts of the 24 invertebrate pests ('known pests') listed in the Plantation Forest Industry Biosecurity Plan between 2000 and 2015.

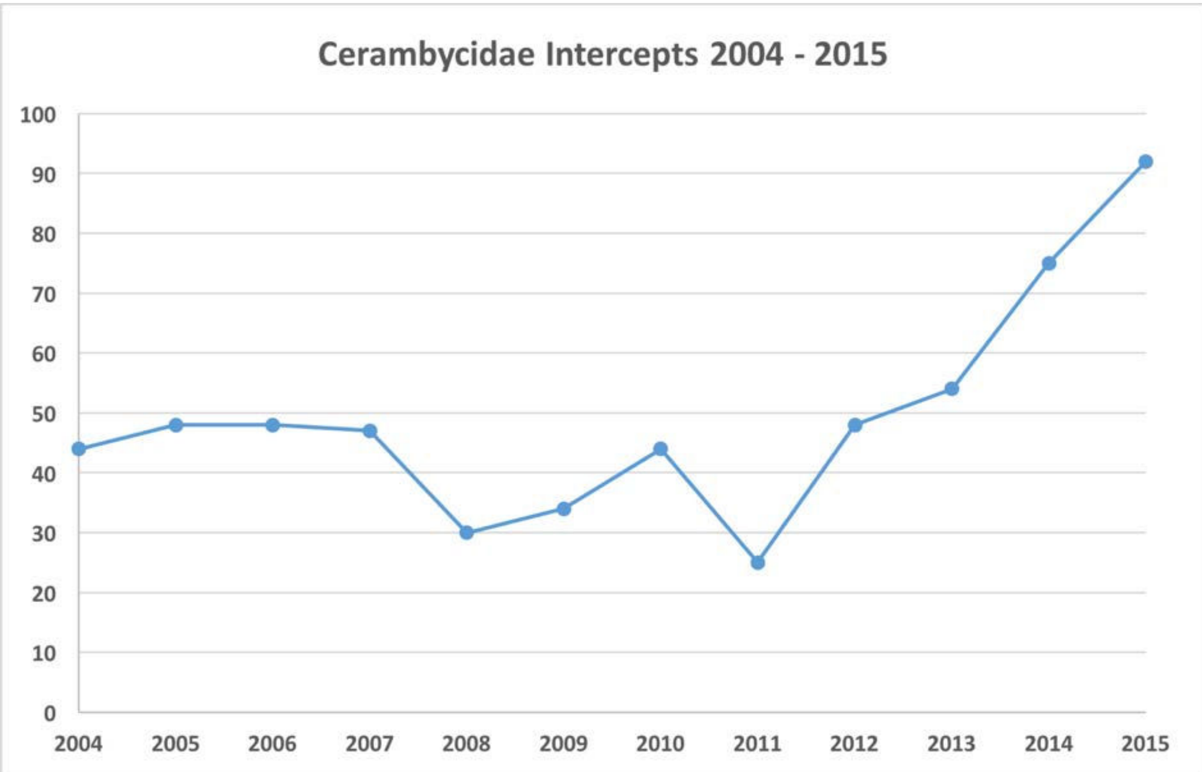


Figure 21: Total numbers of intercepts of Cerambycidae beetles between 2004 and 2015.

Intercepts of beetles in the family Cerambycidae (longicorn beetles) was relatively flat between 2004 and 2011, but has shown a consistent increase since then (Fig. 21). Given that this family is one of the primary targets of ISPM 15, the increased numbers of intercepts since 2011 is of considerable concern. Figure 22 shows that in most years, the proportion of total intercepts was highest for Cerambycidae, followed by Curculionidae (Scolytinae) and Lymantriidae. This again illustrates the fact that the Cerambycidae, a prime target of ISPM 15, drives a large proportion of the year to year variation in intercepts and that numbers of intercepts are rising.

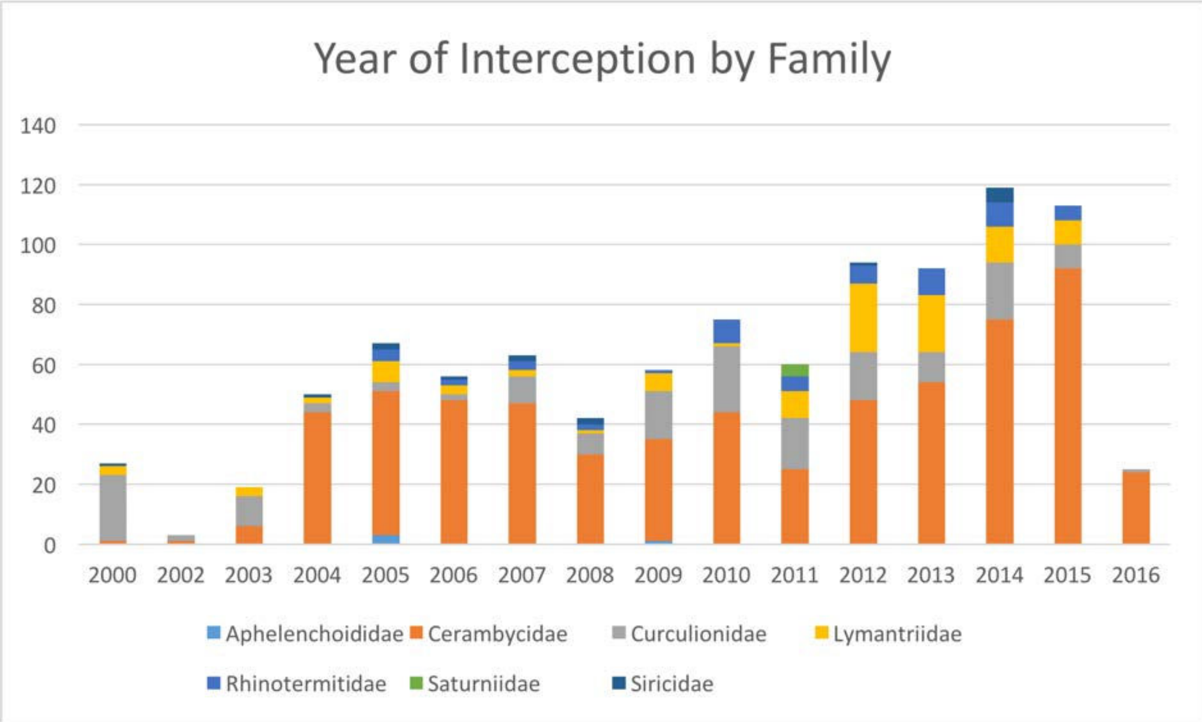


Figure 22: Trends in intercepts by pest families listed as high priority pests between 2000 and 2015

Intercepts of Established Exotic Pests

A number of established exotic pests continue to be intercepted including the cerambycid beetles *Arhopalus syriacus* and *A. rusticus*, the bark and ambrosia beetles *Hylastes ater* and *Hylastes* sp. (probably also *H. ater*), *Hylotrupes bajulus*, *Hylurgus ligniperda*, *Ips grandicollis*, *Xyleborus perforans*, *X. affinis*, *X. saxeseni* and *X. ferrugineus*. Figure 23 shows the trends over time in the interceptions of these established exotics.

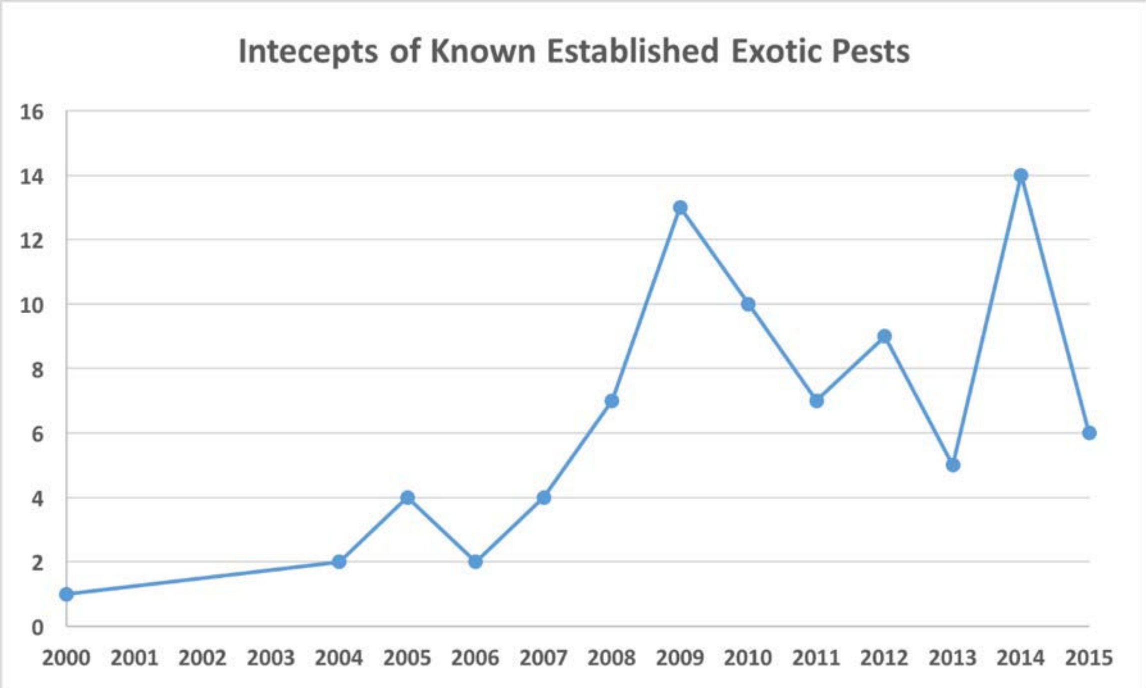


Figure 23: Intercepts of established exotics over the period 2000–2015 (*Arhopalus syriacus A. rusticus*, *Hylastes ater* and *Hylastes* sp. (probably also *H. ater*), *Hylotrupes bajulus*, *Hylurgus ligniperda*, *Ips grandicollis*, *Xyleborus perforans*, *X. affinis*, *X. saxeseni* and *X. ferrugineus*)

Control activities – Biosecurity continuum

What controls are in place to stop exotic pests arriving and establishing in Australia

To detail the control activities that are put in place we introduce the *Biosecurity Continuum* (Fig 24). Biosecurity is the management of risks to the economy, the environment and the community, of pests and diseases entering, establishing or spreading. The Department of Agriculture and Water Resources is the lead agency for biosecurity, working offshore and at the border to manage risks to Australia's plant industries (and the environment, and animal and human health). The Australian Government partners with state and territory governments (e.g. Departments of Primary Industries) — that have primary responsibility for managing biosecurity and pests and diseases *within* Australia — as well as industry and international trading partners. Biosecurity risks are managed offshore (pre-border), at the border, and within Australia — the biosecurity continuum — at the point where intervention is most effective (Department of Agriculture & Department of Environment 2014). The generalised biosecurity invasion curve (Fig. 25) illustrates the changing role of government (both state and federal) and industry as actions to respond to pests and diseases change from prevention, eradication and containment, to asset-based protection.

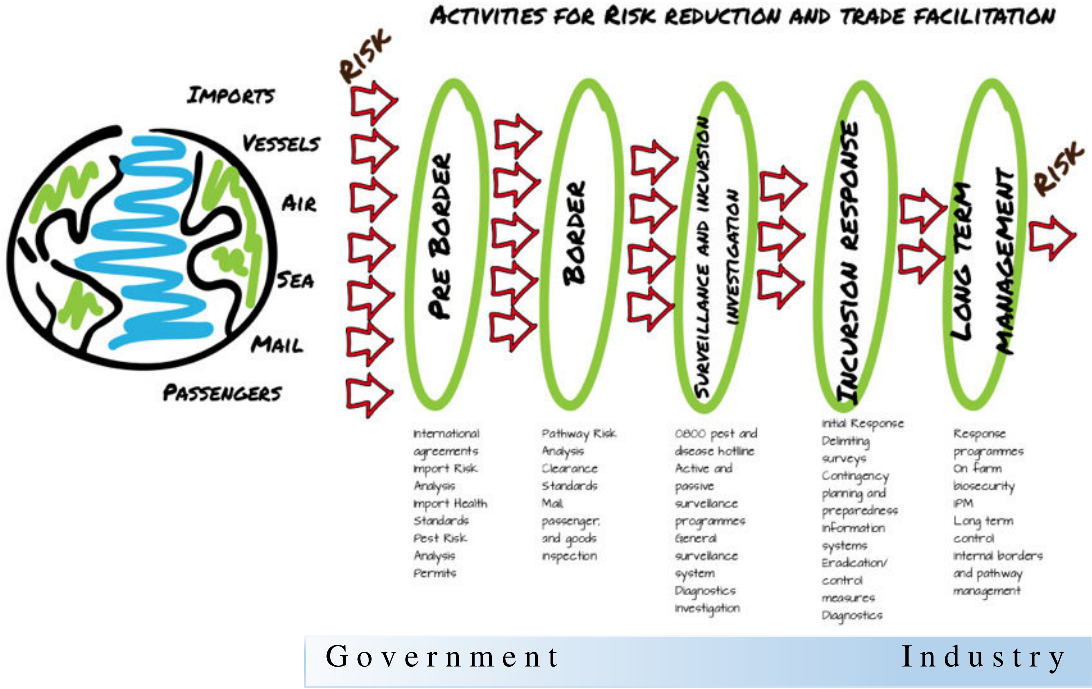


Figure 24: The biosecurity continuum. Biosecurity activities to control risks at each "intervention" point, indicating the primary role of government or industry responsible for these activities [from Gould 2015].

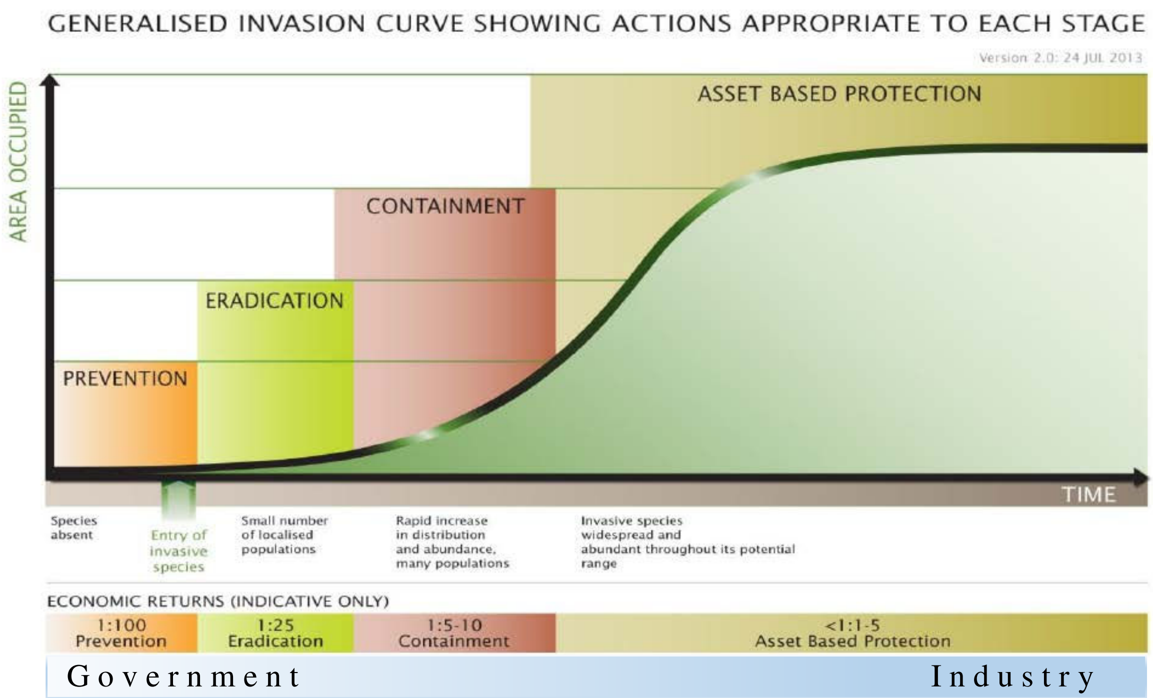


Figure 25: Biosecurity invasion curve, illustrating economic returns on investment at various stages of invasion progression (DPI Victoria), and primary funder of such activities.

As we have described above, exotic forest pests can enter Australia via numerous pathways; activities across the biosecurity continuum aim to minimise the risk of these pests entering and establishing in Australia. These activities can broadly be separated into offshore (pre-border), onshore (border) and within Australia (post-border), with the Federal Government primarily responsible for pre-border and border activities and activities within Australia shared between government and industry. Once a pest is established though, any long-term management is primarily the responsibility of industry.

Pre-border activities

Pre-border activities are focused on reducing the likelihood of pests reaching our border, while still allowing movement of people and goods across the border (Department of Agriculture & Department of Environment 2014). They are primarily conducted by the federal government. These activities include:

- Conducting risk assessments to consider the level of biosecurity risk that may be associated with imports and identifying risk management measures. Examples include Import Risk Analysis for Wooden Packaging (Box 1); Import Risk Analysis for Sawn Coniferous Timber from Canada, New Zealand and the United States; Review of the Policy on Importation of *Phytophthora ramorum* (sudden oak death) Host Propagative Material into Australia (Department of Agriculture 2015) to ensure appropriate measures are in place to protect Australia's environment and industries.
- Conducting offshore verifications, inspections and audits (e.g. of export facilities to ensure that products or cargo have been fumigated/treated appropriately and are free from pests). This does not occur in all countries, only those that have specifically signed up to specific agreements (e.g. the Australia Fumigation Accreditation Scheme).
- Collaborating with international partners on plant health issues and standards. Examples include International Standards for Phytosanitary Measures (e.g. ISPM15); Quality assurance schemes to eliminate pest-affected timber from the export pathway (e.g. CATS, Box 2); approved sources of tissue culture free of media for nursery stock.
- Regional capacity building through collaborative activities. Examples include projects to increase the chance of detecting exotic threats in neighbouring countries (e.g. Wardlaw & Lawson et al. [2012] Establishing pest detection systems in South Pacific countries and Australia. ACIAR Project Report FR2012-09: http://aciar.gov.au/publication/fr2012-09).
- Intelligence and surveillance to determine and assess potential biosecurity risks. Examples include the International Biosecurity Intelligence System (http://biointel.org/); using intelligence and geospatial analysis to identify high risk sites for Asian gypsy moth surveillance (Box 3).
- Quarantine declarations (bans) on specific items may be enforced from time to time to prevent movement of risky materials.

Box 1: Australia strengthens IPSM15 measures to reduce exotic forest pest risk from wood packaging

This review, conducted in 2006, included pest risk assessments of selected pests or pest groups to assess the risks associated with the importation of wood packaging materials with bark into Australia after application of a treatment approved in ISPM 15. It found that the requirement for wood packaging material to be free of bark was justified because: it enhanced the visual inspection process; removed the effects of bark on methyl bromide fumigation and minimised treatment failures; minimised the risk of entry of quarantine pests that depend on bark for food, shelter and one or more stages of development; reduced the risk of infestation and re-infestation after treatment; and minimised the risk of introduction of soil-borne pests and contaminating arthropod pests.

Biosecurity Australia (2006). Technical Justification for Australia's Requirement for Wood Packaging Material to be Bark Free. Biosecurity Australia, Canberra, Australia.

Box 2: Quality-assurance as a means of reducing biosecurity risk for timber borers

The mountain pine beetle (MPB; *Dendroctonus ponderosae*) is a serious forestry pest with outbreaks of the beetle causing extensive damage in Canada. To date, some 16 million hectares of forest in British Columbia, Canada, has been affected by MPB, and the damage caused has been described as one of the largest environmental disasters recorded. The beetle is endemic to the west coast of North America and feeds on softwood species, including pines (*Pinus* spp.) and Douglas fir (*Pseudostuga menziesi*). Although dead trees can be salvaged, production costs are higher due to moisture loss, and the forest products industry in British Columbia predicts that timber production will not recover for the remainder of this century.

Australia imports substantial amounts of rough sawn Douglas fir and Oregon pine (*Pseudostuga menziesi*) timber from Canada. During the 1980s and 1990s, MPB and other timber boring beetles were intercepted many times from this timber trade. The inadvertent transport of MPB was a substantial biosecurity risk to Australian forestry interests. To manage the risk, Australia and Canada jointly developed the Canadian Accredited Timber Scheme (CATS), which was introduced in the early 2000s. The scheme saw Canadian mills develop quality assurance practices that operated along the entire supply chain and eliminated MPB-infested timber from the export pathway. Logs were de-barked to a depth that ensured removal of MPB infestations, and all sides of milled timber was inspected. Borer damaged timber was diverted to the domestic market, ensuring only unaffected timber reached Australia. These measures were a success, as interceptions of MPB and a suite of other borers stopped soon after CATS was introduced. CATS continues to operate, and it has now been some seven years since any timber boring beetle has been intercepted from this trade.

This joint action with Canada demonstrates the role quality assurance plays in biosecurity. Costs borne by timber traders for fumigation were reduced, while the quality of exported products has improved because borer damaged timber is excluded. Similar positive changes have been made to trade pathways worldwide for other products, and quality assurance is now widely regarded as a cost-effective biosecurity measure.

Department of Agriculture and Water Resources, 2015

Box 3: Using geospatial analysis to identify high risk sites for Asian gypsy moth surveillance

Asian gypsy moths (AGM) are endemic to temperate Asia, including parts of China, the Korean Peninsula, Japan and the Russian Far East. Their larvae are defoliators that feed on at least 1000 species of plant. Host plants include the mainstays of the Australian forest product industry, such as *Pinus radiata* and *Eucalyptus* species. Populations of AGM cycle up and down, and in outbreak years the numbers can increase to the point where large areas of forest are denuded. In outbreak years in Asia, huge numbers of the moths can cause great contamination problems. AGM are regularly intercepted by quarantine inspectors on maritime vessels. Eggs are laid on vessels because female AGM are often attracted to lights, and deposit their egg masses on illuminated items beneath the lights. In the past, caterpillars have hatched from egg masses intercepted in Australia by quarantine inspectors. The concern is that caterpillars would hatch from an egg mass on a vessel and find a way into the Australian environment. If they became established in Australia, they would have a considerable impact on Australia's economy and environment.

The Department of Agriculture and Water Resources has intercepted AGM for at least 30 years on maritime vessels departing ports in the Russian Far East. Initially, AGM populations from outside the Russian Federation were not considered, but in 2011 a trial inspection program resulted in AGM egg masses being found on vessels from across temperate Asia. This trial program used geospatial analysis to help target the inspections by identifying potential risk seaports, as it was impractical to inspect every ship from seaports within the known distribution of AGM in Asia. A study of AGM dispersal in Japanese cities (Liebhold *et al.* 2008) demonstrated that all egg masses deposited beneath lights were within 1000 metres of large forest patches. The geospatial analysis conducted by the department was adapted so that any Asian seaport observed to be within 2000 meters of forest patches suitable for AGM (e.g. broadleaf deciduous forest) was considered as potentially of high risk. Forested areas were identified using a forest cover geospatial dataset. Maps generated from this data were overlaid onto Google Earth and risk was estimated by looking for vessel berth sites close to forest patches.

This trial using the geospatial analysis has led inspectors to find egg masses on 45 vessels between 2011 and 2014. Work on AGM is continuing with a focus on the interaction between egg diapause and vessel movement, as AGM eggs are unable to hatch unless they experience a cold spell for diapause. A risk assessment tool is also being developed in a joint project between the department, the CSIRO and the CRC for Plant Biosecurity. This project will produce risk analysis software that will identify potential risk vessels before arrival, allowing inspection resources to be deployed to the highest risk.

Department of Agriculture and Water Resources, 2015

Border activities

Border activities focus on the detection of exotic pest threats at the border, before they can spread and establish into Australia. These activities are risk-based, informed by evidence (e.g. pathway analysis and interception records) and subject to review and continual improvement (Department of Agriculture & Department of Environment 2014). DAWR have primary responsibility for these activities. These activities include:

- Screening and inspection of international vessels, passengers, cargo, mail, plants and plant products arriving in Australia. e.g. in 2013-2014 DAWR inspected 45,6000 sea containers from high risk ports; cleared 17.7 million international passengers, from which 261,000 items were seized due to biosecurity concerns; detected exotic beetles in pallets at major ports in Australia (Box 4).
- Managing the high biosecurity risks of live plants and animals through containment, observation and/or treatment at quarantine facilities.
- Identifying and evaluating specific biosecurity risks facing Northern Australia through the Northern Australian Quarantine Strategy.
- Raising awareness of travellers, importers and nursery operators of Australia's biosecurity requirements.

Box 4: Detection of beetles in pallets May 2014

In May 2014, DAWR in collaboration with state biosecurity agencies and researchers investigated consignments of timber pallets in 337 containers imported from China that were associated with non-timber building material. Pallets from the same consignment were present in Perth, Adelaide, Melbourne, Sydney and Brisbane. Some of the timber pallets were found to contain exotic forest pests including the Asian longhorn beetle, the brown mulberry longhorn beetle and the Japanese pine sawyer beetle. Trace forwards were conducted and all potentially infested pallets were placed under biosecurity control and then fumigated. Beetle traps were established at the sites where pallets were originally located, with trapping now extending over almost two years since the detection and show no further evidence that the beetles have moved from the original detection site. Trace backs to the source of the material were also conducted with cooperation from Chinese Government authorities, and non-compliance with ISPM 15 identified as the cause of the infestations in these pallets.

http://www.agriculture.gov.au/pests-diseases-weeds/plant/detection-exotic-beetles
http://www.agriculture.gov.au/about/media-centre/media-releases/detection-of-significant-timber-pests-in-imported-pallets
http://www.abc.net.au/news/2014-06-17/exotic-bettles-detected/5527440

Post-border activities

Despite all the control activities that have been put in place, some imported good/vessels/passengers may still contain/bring exotic pests of biosecurity concern after they enter Australia. Exotic pests can also arrive via illegal means (e.g. illegal importation of cuttings, seed, etc.) or via natural pathways such as wind. Biosecurity activities *within* Australia are delivered in partnership with state and federal governments, industry and other stakeholders (Department of Agriculture & Department of Environment 2014).
Some surveillance programs are co-funded by state and federal governments (and in some cases industry [see Box 5]) focusing on high risk sites around major ports and quarantine approved premises. However, for forestry pests there is at present no coordinated national approach or methodologies, although this is improving. The Federal Government, with state in-kind support, has funded a trapping program for gypsy moth at high-risk ports around

Australia for almost two decades, and more recently for bark and wood boring insects under the Multiple Pest Surveillance Program (MPSP).

Gypsy Moth

Gypsy moth traps that use a specific pheromone are deployed during the period October to May (e.g. in Brisbane currently 30 traps are co-deployed at sites utilised also for fruit fly trapping for operational efficiency). This system has been based on grid trapping carried out elsewhere, including New Zealand. No gypsy moths have ever been trapped during the life of this program.

Box 5: National Bee Pest Surveillance Program

The National Bee Pest Surveillance Program is an early warning system to detect new incursions of exotic bee pests and pest bees. The program involves a range of surveillance methods conducted at locations considered to be of most likely entry of bee pests and pest bees throughout Australia.

The program is jointly funded by the Australian Honey Bee Industry Council, Horticulture Australia Ltd, Rural Research and Development Corporation, the Australian Government through the Department of Agriculture. In-kind contributions for the implementation of the program are provided through each state and territory Department of Agriculture as well as volunteer beekeepers. At a national level, PHA coordinates and administers the program.

Plant Health Australia: http://www.planthealthaustralia.com.au/national-programs/national-bee-pest-surveillance-program/

Multiple Pest Surveillance Program

The MPSP is less prescriptive than the gypsy moth program, with individual states focussing on the key pests of relevance to them, but largely focused on agricultural and horticultural pests. State participation related to forestry has been driven largely by the forest health capacity available in each state. Forestry panel traps usually baited with an alpha-pinene plus ethanol lure has proven highly effective in Australia and elsewhere in trapping insects in the families of most concern, particularly the Cerambycidae (longicorn beetles) and Scolytinae (bark and ambrosia beetles) (Miller & Rabaglia (2009); Rassati et al. (2014); Wylie et al. (2008)). Numbers and traps and placement is dependent on funding allocated to the forestry component, as the MPSP program also targets a suite of other agricultural and horticultural pests, including Khapra beetle and fruit flies (the latter the largest component in the program in Queensland, for example). Up until recently the MPSP program had not detected an exotic insect in these traps. See Chapter 2 for more detail on this program.

Preparing for and responding to exotic pest incursions.

Response to exotic plant pest incursions are managed under Plant Plan and the Emergency Plant Pest Response Deed, to which the forestry industry is a signatory via the Australian Forest Products Association. Plant Plan is a highly detailed and prescriptive plan that provides a consistent framework for responses to exotic pest incursions. To date a Deed response for a forest pest has only been activated once, for a giant pine scale (*Marchalina hellenica*) incursion in late 2014 in suburban Melbourne and Adelaide (Box 6).

Box 6: Emergency response to the incursion of giant pine scale (*Marchalina hellenica*)

This insect was recorded in Australia for the first time in late 2014, in metropolitan Melbourne and in Adelaide, and was not previously listed as a high priority pest in the Plantation Forest Industry Biosecurity Plan, nor on the larger list in that document. This is the first response to a forest pest incursion under the Emergency Plant Pest Response Deed since AFPA signed the Deed as peak body representative of the forest industry. The incursion is currently under a cost-shared two-year eradication campaign in both Melbourne and Adelaide, following formal categorisation of the pest by industry and government through a Consultative Committee on Emergency Plant Pests (CCEPP) process. More information on the pest and the current progress of the eradication program can be found at:

Agriculture Victoria: http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/pest-insects-and-mites/giant-pine-scale

UPDATE: In November 2016, the National Management Group determined that it was no long technically feasible to eradicate giant pine scale from Victoria and South Australia and has agreed to a Transition to Management program.

Discussion

In this chapter we have illustrated that there is a clear — and ongoing and increasing — risk of exotic forest pests arriving into Australia as well as moving worldwide (see Wingfield et al. (2015) for a comprehensive review of the global situation), but that there are control activities that aim to reduce the chance of these pests entering and spreading into Australia. However, despite these control activities exotic pests have and will continue to establish in Australia, resulting in ongoing and possibly also growing pest management costs to industry. This is due in large part to the huge increases in the volume of world trade and passenger movements swamping our ability to intervene, particularly at the border, where only a small percentage of total trade volume or passengers can be inspected.

There is a very large suite of exotic pests of forests trees that are not yet established in Australia. This has been demonstrated by development of comprehensive pest lists in Australia, New Zealand and elsewhere based on extensive literature researches and practical knowledge. We have identified that more effort should be put into refining the pest lists we have and to carry out risk analyses for the key pests identified on our lists and through our analysis of the intercept data. Keller et al. (2007) reviewed the benefits of risk assessment in regard to importation of plants and animals and found this approach can generate large positive benefit:cost values, suggesting that this tactic will be beneficial and cost effective.

Pest lists are still of value, but fail to capture pests that are not pests in their native range but that only emerge as pests once they have invaded a new environment, often without their natural enemies. To lessen the risks posed by these 'known unknowns' and 'unknown unknowns', much recent effort in global biosecurity has focussed on shutting down the pathways along which these pests move. There is data that suggests that this approach is succeeding to some degree (Haack et al. 2014), but to a large extent we are faced with what is a sheer 'numbers game'. Our analysis of Australian trade data confirms what is reported globally in that movement of goods and people continues to increase hugely (e.g. a recent Senate inquiry showed that movement of containers into Australia increased by 86 % just in the last decade). Therefore, even if management of pathways reduces the incidence of pests moving on the pathway the sheer volume of trade ensures that significant numbers of pests will still be arriving at our borders.

Our analysis of recently obtained interception data demonstrate that only a small proportion of the total number of pests identified in pest lists or by estimates of global diversity of groups, such as the bark and ambrosia beetles, appear to be moving on the various pathways into Australia. A high proportion of our intercepts do occur on the PFIBP high priority pest list (9 of 12 pests intercepted between 2000 and 2015) and these pests include some like the gypsy moth that, if it were to become established in Australia, could have potentially devastating impacts on a large number of industries (including plantation forestry), as well as natural ecosystems. Our analysis of this data showed a general trend in increased numbers of intercepts over time of total pests, including high priority pests, and with an especially rapid increase in numbers since 2010. We also showed that already established exotics such as the bark beetles *Ips grandicollis*, *Hylastes ater* and *Hylurgus ligniperda* continue to be intercepted. Multiple interceptions of species already established increase the risk of new strains of associated fungi being introduced, with unpredictable consequences, or broader genetic diversity of insects that could increase the pest status of established pests. Genetic analysis of introduced exotic species is beginning to show that multiple introductions are common (e.g. Sirex woodwasp – Boissin et al. (2012) and Monterey pine aphid – Théry et al. (2017)).

Disturbingly, numbers of intercepts of one of the main pest groups, beetles in the family Cerambycidae, formed both the major proportion of intercepts and the group showing the sharpest increase in intercepts since 2011. This raises some questions as to the effectiveness of ISPM 15, which was especially designed to try and shutdown the wood packaging material pathway, which is the major route of entry for this group of pests. However, a recent analysis of ISPM 15 in the USA demonstrated that the net benefits of this measure could exceed US$11 billion by 2050 (Leung et al. 2014).

Of particular concern for the pine plantation sector is that a high proportion of all forest pest intercepts have *Pinus* spp. as recorded hosts. This reinforces the fact that at the same time as the Australian forest industry relies heavily on exotic *Pinus* species it is most at risk from introduced exotic pests.

We also know that only a relatively small proportion of pests that move on pathways are likely to enter, establish and then to have serious impacts on the forest industry. The probability of establishment largely depends on propagule pressure, which is a measure of propagule sizes (populations in source countries), propagule numbers (numbers travelling on pathways), and temporal and spatial patterns of propagule arrival (Simberloff 2009). We can use interception data as proxy for more detailed data on propagule pressure and it has been shown that the more times a pest is intercepted the higher the probability that pest may become established. i.e. there is highly significant association between interceptions and establishment (Brockerhoff et al. 2006). On the other hand, there are biological factors that mitigate against establishment of exotic pests in a new environment. A newly arrived pest must find suitable hosts within its dispersal range upon arrival and also be able to mate before it can reproduce (for most species – there are some insect species which are parthenogenetic (e.g. *Essigella californica*), which enable them to invade more easily). ‘Allee effects’ are important in this context, and predict that per capita growth rates decline with decreasing abundance. Liebhold and Tobin (2010) recommend that strategies to eradicate newly established populations should focus on either enhancing Allee effects or suppressing populations below Allee thresholds such that extinction proceeds without further intervention. Recent responses to post-border intercepts of longicorn beetles have used this concept by ramping up trapping systems around the intercept flight within the known dispersal distance of the pest in an attempt to reduce populations of the intercepted pest even further. This is one part of the 'numbers game' that can act in our favour.

In this chapter we have also highlighted activities through the biosecurity continuum that can reduce the likelihood of exotic pests entering and establishing into Australia. In particular, recent programs run by DAWR illustrate the potential cost-effectiveness of pre-border interventions in reducing numbers of pests arriving at the border (i.e. reducing propagule pressure at the source). Given the diminishing returns from biosecurity investment at the border due to the huge increase in volumes of imports and human movement and the limitations caused by budgets on how much can be inspected, targeted pre-border measures may be more cost-effective in preventing future establishment of pests.

Post-border surveillance is also a key measure that can help prevent establishments of new pests. For example, Epanchin-Niell et al. (2014) show that even low levels of surveillance are useful in that the economic benefits from surveillance more than offset the rising costs associated with increasing trapping density. They also show that greater surveillance is necessary in areas closer to at-risk, high-value resources and in areas that receive more imported goods that serve as an invasion pathway. The forest industry would benefit from a better targeted, more nationally structured and long-term funded post-border surveillance system that is currently being discussed in relation to specific activities under the Federal Government's 2015 Agricultural Competitiveness White Paper.

In following chapters we report on benefit-cost analyses of an endemic pest (leaf beetles in Tasmania), an established exotic (Sirex wood wasp) and a key exotic risk to the Australian pine plantation industry, the Japanese pine sawyer beetle (*Monochamus alternatus*), vector of pine wilt disease. The first two cases analyse investments made in research and operational activities against benefits in higher wood volumes through higher growth rates or lower tree mortality, while the third case looks at the costs of investment in surveillance in relation to the benefits of deferred losses due to the pest. Similar work carried out in New Zealand a little over a decade ago (Turner et al. 2004) established B:C ratios of between 103:1 to 172:1 for forest biosecurity under various scenarios there. These results indicated that there were considerable benefits to investing in biosecurity research to reduce economic losses in the New Zealand forest-growing industry and urban forest estate. In this project, we provide similar analyses, more tightly focussed on the plantation forest industry and key pests, that will help inform decisions on investment in forest biosecurity in Australia for the future.

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Federal and State biosecurity agencies and researchers to better protect Australia from biosecurity threats. We also thank DAWR for providing information presented in Boxes 1 to 3.

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Appendix 1

Table 1: Pests and pathogens of arborescent hosts (including *Pinus, Eucalyptus, Salix* etc.) that have established in Australia since 1901.

Species Name	Common name	Host	Year of Introduction	Reference
Diaspidiotus perniciosus	San Jose scale	Generalist, *Eucalyptus*	1900	APPD (P. Gillespie); Paine et al. 2011
Phytophthora cinnamomi	Root rot	Generalist	1900	
Ceroplastes rubens	Pink wax scale	Generalist, *Pinus*	1901	APPD, Elliott et al. 1998
Taphrina populina	Poplar leaf curl	*Populus*	1901	APPD, Marks et al. 1982
Otiorhynchus cribricollis	Apple weevil	Generalist, *Eucalyptus*	1908	APPD; Loch 2006
Apiognomonia veneta	Plane tree anthractnose	*Platanus*	1909	Marks et al. 1982
Ceroplastes floridensis	Florida wax scale	Generalist, *Pinus*	1909	Elliott et al. 1998
Apiognomonia (=Gnomonia) errabunda	Plan tree leaf scorch	*Platanus*	1909	Marks et al. 1982
Diplodia sapinea	Diplodia canker	*Pinus*	1912	APPD (F.M. Bailey)
Valsa sordida		*Populus*	1916	APPD
Pineus pini	Woolly pine aphid	*Pinus*	1920	Froggatt 1923
Cinara cupressi	Cypress pine aphid	*Callitris*	1921	Froggatt 1923
Coccus hesperidum	Soft brown scale	Generalist, *Eucalyptus*	1923	APPD; Paine et al. 2011
Macrophomina phaseolina	Charcoal rot	*Eucalyptus*, *Pinus*, Other	1924	APPD (J. Walker); Neumann & Marks 1976
Heteronychus arator	African black beetle	Generalist, *Eucalyptus*	1925	APPD (P.B. Carne); Abbott 1993
Ernobius mollis	Pine bark anobiid	*Pinus*	1928	APPD
Phlyctinus callosus	Garden weevil	Generalist, *Eucalyptus*	1928	APPD (G.A.K. Marshall); Matsuki and Tovar 2012
Drepanopeziza sphaerioides (=Marssonina salicicola)	Willow anthracnose	Salix	1931	APPD (G. Samuel); Marks et al. 1982
Naupactus leucoloma	Whitefringed weevil	Generalist, *Eucalyptus*	1931	APPD (R. Oberprieler); Matsuki and Tovar 2012
Sydowia polyspora		*Pinus*	1932	APPD (J. Walker)

Species Name	Common name	Host	Year of Introduction	Reference
Ralstonia solanacearum	Bacterial wilt	Generalist, *Eucalyptus*	1933	APDD,
Naupactus (=Asynonychus) cervinus	Fuller's rose weevil	Generalist, *Eucalyptus*	1934	APPD (R. Oberprieler); Matsuki and Tovar 2012
Hylastes ater	Black pine bark beetle	*Pinus*	1936	Boomsa & Adams 1943
Atrichonotus taeniatulus	Small lucern weevil	Generalist, *Eucalyptus*	1938	APPD; Loch 2006
Xyleborinus saxenesi	Fruit tree pinhole borer	Generalist, *Pinus*	1938	APPD; Elliott et al. 1998
Hypothenemus eruditus	bark beetle	Generalist, *Pinus*	1938	APPD; Stone et al. 2010
Oligonychus ununguis	Spruce spider mite	*Pinus*, Other	1940	Gutierrez & Schicha 1983
Sphaceloma populi		*Populus*	1941	APPD (J. Walker)
Hylurgus ligniperda	Goldenhaired bark beetle	*Pinus*	1942	Swan 1942
Ips grandicollis	Five-spined bark beetle	*Pinus*	1943	Morgan 1967
Ophiostoma ips	blue stain	*Pinus*	1943	Morgan 1967
Phloeosinus cupressi	Cypress bark beetle	*Cupressus, Callitris*	1947	APPD; ?????
Melampsoridium betulinum	Birch rust	*Betula*	1948	Marks & Walker 1972
Lepteutypa cupressi (Seiridium cupressi)	Cypress canker	*Cupressus*	1949	APPD (J. Walker), Marks et al. 1982
Sirex noctilio	Sirex wood wasp	*Pinus*	1951	Gilbert 1952
Amylostereum areolatum	Sirex fungus	*Pinus*	1952	Gilbert & Miller 1952
Elatobium abietinum	Spruce aphid	*Picea*	1952	APPD, Elliott et al. 1998
Meloderma desmazieri		*Pinus*	1957	APPD (J. Walker)
Erysiphe (=Microsphaera) alphitoides	Oak mildew	*Quercus*	1957	APPD (R.Langdon); Marks et al. 1982
Arhopalus syriacus	longicorn beetle	*Pinus*	1958	Webb & Eldridge 1997
Nectria coccinea		*Acer*	1958	APPD (J. Walker)
Cyclaneusma minus	Cycleneusma needle cast	*Pinus*	1959	Stahl 1966
Eulachnus thunbergii		*Pinus*	1959	Moore 1962
Lophodermium nitens	Lophodermium needle cast	*Pinus*	1959	APPD (J. Walker)
Lophodermium canberrianum	Lophodermium needle cast	*Pinus*	1960	Stahll 1966
Lophodermium pinastri	Lophodermium needle cast	*Pinus*	1960	Stahl 1966

Species Name	Common name	Host	Year of Introduction	Reference
Valsa nivea		*Populus*	1960	APPD (J. Walker)
Cyclaneusma niveum	Cycleneusma needle cast	*Pinus*	1964	APPD (J. Walker)
Lophium mytilinum		*Pinus*	1964	APPD (P. Talbot)
Xyleborus ferrugineus	Black twig borer	Generalist, *Pinus*	1965	APPD; PaDIL; Wylie et al. 1999
Amphiporthe leiphaemia		*Quercus*	1969	APPD (A.L. Bertus & J. Walker)
Melampsora epitea	Willow rust	*Salix*	1972	Marks & Walker 1972
Melampsora larici-populina	Poplar rust	*Populus*	1972	Walker et al. 1974
Melampsora medusae	Poplar rust	*Populus*	1972	Walker & Hartigan 1972
Xyleborus perforans	Island pinhole borer	Generalist, *Pinus*	1973	CABI; Elliott et al. 1998
Dothistroma septosporum	Dothistroma needle blight	*Pinus*	1974	Edwards & Walker 1974
Phaeocryptopus gaeumannii	Swiss needle cast	*Pseudotsuga*	1974	Marks 1975
Scolytus multistriatus	European elm bark beetle	*Ulmus*	1974	Neumann & Minko 1985
Sphaceloma murrayae		*Salix*	1974	APPD (J. Walker)
Taphrina rhizophora		*Populus*	1974	APPD (J. Walker); Sharma & Heather 1975
Phyllonorycter messaniella	Oak leafminer	*Quercus*	1975	APPD, Elliott et al. 1998
Cryptosphaeria ligniota		*Populus*	1976	APPD (H. Swart)
Erysiphe platani	Platanus powdery mildew	*Platanus*	1977	Marks 1981
Melampsora coleosporioides	Willow rust	*Salix*	1978	Walker 1978
Dicarpella dryina		*Quercus*	1982	APPD (J. Walker)
Xanthogaleruca luteola	Elm leaf beetle	*Ulmus*	1982	Elliott et al. 1998
Lophodermium australe	Lophodermium needle cast	*Pinus*	1983	APPD (A. Sivanesan)
Drepanopeziza populi-albae (=Marssonina castagnei)	Marssonina leaf spot & blight	*Populus*	1984	Walker et al. 1985
Diplodina acerina		*Acer*	1986	APPD (M.J. Priest)
Discosia strobilina		*Acer*	1987	APPD (J. Walker)
Drepanopeziza punctiformis (=Marssonina brunnea)	Marssonina leaf spot & blight	*Populus*	1987	Simpson 1990
Lophodermium pini-excelsae	Lophodermium needle cast	*Pinus*	1988	APPD (I.G. Pascoe)
Microthyrium pinophyllum		*Pinus*	1988	APPD (I.G. Pascoe)

Species Name	Common name	Host	Year of Introduction	Reference
Strasseria geniculata		*Pinus*	1989	APPD (T. Wardlaw); Podger & Wardlaw 1990
Phaeolus schweinitzii	Brown cubicle rot	*Pinus*	1990	Simpson & May 2002
Discochora pini		*Pinus*	1991	APPD (M.J. Priest)
Pleonectria cucurbitula (Zythiostroma pinastri)		*Pinus*	1994	APPD (I.G. Pascoe)
Adelges cooleyi	Cooley spruce aphid	*Pseudotsuga*	1996	JA Simpson pers. comm.
Tremex fuscicornis	Tremex wasp	*Salix, Populus*	1996	APPD (I. Naumann); State Forests NSW unpublished
Essigella californica	Monterey pine aphid	*Pinus*	1998	Carver & Kent 2000
Grosmannia (=Ophiostoma) huntii	blue stain	*Pinus*	1998	Jacobs et al. 1998
Arhopalus rusticus	longicorn beetle	*Pinus*	2000	Smith et al. 2008
Lophodermium conigenum	Lophodermium needle cast	*Pinus*	2001	Simpson & Grrinovic 2004
Corythucha ciliata	Sycamore lace bug	*Platanus*	2006	APPD (P.S.Gillepsie); Dominiak et al. 2008
Diplodia africana	diplodia canker	*Pinus*	2010	APPD (J.H. Cunnington)
Puccinia psidii	Myrtle rust	*Eucalyptus*	2010	Carnegie et al. 2010
Thyronectria pinicola		*Pinus*	2012	Carnegie et al. 2015
Diplodia seriata	diplodia canker	*Pinus*	2012	VPRI; J. Edwards pers. com.
Marchelina hellenica	Giant pine scale	*Pinus*	2014	D. Smith pers. comm.
Thelonectria veuillotiana	canker	Other, *Araucaria*	2016	VPRI; J. Edwards pers. com.
Ilyonectria radicicola	canker	Other, *Araucaria*	2016	VPRI; J. Edwards pers. com.

2. Benchmarking forest health surveillance and biosecurity activities for managing Australia's exotic forest pest and pathogen risks

Summary

A review of current forest health surveillance and biosecurity surveillance activities and programs in Australia was conducted, including a grower questionnaire. This focused more on on-ground activities, as opposed to national processes and preparedness, which were previously reviewed by Mohammed et al. (2011). A broad range of activities are conducted to detect pest and disease damage or outbreaks. More than 60% of the respondents' plantation estate has some form of systematic surveillance activities, including aerial and ground surveys, plot-based surveys, or pest population monitoring, or a combination of these. However, there is no coordination of activities (other than the IPMG) and no consistent approach to surveillance methodology or data capture. There is no mechanism to ensure consistency in data capture, nor an ability to collate forest health data at regional, State or national levels. There is little structured surveillance of native forests in Australia. Industry highlighted consistency and coordination in forest health surveillance as a priority.

Forest biosecurity surveillance in Australia is inadequate, including both post-border surveillance and plantation surveillance. The government funded National Plant Health Surveillance Program is not specifically designed to capture forestry pests, with only one forestry pest (gypsy moth) surveyed for nationally. Multiple forestry pests are, however, targeted in post-border surveillance in Queensland, New South Wales and Victoria, but more through pro-active interest by individual forest health technical experts than design; an exception being Victoria, which has a forestry-specific program. Industry highlighted high risk site surveillance and training of operational staff as a priority. The Bee Industry Biosecurity Surveillance Program is a potentially good model for an industry and government funded forest biosecurity program.

The New Zealand forest biosecurity surveillance system is more mature and advanced than that in Australia, with a nationally consistent and coordinated program, a dedicated forest biosecurity officer/manager, and industry actively engaged. The New Zealand forest industry also actively funds forest biosecurity surveillance.

There has been a notable improvement of forest biosecurity preparedness in Australia from that reported by Mohammed et al. (2011), with the recent signing of the Emergency Plant Pest Response Deed by AFPA and the establishment of the Forest Health and Biosecurity Subcommittee. However, there are still gaps in Australia's ability to manage exotic pest and disease threats, including:

- A need for coordination of current forest health surveillance activities, including a national coordinator
- Development of a national biosecurity surveillance program
- Closer ties with government biosecurity agencies and processes
- Training of industry staff
- A need to address the ongoing reduction in capacity in technical expertise

- Industry leadership and engagement in biosecurity
- A need for involvement from other stakeholders, especially environmental agencies who manage the bulk of the native forest estate.

Review of current forest health surveillance and biosecurity surveillance activities and programs in Australia

Generally speaking, *Forest health* deals with pests and diseases that are already established in Australia (e.g. sirex wood wasp, dothistroma needle blight, eucalypt leaf beetles, weevils). Activities in this area include forest health surveillance, diagnostics, impact assessment, pest and disease management, and research. *Biosecurity* deals with pests and disease not yet present in Australia (e.g. gypsy moth, mountain pine beetle, pitch canker), and includes pest risk assessments, quarantine, early detection surveillance (including at ports and in plantations), diagnostics, and emergency response and eradication activities. *Biosecurity* also includes activities to reduce movement of pests and diseases between regions *within* Australia, including inter-state quarantine restrictions, machinery movement and hygiene, nursery biosecurity, as detailed in the *Biosecurity Manual for the Plantation Timber Industry*.

This section summarises the forest health surveillance programs in Australia — including historical programs and more recent developments — and the current biosecurity surveillance programs in Australia focused on forestry pests. We look at these in the context of Australia's ability to detect and respond to biosecurity threats.

Forest health surveillance

Forest health surveillance is generally described as the *process of formal inspection of planted and natural forests by trained observers for the purpose of detecting damage*. This differs from health or condition monitoring (which often applies to plot-based assessments in native forests), pest population monitoring (which is pest-specific and usually carried out for decisions on control operations) and *ad hoc* detection (which is generally conducted by forest workers). See definitions provided by Wardlaw et al. (2007), Table 1.

Table 1: Definitions of the four main forest health surveillance and monitoring activities done by forest managers in Australia (from Wardlaw et al. 2007).

Activity	Definition
Forest health surveillance (FHS)	Damage-focussed and optimised to detect and then quantify damage (i.e. rate the incidence and severity of damage by a pest in a defined area). Often covers large proportion of estate, and includes aerial and ground surveys by trained professionals.
Health / condition monitoring	Tree or forest focused and optimised to describe the condition of trees to detect change over time. Often ground-based, and focused on "generic" attributes of health, such as crown transparency/density or discolouration.
Pest population monitoring	Pest-focused and optimised to measure populations of the target pest. Often used to identify a threshold of pest population that would result in growth impact and could initiate control operations.
Ad hoc detection	Unstructured and damage-focused, designed to incur the least cost (for detection). Often conducted by un-trained staff. The term "guided ad hoc detection" is used if forest workers receive training to focus attention on specific pest and disease problems.

In Australia, there is no national coordination of surveillance activities and no national industry/technical body that oversees the program. Formal forest health surveillance activities began in 1996/1997 led by the main growers in New South Wales, Queensland and Tasmania (*Australian Forestry* **71**, 2008). Although surveillance methodologies are similar between the States, there are differences based on State-grower needs. This historical State-based context remains, with formalised, systematic forest health surveillance activities largely confined to these original growers/managers. Costs of forest health surveillance (aerial, drive-through and ground) in Australia are \$0.6 to \$1.0 ha^{-1} for softwood plantations, but up to \$3.0 ha^{-1} for hardwood plantations (which have a more disparate distribution). *The focus of these forest health surveys is mainly mapping the extent and severity of established or endemic pests, not the detection of new exotic pests.*

Following is a summary of forest health surveillance activities in Australia, including an historical context, summary of surveillance activities reported in the special edition of *Australian Forestry* (**71**, 2008), as well a synthesis of data and information gained from the grower questionnaire on more contemporary forest health-related activities.

Forest health surveillance prior to 1996

Prior to 1996, the general detection of pest and disease problems relied on infrequent visits by a small number of forest pathologists and entomologists, supported by *ad hoc* detections by forest workers during visits to the forest for routine operations. Targeted surveillance of pests and pathogens was generally conducted at a pest-specific level, or following detection of a problem. For example, aerial and ground surveys for sirex wood wasp occurred in all states soon after sirex was detected in each state. These surveys generally targeted susceptible forests, and so covered only a proportion of the planted area. Aerial and ground surveys also occurred for dothistroma needle blight, mainly in high risk areas in Victoria and NSW, to assist with potential control operations. Aerial surveys of pest outbreaks were conducted over native forest, such as phasmatid damage in north-eastern Victoria and south-eastern NSW. Pest population monitoring was also conducted, such as for sirex and eucalypt leaf beetles, and dothistroma monitoring. *Ad hoc* detection was an informal activity, and involved forest workers reporting pest and disease activity or issues noticed during the course of their routine daily activities, such as outbreaks of ips bark beetle or areas of defoliation and tree mortality. Prior to 1996 the approach was considered relatively effective as there was a much larger field workforce than today. However, the sirex outbreak in the Green Triangle in the late 1980s was a sobering reminder of the consequences of not detecting and managing pest outbreaks early, and was a major argument used in persuading forest managers to establish formal forest health surveillance units.

Forest health surveillance 1996–Present day

Formal, systematic forest health surveillance began in many States in the mid-1990s. Details of these activities have been summarised in a special issue of *Australian Forestry* (Carnegie 2008; Carnegie et al. 2008; Lawson et al. 2008; Wotherspoon 2008; Phillips 2008; Robinson 2008) (Table 1). These activities were generally conducted by the larger growers in each state, including Forestry Plantations Queensland, Forests NSW, Forestry Tasmania, Hancock Victoria Plantations, Forestry SA (note the use of historical names as indicated in the publications). At the time of the *Australian Forestry* publication there was little information about surveillance activities by the smaller growers.

Table 2: Forest health surveillance activities in Australia 1996–2007 (*Australian Forestry* 71, 2008), based on definitions from Table 1 (adapted from Wardlaw et al. 2007).

State	Plantations		Native Forest
	Softwood	Hardwood	
New South Wales	FHS[1] Pest population monitoring (sirex)[1]	FHS[1] Limited pest population monitoring (creiis)[1,2]	BMAD surveys
Queensland	FHS[1]	FHS (1996–2002) or guided (trained operational staff) *ad hoc* detection by field staff[1]	Minimal during early 1990s
Tasmania	FHS[1,2] Pest population monitoring (sirex)[1,2]	FHS[1,2] Pest population monitoring (leaf beetles)[1,2]	FHS of thinned native forest and wildlife habitat strips Pest monitoring (browsing mammals)
Victoria	Plot-based health and condition monitoring[1] Pest population monitoring (sirex)[1,2]	Plot-based health and condition monitoring[1] Guided (by IPMG) *ad hoc* detection by field staff[2]	*Ad hoc* detection by field staff Pilot study of plot-based health and condition monitoring
South Australia	FHS (but primarily focused on sirex, diplodia and essigella)[1,2]	Guided (by IPMG) *ad hoc* detection by field staff[2]	None done
Western Australia	Pest population monitoring (sirex)[1]	Guided (by IPMG) *ad hoc* detection by field staff[2]	*Phytophthora* detection/ mapping Plot-based forest condition and biodiversity monitoring
ACT	No formal programs reported		
NT	No formal programs reported		

[1] Indicates activity conducted in estate of the major grower, which was often State-based (e.g. Forests NSW), but could be private (e.g. HVP)

[2] Indicates activities conducted in estate of secondary grower in the State, such as smaller private growers

New South Wales

In NSW, annual surveys of State-owned softwood plantations have been conducted since 1996, with an aerial survey covering the majority of the estate and follow-up ground truthing targeting aerial observations (Carnegie et al. 2008). The methodology has not changed significantly, other than a move from sketchmapping using paper maps to digital aerial sketchmapping. Digital aerial sketch-mapping (DASM) for forest health — developed by the US Forest Service — was pioneered in Australia by NSW (Carnegie et al. 2008). Ground surveys now involve the use of the FCMappApp on an iPad, developed by Forestry Corporation of NSW, for navigation and data capture. We are aware of some private softwood growers conducting occasional surveillance, including aerial surveys, often with technical advice sought from NSW DPI forest health experts, as well as *ad hoc* detections.

Annual surveillance of the State-owned hardwood plantations has evolved from ground surveys of the majority of plantations (1996–2002), to include aerial and ground surveys when the estate was large and disparate (2003–2009, also coinciding with creiis psyllid damage in *E. dunnii* plantations), and now back to ground surveys only, but mainly focusing on the second rotation estate (2010–2016). For the private hardwood estate (MIS), some pest population monitoring has been conducted for creiis, occasional contract forest health surveillance (by NSW DPI), and *ad hoc* detections.

There is minimal forest health surveillance of native forests. Aerial surveys of bell miner associated dieback (BMAD) over State Forest, National park and private forests on the north coast of NSW were conducted in 2004 (Carnegie & Price 2004) and are currently being conducted again (Carnegie et al. 2016 unpublished).

Queensland

In Queensland, annual surveys of State-owned softwood plantations began in 1997, and included aerial and ground surveys over the majority of the estate (Lawson et al. 2008). Aerial surveys were enhanced by the use of laser technology, with laser rangefinders linked to palmtop computers with GPS capabilities for accurately locating and mapping damage (Ramsden et al. 2005). Systematic aerial and ground surveys, however, have not been conducted since ~2007 in Queensland, with a greater reliance on guided *ad hoc* detections and pest population monitoring (sirex).

For the State-owned hardwood estate, forest health surveillance was conducted by trained professionals from 1997 to 2002 using drive-through and ground transect methods. From 2003 onwards, however, there has been a greater reliance on guided *ad hoc* detection by trained operational staff. For the private hardwood estate (MIS) in Queensland, some pest population monitoring has been conducted (e.g. for creiis and chrysomelids) and *ad hoc* detections. Wardlaw et al. (2007) identified this lack of regular surveillance in the expanding MIS estate as an increasing risk as these stands age.

Apart from a few individual forests surveyed following the establishment of the forest health surveillance unit in 1997, there has been no ongoing surveillance of native forests in Queensland.

Tasmania

Forest health surveillance in Tasmania began in 1997 with annual aerial and ground surveys, and drive-through surveys, of both the softwood and hardwood estate (Wotherspoon 2008). These surveys covered both State-owned plantations as well as a majority of the private softwood estate and about half the private hardwood estate (Wardlaw et al. 2007). Generally, the same methodology is being conducted today.

There is some forest health surveillance in thinned native forest and wildlife habitats in Tasmania (Wardlaw et al. 2007).

Victoria

Systematic forest health surveillance in Victoria began in 2001 following the USFS Forest Health Monitoring (Bennet and Tkacz 2008) plot-based methodology (Smith et al. 2008). This method utilises a system of permanent plots to monitor the change in health of softwood and hardwood plantations managed by HVP. Strictly speaking this is health/condition monitoring, as defined by Wardlaw et al. (2007), but encompasses much of the same detection techniques as forest health surveillance, such as drive-through surveys and being conducted by a trained forest health professional. More recently (from ~2008) systematic aerial surveys have been conducted over HVP softwood plantations, utilising DASM techniques (D. Smith, pers. comm.), thus combining health monitoring with forest health surveillance. Surveillance in the remainder of the softwood and hardwood estate has mainly relied on *ad hoc* detections by operational staff, some of whom have been trained.

Surveillance in native forests consists of ground plots and aerial surveys in response to *ad hoc* detections. However, more recently a plot-based system similar to the USFS FHM program has begun in Victorian native forests, the Victorian Forest Monitoring System (Haywood et al. 2016).

South Australia

In South Australia, ForestrySA has conducted annual aerial and ground forest health surveillance of its softwood estate since the late 1990s (Phillips 2008). These have either been by a forest health professional, or by trained operational staff, more often the latter in recent years following privatisation. Other private softwood growers generally conduct annual aerial surveys for sirex. Surveillance in the hardwood estate has generally been reactive and *ad hoc*, but with some targeted pest population monitoring (e.g. *Heteronyx*). For several years these plantations were covered under an IPMG-like system, but not presently.

There is no formal surveillance in native forests in South Australia.

Western Australia

In State-owned softwood plantations, *ad hoc* surveillance has occurred for ips bark beetles and essigella, and pest population monitoring for sirex. With the expansion of the hardwood estate in the late 1990s, pest population monitoring of a range of insect pests (e.g. *Heteronyx,* weevils, leaf beetles) and mycosphaerella leaf disease monitoring has been conducted by a trained professional, later as part of the IPMG program. This also includes guided *ad hoc* detection by trained operational staff.

Western Australia is the only State which has extensive surveillance of native forests (Robinson 2008). This includes dieback in jarrah forest, armillaria root disease, insect pests in jarrah forests, and monitoring of a range of declines, including marri, wandoo and tuart. More recently (2001) a forest condition and biodiversity monitoring program (FORESTCHECK) was implemented to monitor indicators of ecological sustainable forest management (Robinson 2008; McCaw et al. 2011).

Australian Capital Territory

In the ACT softwood estate, pest population monitoring for sirex occurs, and *ad hoc* detection of forest health issues by operational staff.

Northern Territory

Surveillance in the Northern Territory is mainly to *ad hoc* monitoring of the expanding African mahogany estate for shoot borer damage, and in the small Tiwi islands softwood and hardwood estate.

Industry survey of forest health activity

In May 2016 we conducted a survey of Australian plantation growers, both softwood and hardwood, to gauge the current level and activity of forest health surveillance within Australia. Part of the aim of this was to capture what is being conducted in the smaller estates (i.e. not captured in the above information) and changes since the last review of forest health surveillance in 2008. The questionnaire, distributed via SurveyMonkey, is reproduced in Appendix I. Mohammed et al. (2011, *An audit of forest biosecurity arrangements and* *preparedness in Australia*) conducted a more in-depth survey of industry, government and technical experts on forest biosecurity preparedness and response.

Proportion of plantation estate surveyed

Surveys were distributed to key personnel within the majority of Australia's plantation growing companies, including membership provided by AFPA; in total we received 16 responses. The position of survey respondents within their respective organisations included: Chief Operating Officer, General Manager, Associate Director Operations, Plantation Manager, Science Manager, Forest Manager, Technical Forester, Research Manager, Technical Services Manager, Plantation Operations and Services Manager; all of which have some expertise and knowledge of forest health activities within their organisations. Responses were received from growers in all states (Figure 1) and covered the majority of both the softwood (~900,000 ha, 88%) and hardwood (~523,000 ha, 58%) estate (Figure 2). Responses were received from: Forestry Corporation of NSW, Green Triangle Forest Products, SFM Forests Products, African Mahogany Australia, Forico, PFOlsen, 141, ACT Parks and Conservation Service, Hancock Queensland Plantations, Forest Products Commission, Integrated Pest Management Group, Forestry Tasmania, New Forests, Hume Forests Ltd. and Hancock Victoria Plantations. In future, we aim to obtain data from a greater number of growers, encompassing more of the plantation estate, especially the hardwood estate. The following analysis deals only with data from the survey, and so proportions are based on 900,000 ha of softwood and 523,000 ha hardwood plantations.

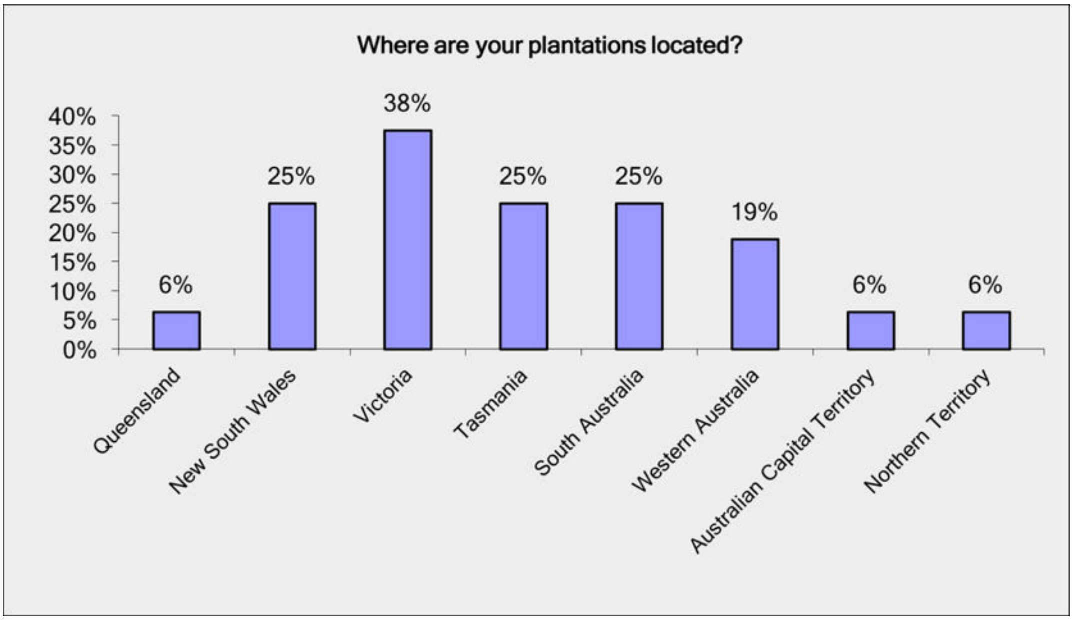

Figure 1: Proportion of survey respondents' plantation estate by State (NB: not area of plantation), based on growers surveyed, with several growers having estates in multiple States.

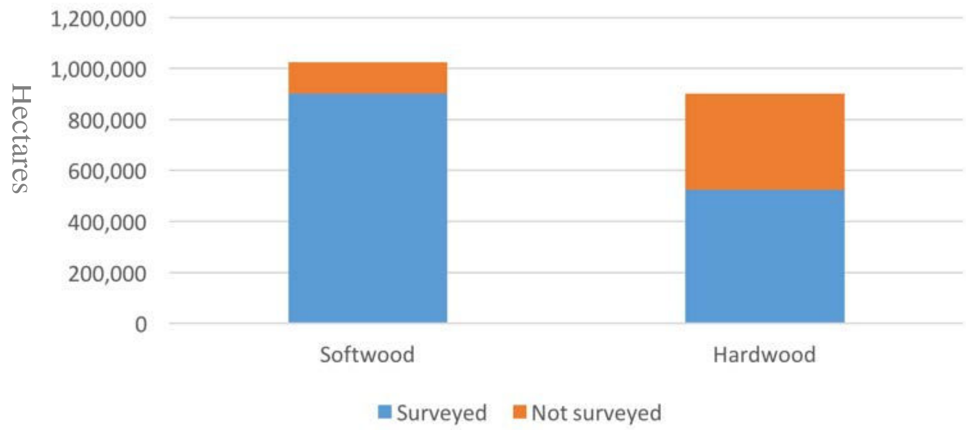

Figure 2: Area of softwood and hardwood estate covered by the questionnaire.

Forest health surveillance activities

All growers indicated they conduct multiple activities that have the potential, or are designed specifically, to detect pests and diseases (Figure 3). These included structured forest health surveys and pest population monitoring that are designed to detect and capture data on pests and diseases. But establishment surveys, inventory plot assessments, pre-harvest surveys and research trial assessments all have the capacity to detect and capture data on pests and diseases. Staff awareness campaigns, such as workshops and Pest Fact Sheets, are used to assist in *ad hoc* detection by operational staff during the course of their daily duties.

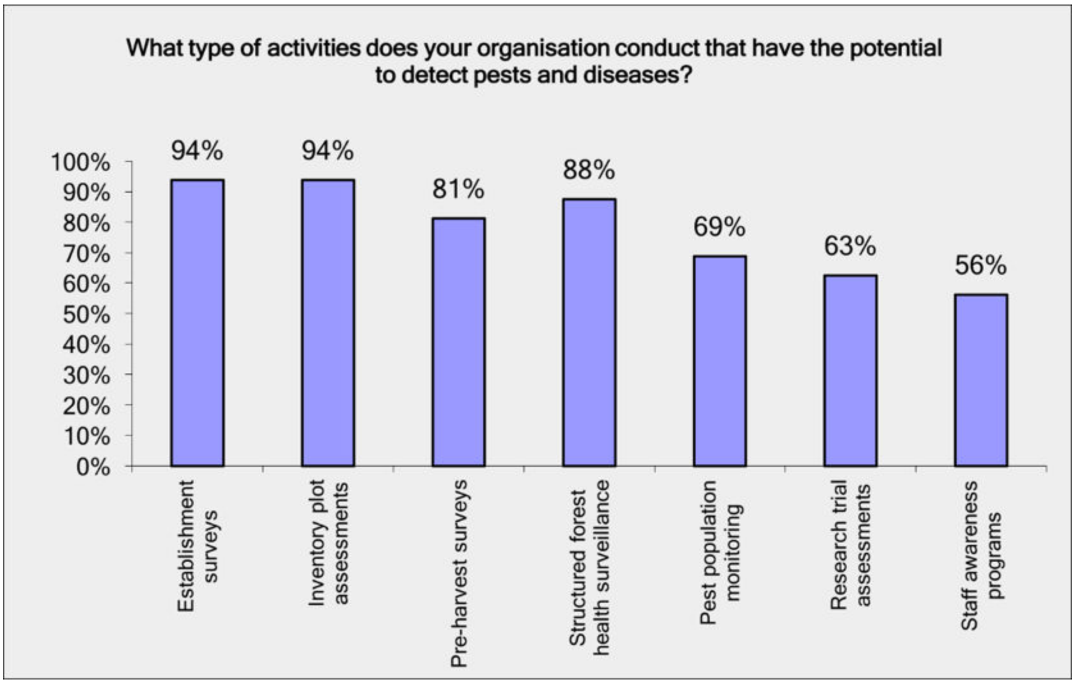

Figure 3: Surveillance activities conducted by growers that have the potential to detect pests and diseases, based on growers surveyed.

Of those growers that conducted structured forest health surveys, the majority conducted pest population monitoring, such as for sirex and eucalypt weevils (80%) and targeted responses to pest detections (80%), with a smaller number conducting aerial and ground surveys (47%) or plot-based surveillance (40%) (Figure 4). Figure 5 shows the proportion of softwood and hardwood estate, separately, covered by each of these systematic surveillance methods (based on respondents). For the hardwood estate, targeted responses to pest detections (87% of the estate) and pest population monitoring (75% of the estate) were the most common types of systematic surveillance, with ground-based plots 51% and minimal aerial surveys (15%). For the softwood estate, targeted responses to pest detections (97% of the estate) and pest population monitoring (67% of the estate) were again the most common types of systematic surveillance, but with 68% covered by aerial surveys and only 18% covered by ground-plots. Note that most growers conduct more than one of these surveillance methods, such as targeted responses to pest detection *and* pest population monitoring. Note that technically, targeted responses to pest detections is not strictly a "systematic" survey.

Overall, more than two-thirds of the plantation estate is covered by some form of systematic surveillance, either aerial and ground surveys, plot-based surveys, or pest population monitoring, or a combination of these. A proportion of the "unsurveyed" estate is likely to be considered low risk for pest or disease outbreaks, and as such perceived to not require surveillance. The softwood estate has a greater intensity of surveillance activity, with over 65% having aerial surveillance.

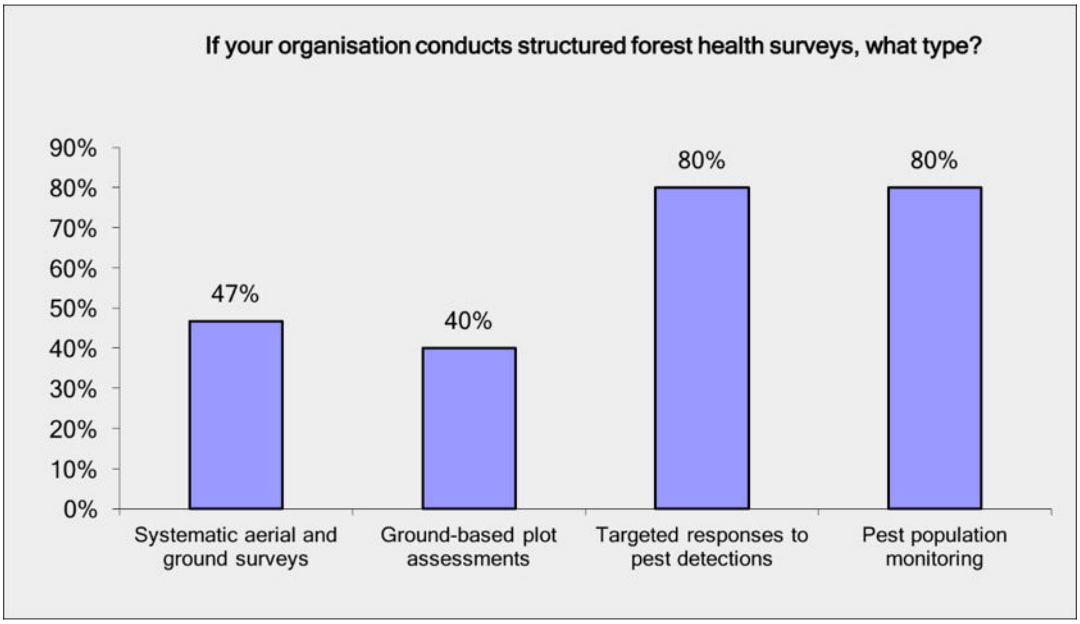

Figure 4: Types of structured forest health surveys conducted by growers, based on growers surveyed.

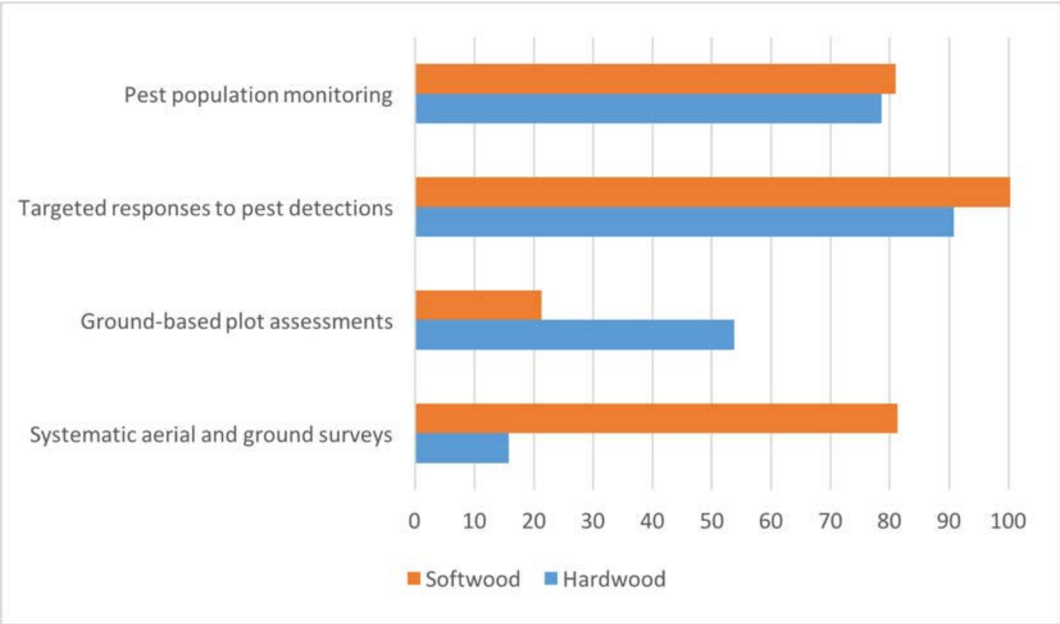

Figure 5: Percentage of planted area of softwood and hardwood estate which receives various surveillance activities, based on growers surveyed.

Sixty-nine percent (69%) of growers were aware of other growers in their region conducting forest health surveys, and 19% were "unsure". Sixty-nine percent (69%) of the surveyed growers indicated they collaborated on forest health issues with other growers, including the formal IPMG in WA, informal collaborations with other growers and forest health experts, and coordination of flights and sharing observations from surveys amongst growers in the Green Triangle, and coordination of the sirex biological control program in NSW, Victoria and South Australia.

Fifty-seven percent (57%) of growers surveyed utilise in-house expertise for forest health surveillance activities, with the remainder contracting external expertise; in some instances, growers who contract external experts have in-house expertise in certain areas (e.g. sirex). This "in-house" expertise accounts for approximately 49% (693,000 ha) of the plantation estate surveyed. Those that don't have readily available access to forest health expertise indicated that they would "consider conducting structured forest health surveillance, or have staff trained to conduct such surveillance" if they did have access to external expertise.

Seventy-five (75%) of respondents indicated that they have a structured process in place to document pest and disease detections. This included field observation *pro formas*, incident reporting processes, site inspection forms, data capture of sirex plots and aerial surveys, issue-specific reports, field staff entering detections into a database, in-field GIS-based data capture, and a procedure for integrated forest health management. Details of such processes, and whether such data can be shared at a regional and national level, would be useful to gain a better understanding of regional and national forest health issues. This also has the added benefit of being able to utilise this data to declare Pest Area Freedom from biosecurity threats. The majority of respondents responded positively (69%) to the potential of developing a nationally agreed process for collecting pest and disease data, such as a ForestHealth app. This would again assist in identifying regional and national issues and declaring Pest Area Freedom from biosecurity threats.

Respondents identified a range of reasons to collect forest health data (Figure 6), with the majority (88%) conducting surveys to monitor plantation health and detect and manage pests and diseases, but with 75% indicating forest certification a major reason to conduct surveillance. Sixty-three percent (63%) of the respondents cited “detection of biosecurity threats” as a reason to conduct surveys. Carter (1989) and Wardlaw et al. (2008), however, showed that general forest health surveillance is not adequate for detecting cryptic pest and disease damage, such as would occur in the early stages of establishment of biosecurity threats, and that specifically targeted biosecurity surveys are required for early detection of these pests.

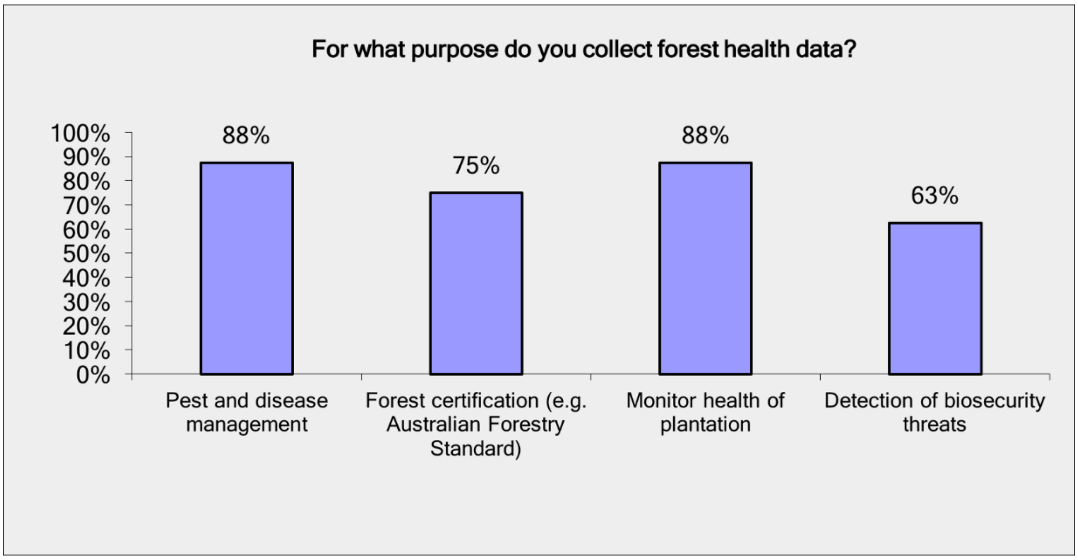

Figure 6: Reasons respondents provided for why their organisation collects forest health data.

Key Findings

- Our survey captured 88% of the national softwood estate and 58% of the national hardwood estate, with respondents mostly the larger growers. It is likely that the smaller growers not captured are less well-resourced and not undertaking as much surveillance. This gap poses a possible risk to those conducting surveillance activities.
- Australia has a fairly comprehensive forest health surveillance system, but this lacks consistency in approach and coverage of the estate. More than two-thirds of the plantation estate is covered by some form of systematic surveillance, either aerial and ground surveys, plot-based surveys, or pest population monitoring, or a combination of these.
- Current surveys are designed to map the extent and severity of established or endemic pests for later management, but not generally designed to detect cryptic biosecurity threats
- There are inconsistencies in surveillance methodology between states, but generally the base data are similar (i.e. pest species recorded, distribution and severity quantified, data recorded electronically, management options identified).
- There are large discrepancies between States and within States in what surveillance activities growers are actually conducting, but there are many surveillance activities being conducted that can, or are specifically designed to, detect pests and diseases.
- There is no formal coordination of surveillance activities at a State or national level, other than the IPMG in WA.
- There is no mechanism to ensure consistency in data capture, nor an ability to collate forest health data at regional, State or national levels.
- There is little or no structured surveillance in Australia's native forests that comprise 98% of the national forest estate.

Biosecurity surveillance

The aim of biosecurity surveillance is early detection of new pest incursions before they have spread too far so as to increase the chance — and reduce the cost — of eradication. High risk site surveillance involves conducting surveys in the vicinity of sites where initial incursions of exotic forest pests are most likely such as points of entry (e.g. sea ports and airports) or quarantine approved premises (QAPs) that hold imported materials. This is because targeted surveillance closer to the likely point-of-entry improves the probability of early detection of introduced exotic pests. In turn, this will increase the chances of successful eradication of any incursion and minimise the costs associated with it (Epanchin-Neill et al. 2014).

Previous audit of forest biosecurity

Mohammed et al. (2011) conducted an audit of forest biosecurity arrangements and preparedness in Australia. They highlighted that forestry was not well integrated with government biosecurity agencies compared to agriculture and horticulture; this has slightly changed for the better following the forest industries' signing of the Emergency Plant Pest Response Deed, which was a major recommendation by Mohammed et al. (2011). Mohammed et al. (2011) also highlighted the fragmented communication pathways between health specialist, industry and biosecurity agencies, and identified the need for a national body of forest health and industry experts to represent the forest industry in this arena, inclusive of a dedicated biosecurity officer. The Forest Health and Biosecurity Subcommittee, under the AFPA Growers Chamber, now fills this role, with discussions currently investigating a National Forest Biosecurity Coordinator role.

Following a questionnaire and national workshop, Mohammed et al. (2011) identified key issues raised by industry, technical experts and government that affect Australia's forest biosecurity preparedness, including:

- No biosecurity surveillance program and lack of surveillance capacity and investment
- Decline in forest health capacity
- Agri-centric nature of State and federal biosecurity agencies
- Lack of training in biosecurity for industry operational staff
- Apathy and/or lack of support in biosecurity from forest industry
- Delays in implementing emergency responses
- Lack of biosecurity awareness and involvement by environmental agencies

The key recommendations by Mohammed et al. (2011) were (1) the establishment of a national forest health and biosecurity committee, with a national biosecurity officer, and (2) the need to demonstrate the benefits of industry investment in biosecurity or the potential cost of non-participation. The first recommendation has recently been dealt with (FHaB Subcommittee), except for the national coordinator role, with the second recommendation the impetus for the current FWPA project investigating the costs and benefits of forest health and biosecurity. Further recommendations, not covered above, include (Mohammed et al. 2011):

- Development of an Industry Biosecurity Plan and pest specific contingency plans and pathways analyses
    - Note that a *Plantation Forest Biosecurity Plan* (PHA 2013) was developed based on this recommendation

- Pest Risk Analyses for key pests inclusive of cost benefit analyses
    - Note that a PRA for pinewood nematode was conducted as a response to this recommendation (current FWPA project)
- Development of a national biosecurity surveillance program (High Risk Site Surveillance) funded by industry and government
    - Note that a Department of Agriculture and Water Resources funded project has just been initiated to develop an operational procedure for such a program and identify stakeholders and funding options, as detailed in the Forest Biosecurity Surveillance Strategy
- Training of operational staff and maintenance of technical capacity for "triage" diagnostics of biosecurity threats for early detection
- Forest industry sign the Emergency Plant Pest Response Deed
    - Note this has now occurred
- A national biosecurity officer or coordinator to strengthen communication between industry and government and facilitate national reporting
- Training of industry operational staff, including pest identification and biosecurity response arrangements, to enhance industry preparedness to an incursion
- More coordinated and targeted research to enhance preparedness, such as cost benefit analyses to engage industry in forest biosecurity, pest risk assessments, pathways analysis, and better systems to respond to exotic incursions.

Bailey (2012) also reviewed forest biosecurity in Australia, with an aim of identifying priorities to guide FWPA investment in research, development and extension relating to forest biosecurity and preparedness. Based on responses from interviewees, with respect to current biosecurity R&D capabilities, Bailey (2012) identified *strengths* with high quality forest managers and technical experts; *weaknesses* with diagnostic capacity; *opportunities* to develop a coordinated pest database; and *threats* in continued loss of technical expertise, and forestry not being well integrated with government biosecurity arrangements. The following areas were identified as high priorities for RD&E investment in forest biosecurity in Australia:

- Update industry biosecurity plan
    - Completed in 2013
- Pest distribution, ecology and resistance
- Economic impact of pests
    - Being dealt with in the current project
- Preparedness planning

Pilot forest biosecurity programs

Pilot high risk site surveillance projects targeting exotic forest pests were initiated in Brisbane and Tasmania in the early 2000s (Wylie et al. 2000). These programs continued in 2005–2006, with Commonwealth funding, for high risk site surveillance again in Brisbane and Tasmania (Wylie et al. 2008; Bashford 2012), with the Tasmanian program running through to 2011. A separate program, focused on sentinel plantings, was initiated in Victoria in the late 2000s, utilising local council tree databases to assist in identifying risks for potential establishment of pest incursions (Smith et al. 2010). A more recent program was initiated in NSW, following the detection of Japanese pine sawyer beetle and Asian longhorn beetle, which focuses on insect trapping and sentinel tree surveillance (Carnegie et al. 2014). Despite these efforts, post-border forest pest surveillance is relatively *ad hoc* in terms of where and when it occurs. Surveillance is not coordinated nationally and suffers from fluctuating levels of funding, operational and diagnostic support. Further, the effectiveness of the surveillance that is undertaken relies heavily on a small number of State-based forest health experts who have differing levels of technical expertise and experience.

National Plant Health Surveillance Program

The federal Department of Agriculture and Water Resources (DAWR) funds a National Plant Health Surveillance Program (NPHSP) that includes insect trapping and multi-pest surveillance in and around major ports in each State. This is conducted by State agricultural agencies, with the focus mainly on agricultural and horticultural pests (Appendix II). The DAWR funding for this national program is approximately $800,000 pa, which is generally matched in-kind by the State-based agencies (Blomfield & Gillespie 2014). The pest target list for this program is not consistent across States and is often related to the expertise of personnel conducting the surveillance and diagnostics within the State (e.g. aphid expert, horticultural pest expert) or State-based industry priorities (Appendix II). Currently, the forest sector is poorly served by the NPHSP. Surveillance targets for forestry or environment/amenity make up 4% and 7%, respectively, of all targets that are surveyed (Tovar et al. 2016). Only Asian gypsy moths are surveyed for nationally, and while additional exotic forest pests are surveyed for in Victoria and Queensland under this program, this is due mainly to input from State-based forest health practitioners rather than design. *Of the 31 exotic forest pests deemed to be of high to medium risk to Australia as identified in the Plantation Forest Biosecurity Plan (PHA 2013) only one species is specifically surveyed for at a national level (i.e. gypsy moth).*

Recent forest pest incursions

Giant pine scale

The giant pine scale (*Marchalina hellenica*) was detected in October 2014 in Melbourne, and subsequently in Adelaide, based on a member of the general public reporting a pest in their pine tree. It was deemed an Emergency Plant Pest by the CCEPP and an Emergency Response Plan was developed and implemented. This is the first emergency response under the EPPRD that the forest industry has been involved in. Over 4,000 trees have now been identified infested with giant pine scale in Victoria, and the chemical control option used has been shown to not be effective. Affected trees in Adelaide were felled and destroyed, and this is now proposed as the primary (more expensive) control option in Victoria. (http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/pest-insects-and-mites/giant-pine-scale). UPDATE: In November 2016, the National Management Group determined that it was no long technically feasible to eradicate giant pine scale from Victoria and South Australia and has agreed to a Transition to Management program.

Pinewood nematode

The benefits of high risk site surveillance were recently illustrated by the detection of a pinewood nematode in a *Pinus radiata* tree in Sydney during the *NSW Forestry High Risk Site Surveillance Program* (funded by FCNSW and NSW DPI). During surveillance of over 800 *Pinus* trees over summer 2015–2016 a single “suspiciously” dying tree was detected and sampled. Diagnostics revealed an exotic nematode in the pinewood nematode (*Bursaphelenchus*) complex, and it was agreed nationally (by the CCEPP) to attempt to eradicate it. Surveillance within a 3 km radius has identified 1500^+ pine trees, with currently seven trees being positive for the exotic nematode. The affected trees have been removed and destroyed by deep burial. Surveillance is ongoing. UPDATE: Further surveillance has revealed the nematode more widely distributed in the Sydney basin and further afield in commercial pine plantations in NSW, and the CCEPP determined it is no longer technically feasible to eradicate it. http://www.dpi.nsw.gov.au/content/biosecurity/plant/pine-nematodes

Opportunities for supplementary biosecurity surveillance

There are good opportunities to conduct surveillance for biosecurity pests while undertaking other forest activities. Although forest health surveillance focuses on established and endemic pests, and Wardlaw et al. (2008) showed that general forest based surveillance is not effective at detecting cryptic disorders, there is a strong economic argument for integrating biosecurity surveillance with more general surveillance. For example, during forest health surveys in NSW, DPI conducts pest-specific surveys for biosecurity threats for very little additional cost. The biosecurity surveys target dead trees which are inspected and sampled for exotic bark beetles and nematodes. In areas of dothistroma needle blight (an existing disease) DPI also inspect and sample for symptoms of red needle cast (*Phytophthora pluvialis*) (an exotic threat). Although the chance of eradication of an exotic disease if detected within a plantation may be limited, the probability of containment and effective management can be high if the pest is detected before it has had the opportunity to establish and spread.

General surveillance — that conducted by the general public or non-specialists — can also increase the chance of detecting exotic pests. In NZ, by sheer numbers, the general public finds more exotic pests than trained professionals (B. Gould, Ministry for Primary Industries, 2015, unpublished). For example, for the period 1 July 2011 to 30 June 2014, over 2280 reports of suspect exotic pests were made by the general public to the Exotic Plant Pest Hotline; however, only 8% of these were actually deemed biosecurity pests by authorities. In contrast, biosecurity officers reported 77 cases of suspect exotic pests, with 45% of these positive; the scientific community (e.g. researchers) reported 333 cases, of which 42% were positive; local government and forestry staff reported 255 cases of which 23% were positive. By sheer numbers, the general public detected more exotic incursions (42%), compared with 34% by biosecurity officers, 13% by government officials, 15% by local government and forestry staff and 8.5% by researchers. An earlier study of forestry incursions into NZ between 1988-1998 showed that 77% of incursions were detected by technical/biosecurity experts, 17% by government officials or forestry workers, and only 6% by the general public (Hosking et al. 1999). The contrasting results here are indicative of the fact that the Gould data reports *all* exotic pest detection, including horticulture and agriculture, which are more likely to be encountered by the general public (e.g. gardens, parks, farms, orchards), whereas the Hosking et al. data reported forestry pests, which by their very nature are more likely to be in plantations or amenity trees less visited by the general public. Regardless of the relative contributions, NZ biosecurity authorities actively encourage the community to report potential biosecurity pests. There is less active encouragement in Australia to capture this broader community (general public), although targeted publicity campaigns occur during emergency responses (e.g. media campaigns for giant pine scale [http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/pest-insects-and-mites/giant-pine-scale], myrtle rust [http://dpipwe.tas.gov.au/biosecurity/plant-biosecurity/pests-and-diseases/myrtle-rust], and pinewood nematode [http://www.dpi.nsw.gov.au/content/biosecurity/plant/pine-nematodes]).

The majority of recent detections of exotic forest pest incursions in Australia have also been by the general public (Table 3). Examples in Australia of exotic pests detected by the general public include pinewood nematode in Melbourne in 2000 (subsequently eradicated), myrtle rust in 2010 (failed eradication) and giant pine scale in 2014 (currently under eradication campaign). General surveillance includes that by general public (e.g. keen gardeners), arborist, parks and gardens staff and nursery workers. Effective response to such surveillance relies on specialists who staff pest hotlines in each State (PlantPestHotline [http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/560712/emergency-plant-pest-reporting-and-what-happens-next.pdf]) and the ability of the State specialists to investigate suspect incursions. In Australia, Victoria does this particularly well, as they have a long history of urban tree health activities (e.g. monitoring for Dutch elm disease) and relationships with councils and arborists. Victoria also currently has a forest health technical expert embedded within their biosecurity operational division; no other State biosecurity organisation has this.

Table 3: Detection of recent exotic pest incursions in Australia

Pest	Where	When	Who detected	Response
Bursaphelenchus nematode	Melbourne	2000	General public	Eradicated
Arhopalus rusticus (pine longicorn)	Melbourne	2001	Biosecurity officers (as part of above response)	Established
Myrtle rust	Central Coast NSW	2010	General public	Emergency response (failed); established
Diplodia africana	Melbourne	2010	General public	Established
Thyronectria pinicola	Bombala, NSW	2012	Forest health surveillance	Established
Japanese pine sawyer beetle / Asian longhorn beetle	Major Australian ports	2014	General public (port worker)	Survey and trapping; not established
Bursaphelenchus nematode	Brisbane	2014	Biosecurity officers*	Ongoing surveillance
Giant pine scale	Melbourne/ Adelaide	2014	General public	Emergency Response (status unresolved)
Bursaphelenchus nematode	Sydney	2016	Biosecurity officer*	Under eradication

* Note that these detections were part of structured biosecurity high risk site surveillance programs.

Example of industry-lead biosecurity surveillance

The Honey Bee Industry has recently initiated a bee health and biosecurity surveillance program that includes surveillance of current established pests in hives as well as surveillance for early detection of exotic pests (http://honeybee.org.au/). This has been funded by the honey bee industry (via a biosecurity levy) as well as DAWR, Grain Producers Australia, and in-kind from state agencies. The Honey Bee Industry raised $450,000 under a new levy for biosecurity activities. The program is managed by PHA. The Melon industry is also in discussions with PHA to instigate a similar program. These programs provide good examples for the forest sector to follow should it seek to develop a National Forest Biosecurity Surveillance Program.

The state of State forest biosecurity in Australia

Queensland currently has forest pests as part of their target list for trapping as part of the National Plant Health Surveillance Program (NPHSP), as well as forest health technical experts involved. In the past year the Queensland government has also funded a "mapping and trapping" pilot study to improve forest pest surveillance around high risk sites (G. Pegg, pers. comm.).

New South Wales does not have any forest pests targeted under the NPHSP. However, over the past two years NSW DPI has initiated a *Forestry High Risk Site Surveillance Program* around key ports in NSW, which includes trapping and surveillance of sentinel trees (Carnegie et al. 2014). This program, however, is currently funded by Forestry Corporation of NSW, with no guarantee of ongoing funding past June 2017.

Victoria have key forest pests that are targeted under the NPHSP. They also have a long history of biosecurity surveillance and sentinel site surveillance (Smith et al. 2010), and a State-based pilot program for forest biosecurity surveillance (D. Smith, pers. comm.). This is currently the most adequate program for forest biosecurity at ports-of-entry in Australia (Figure 7).

Tasmania has had a history of biosecurity surveillance and has technical experts with previous experience in such activities. However, there are currently no forest pests targeted under the NPHSP, apart from myrtle rust, and they no longer have a forest entomologist.

South Australia has in the past had a technical expert involved in biosecurity surveillance, but none now. The giant pine scale incursion has raised biosecurity awareness in the State.

Western Australia and the Northern Territory do not have forestry pests on the target list for the NPHSP, apart from myrtle rust. However, the Northern Australian Quarantine Strategy (NAQS) conducts biosecurity surveillance in northern Australia, which does include some forestry pests, targeting high-risk entry pathways from Asia (http://www.agriculture.gov.au/biosecurity/australia/naqs).

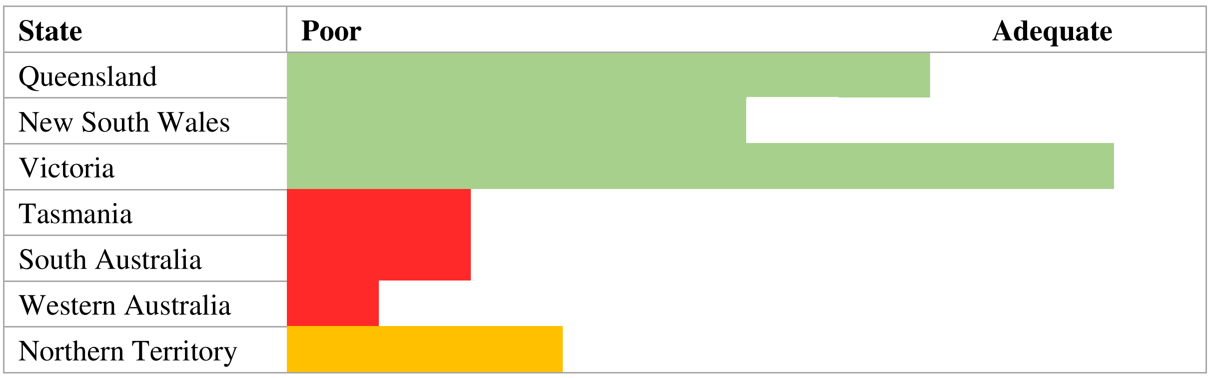

Figure 7: Adequacy of biosecurity surveillance at ports-of-entry to reduce the risk of forest pests entering and establishing in Australia. Rating takes into account pests targeted for surveillance, whether sentinel sites are surveyed, and likely longevity of funding for programs.

Industry survey of biosecurity awareness

In the 2016 survey of Australian plantation growers we also investigated biosecurity awareness and activity in Australia (see Appendix I for questionnaire).

Technical expertise within Australia

The majority (82%) of respondents were aware of the recently formed *Forest Health and Biosecurity Subcommittee* under the AFPA Growers Chamber. This committee replaced the Subcommittee on National Forest Health (SNFH) under Plant Health Committee, and now includes a mix of technical experts and industry experts. The 18% (3 respondents) that were not aware of FHaB indicate that these changes have not filtered throughout the industry, and a greater effort is required for this to occur.

The number of forest health and biosecurity technical experts has declined over the past two decades, following the same trend in other science-based disciplines. In 1995, there were over 25 FTE actively working in forest health, with many of these within industry R&D divisions, but also CSIRO and universities. Now there are approximately 12; most now in State-based primary industry divisions, but also some still within industry and universities. [Note that forest health and biosecurity requires expertise separately in forest pathology and forest entomology. Some States no longer have technical experts separately covering these two disciplines (e.g. Tasmania is without a forest entomologist for the first time in 40 years).] There are no longer any experts within CSIRO. This does not include those strictly conducting research, as these experts are less likely to be able or involved in response activities or provide technical expertise to emerging issues. However, the definition of a "forest health specialist" was not strictly defined, and the respondents' answers to this question (Figure 8) may reflect this ambiguity.

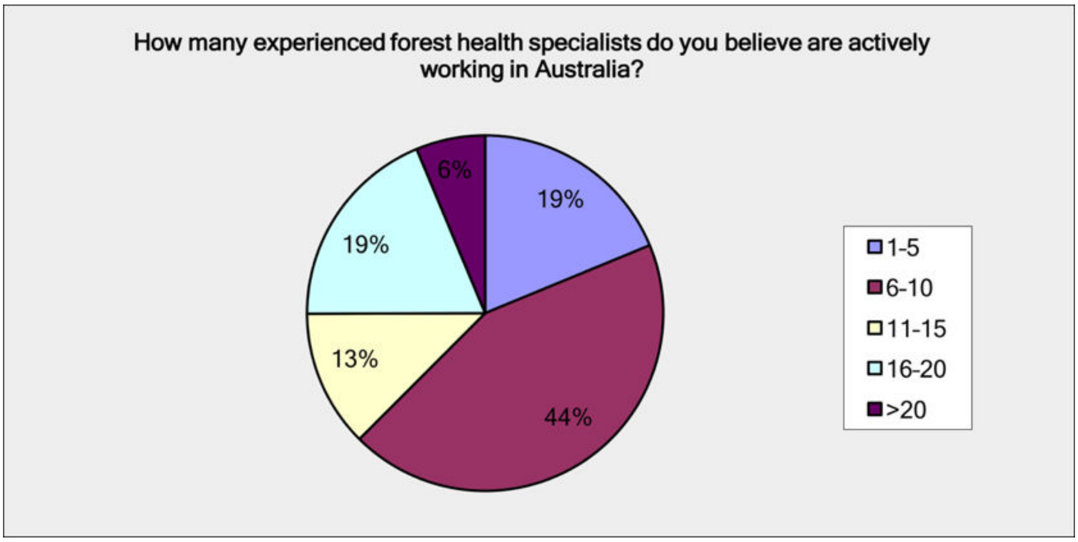

Figure 8: Respondents' estimates of the number of forest health specialists actively working in Australia.

The majority of respondents (75%) had consulted a forest health expert in the past five years, and this included advice on surveillance processes and a range of pest issues in plantations and nurseries. The majority of respondents thought that having access to forest health expertise when required was important (score 4) to vital (score 6): average 5.1 (with 1 = not important and 6 = vital). All but one respondent believed that the responsibility for funding forest health expertise to ensure adequate and timely response to new forest health threats and biosecurity incursions lay with both industry AND government; the lone grower thought that government should fund this. That being said, only a small proportion of the industry actually directly fund these technical experts, with some being funded solely by a single grower or a "consortium" of growers, some a combination of grower and government, while others solely by government or in the university sector.

Industry training

All but one grower surveyed had at least 1–5 staff trained in some aspect of forest health, with some growers having 6–10 or greater than 15 (Figure 9). Eighty-seven percent (87%) of these staff had had in-field training, about half had attended seminars or workshops, and 60% had university training (note the exact nature of forest health training at university is unknown). The majority (82%) of respondents indicated that if there was a nationally accredited forest health and biosecurity training module they would consider using it, with the remainder "unsure".

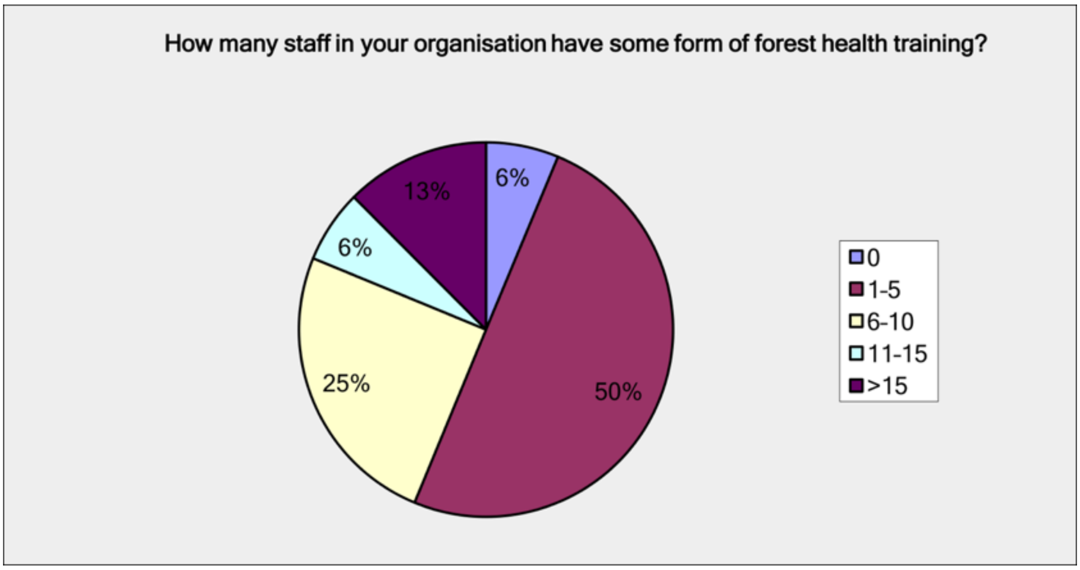

Figure 9: Number of forestry staff trained in aspects of forest health, based on growers surveyed.

Biosecurity Manual for the Plantation Timber Industry

Less than 70% of respondents (67%) were aware of, or had received, the Biosecurity Manual, which was released by Plant Health Australia and AFPA in July 2015. PHA, AFPA and FHaB need to ensure all industry representatives and growers are aware of the Biosecurity Manual (note that AFPA members were made aware of the *Biosecurity Manual* through the AFPA Resources Chamber). Of those that had the *Biosecurity Manual*, 4/12 did not agree that it was useful, while 8/12 agreed that it was useful (average 4.0, with 1 = strongly disagree and 6 = vital). Further investigations are warranted to ascertain why some growers did not think the manual was useful: did they know it all already, did they think the manual could have been useful if put together differently, or did they think the manual was designed for someone other than themselves? Of those that had received it, most (64%) had implemented, or planned to implement, recommendations from it. These included: nursery hygiene and monitoring; rapid response to detections, monitor target pests; integrating manual into or forest health procedure; targeting staff training and awareness. Almost ninety percent (88%) of respondents have a staff member directly responsible for forest biosecurity.

Industry awareness of pest incursions and responses

The majority of respondents were aware of recent exotic pest incursions, including myrtle rust, giant pine scale, European house borer, pinewood nematode, as well as some more historic incursions, such as essigella, sirex, ips and pine woolly aphid. Many also indicated that eradication had been attempted for some of these (myrtle rust, sirex), or under eradication (giant pine scale). Only one mentioned that Bursaphelenchus nematode in Melbourne had been successfully eradicated in the early 2000s. This was a pest that was detected early in amenity trees and eradication attempts were instigated immediately, ultimately with success (Smith et al. 2008; Hodda et al. 2008). Such successful eradication campaigns need to be advertised more broadly within industry. Most respondents had a moderate to good knowledge of the emergency response procedures following the detection of an exotic pest: average 4.2, with 1 (not at all) and 6 (very well).

With respect to key biosecurity questions (Figure 10), respondents pretty much consistently agreed or disagreed with these propositions. Most moderately to strongly agreed (average score 4.3) that industry has an equal voice at the table for decision making processes during emergency responses. This was to some extent the opposite of what we expected, and may be due to the interpretation of the question. We were asking *do they,* while we believe respondents may have interpreted this as *should they.* We were expecting that industry would interpret one member (AFPA) on the CCEPP among eight government representatives as an unequal voice at the table. Respondents strongly agreed (average score 5.4) that national biosecurity activities should be targeted to areas of greatest risk. Most moderately to strongly agreed that biosecurity is a whole-of-industry responsibility (average score 4.9) and is a shared responsibility between governments, industry and the public (average score 5.1). Following on from this “shared responsibility”, respondents did not agree that biosecurity is mainly the responsibility of affected industries or solely the Government.

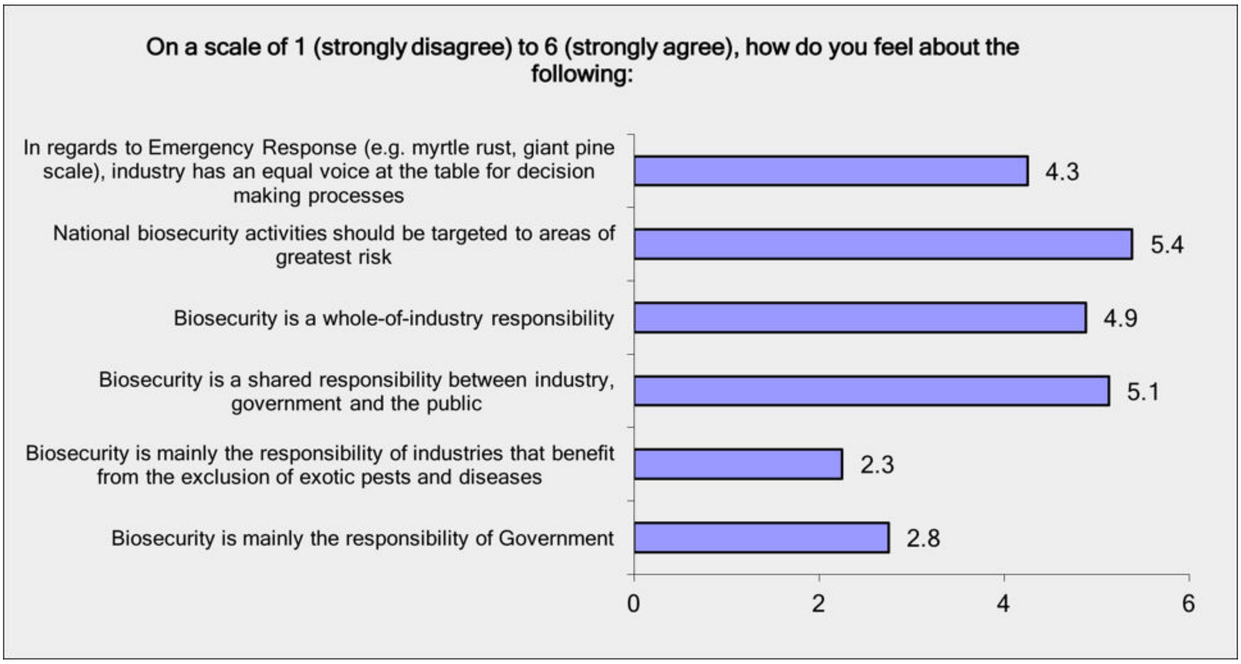

Figure 10: Industry responses to key biosecurity questions.

Maintaining or improving forest biosecurity in Australia

Growers were asked "what they saw as the top needs to maintain or improve forest biosecurity in Australia".

- Improving coverage, consistency and collaboration in forest health surveillance was identified by 9/16 respondents as a top need, including standardised reporting protocols, information sharing, and a single reporting database for regional and national reporting
    - More comprehensive forest health surveillance/systematic surveillance/consistent survey methodology/Single reporting database to support consistent survey methodology/standardised reporting of surveillance/Improved information sharing and coordination of efforts/better national coordination of forest health and biosecurity/more open collaboration between industry and government
- Half (8/16) of growers highlighted surveillance around ports-of-entry as a top need, including improving post-border and border surveillance and stronger border inspections, specifically related to forest pests.
    - Stronger border inspections/better detections and quarantine at ports/high risk site surveillance/port environ surveys/improved pre-border and post-border surveillance/improved monitoring for forest-specific pests/high risk site surveillance/effective quarantine
- Training of industry staff was a top need identified (6/16), including to assist in early detection of forest health issues and biosecurity threats, as well as awareness of the possible consequences arising from a serious incursion.
    - Further training/increase training of forest workers in pest detection/increased training nationally in forest health/Awareness campaigns at industry

    - level/Increased industry awareness of possible consequences arising from serious incursion
- Maintaining expertise and capability was highlighted by four respondents.
- The ability to respond quickly to emergency responses (incursions) was highlighted as a need by 3/16, including robust emergency response plans, increased industry awareness of their responsibilities, and political appetite to commit quickly to incursions.
    - Agile and quick response to biosecurity detections/Robust emergency response plans/Political appetite to aggressively attack foreign pests/
- Diagnostics was highlighted by 3/16, including ensuring diagnostic capability for forestry pests as well as diagnostic tools for industry.
    - Good diagnostics/increased diagnostic capability/accessible diagnostic images for layman

A range of other suggestions were identified, including (in no particular order):

- Transparency of post border and border activities:
- Cheap aerial surveillance
- High skills in interpreting information
- Be wary of importing timber products
- Instigating ongoing and efficient forest biosecurity management and people
- Raising awareness of forest biosecurity among importers, travellers and customs agency
- Stronger preventative communication plan with all stakeholders
- Willingness of industry to commit to increasing internal capacity to contribute to biosecurity effort
- Public education
- Systematic evaluation of risks

Key Findings

- Forest biosecurity surveillance in Australia is inadequate, especially with regards to post-border surveillance.
- The government-funded National Plant Health Surveillance Program does not cover forestry pests adequately, with only one (gypsy moth) nationally surveyed for and large gaps and lack of consistency in all State programs with respect to forestry pests.
- Multiple forestry pests are targeted for in post-border surveillance only in Queensland, Victoria and NSW.
- There are good examples of high risk site surveillance programs integrating well with general surveillance (i.e. general public reporting), as well as and stand-alone high risk site surveillance programs aimed at detecting exotic pests before they establish and spread into production areas (e.g. NSW, Qld, Vic); these could be used as templates for a national program.
- Industry has highlighted border and post-border surveillance as a priority, and that biosecurity is a shared responsibility between industry and government. The Bee industry has recently initiated a biosecurity surveillance program; a potentially good model for the forest industry to follow.
- The forest industry generally has a good awareness of biosecurity issues. This may not be surprising, based on the individuals that responded to this questionnaire being in charge of forest health in their respective organisations, and so may not necessarily represent whole-of-industry awareness.
- Training of foresters and field staff was identified as a need, and industry training in forest health could increase the potential for detection of emerging forest health issues as well as biosecurity threats. This training will also be essential to supplement the decrease in the core group of technical experts in Australia.

Benchmarking with New Zealand's forest health and biosecurity system

Forest health surveillance

The NZ forest industry has a much greater focus on biosecurity in their surveillance programs compared to Australia. The primary purpose of plantation surveillance in NZ is to "*detect new pest and disease incursions early before they can establish*" (http://www.nzffa.org.nz/farm-forestry-model/the-essentials/forest-health-pests-and-diseases/forestry-biosecurity-surveillance-in-new-zealand/). Australia's plantation surveillance has a much greater focus on forest health; "*mapping the extent and severity of damaging agents ... to effectively manage their impact*". The methodologies for plantation surveillance in the two countries are very similar, including aerial surveys, drive-through surveys and the use of plots or transects. In NZ, ~65% of the plantation estate currently receives aerial, drive-through and ground surveillance annually, on a user-pays system. The area covered is likely to increase under the new Commodity Levy arrangements (http://fglt.org.nz/). However, it would be logistically impossible to survey 100% of the plantation estate, and also not technically justifiable under their aims of early detection.

Data collected during the current project indicate that approximately half of the softwood plantation estate and a quarter of the hardwood estate in Australia is adequately covered by surveillance, which includes pest population monitoring, targeted responses to pest detections, aerial and ground surveillance or ground-based plots. Note that the native forest estate in both countries receives negligible surveillance. The surveys in Australia are *forest health* focused, but if conducted by trained professionals are able to supplement targeted biosecurity surveys. Some states conduct biosecurity surveys in plantations targeted at high priority pests, but this forms a relatively small part of the surveillance program.

The NZ Forest Health Surveillance Scheme is nationally coordinated, with data pooled in a national database for wider industry benefit. This national coordination stems from the FOA managing the program on behalf of their members. The 2015 budget for the forest health surveillance scheme was $830,000. This amount was based on the historical context of members of the Forest Owners Association, which at the time made up only ~60% of growers. The FHS scheme includes surveillance ($0.5–0.7 / ha), diagnostics ($130,000), database ($15,000) and administration ($30,000) (http://fglt.org.nz/images/contentimages/2015_work_programme_201114v3_web.pdf). This budget also includes funding for a project to review and redesign the surveillance program to take into account the larger area now required to be covered under the new Grower Levy (effectively 100% of the estate[2]), but still focusing on early detection (MPI are also funding this [$250,000]). Farm forests are not currently included in this surveillance.

In Australia, individual growers pay for forest health surveillance, resulting in large gaps in coverage of pest and disease issues across the plantation estate. Data on pest and disease issues is not pooled nationally (apart from the sirex program), with the Western Australian IPMG the only group of growers to pool data at a regional level.

[2] While the biosecurity and forest health surveillance strategy is designed to protect 100% of the estate, this does not mean that 100% of planted area needs to be regularly inspected to achieve this. For example, it may mean that more effort is required at High Risk Sites – although it is contentious exactly who pays for this.

There are also several smaller projects within the NZ forest health/biosecurity budget, including a revision of the incursion response plan for pine pitch canker ($20,000) and a Nursery Biosecurity Scheme and Guidelines ($15,000) to provide greater assurance that stock going into forests is pest and pathogen free. Australia has out-dated response plans for key pests. The *Biosecurity Manual for the Plantation Timber Industry* provides recommendations on ways to ensure planting stock is free of pests and diseases, but Australia has no national "scheme".

Biosecurity surveillance

Port environ surveys, or high risk site surveillance (HRSS), are those surveillance activities around ports of entry to detect exotic pests that have managed to escape quarantine-authority surveillance and inspections. The aim is to detect these pests early — prior to reaching production areas — to increase the chance of eradication.

In NZ, HRSS is funded by MPI and focuses on surveys of arborescent species (thus covering forestry) around ports and other high risk sites (http://www.biosecurity.govt.nz/pests/surv-mgmt/surv/high-risk). The focus is on detecting tree damage, then identification of the causal agent. The annual program costs NZ$1.1 million. MPI also fund a fruit fly ($1.5 million) and gypsy moth ($400,000) trapping program. At present, NZ does not have a national bark and wood boring insect trapping system, which may be considered a current gap in their system. A review is currently underway in NZ into their HRSS system which may address this issue.

In Australia, DAWR funds a National Plant Pest Surveillance Program (National Plant Biosecurity Surveillance Strategy 2013–2020, www.planthealthaustralia.com.au) that includes entry trapping (e.g. fruit fly, gypsy moth) and multi-pest surveillance. This is conducted by State-based agricultural agencies, with the focus mainly on agricultural pests. Some States have minimal forestry-related port environ surveys, including insect trapping and sentinel tree surveys. The DAWR funding for this national program, including fruit fly and gypsy moth trapping and the port environ surveys focused on agricultural pests, is ~$800,000 pa, which is often matched in-kind by the state-based agencies.
The NZ Forest Grower Levy Funded Work Programme (http://fglt.org.nz/images/contentimages/2015_work_programme_201114v3_web.pdf) identifies $3.43 million for Research Science and Technology. This includes $1 million pa for forest health/biosecurity projects, including Phytophthora species, red needle cast and the use of beneficial organisms (e.g. endophytes such as *Trichoderma*) to increase growth and protect against pathogens. These are all multi-year projects. New Zealand's forest health research and diagnostic capability has increased over recent years, including the recent hiring of Australian scientists (http://www.scionresearch.com/__data/assets/pdf_file/0009/44991/FP_annual_report_2014.pdf). In contrast, Australia's forest health expertise has dramatically declined over the past two decades.

Forest health technical expertise

The majority of forest health expertise in NZ resides in the research organisations (e.g. Scion) and government agencies; note these are not the people who do the forest health surveys. Most forest health survey practitioners in NZ are not "scientists" but trained technical staff. A few key senior individuals who conduct surveillance do, however, provide forest health and biosecurity technical advice (i.e. included in the NZ "expert" contingent). In contrast, most practitioners who conduct forest health surveys in Australia are also scientists/experts, with the remaining experts situated in government departments and universities. As such, the forest health surveillance practitioners are part of Australia's forest health and biosecurity capacity, unlike in NZ.

Forest diagnostics in NZ is mainly carried out in a single main laboratory (Scion), with internationally recognised forest pest and pathogen specialists. Up to 1,000 samples are submitted to the laboratory each year, many from the plantation health surveillance and the High Risk Site Surveillance programs. The annual budget for this diagnostics is ~$500,000, funded by FOA and MPI. NZ have a very good understanding of what pests and pathogens are present, including major, minor and non-significant pest species (http://nzfungi2.landcareresearch.co.nz).

Diagnostics in Australia is reliant mainly on State-based laboratories, either primary industry departments, or botanic gardens. Diagnostic triage is carried out by forest health specialists during surveillance, who are able to identify the main pests and pathogens and have a good understanding of symptoms of exotic pests. Some of these also carry out laboratory diagnostics, but they are not diagnostic specialists. Australia makes use of a good network (both formally and informally) of diagnosticians for both the plant and forest sector (http://plantbiosecuritydiagnostics.net.au/). A national database holds records of pests and pathogens recorded in Australia (http://www.planthealthaustralia.com.au/resources/australian-plant-pest-database/). However, the field of forestry diagnostic specialists is woefully small.

Industry representation

In NZ, forest biosecurity and R&D committees include senior industry members (e.g. David Cormack, CEO, Wenita Forest Products, is Chair of the Forest Biosecurity Committee). The NZ forest industry has a Forest Biosecurity Committee (http://www.nzffa.org.nz/farm-forestry-model/resource-centre/tree-grower-articles/treegrower-2014-november/forest-biosecurity-committee/). The Forest Biosecurity Committee is responsible for the forest health surveillance scheme; liaising with the MPI on border biosecurity and incursion response; recommending biosecurity research programmes to the FOA research and development manager; maintaining a close oversight on research relevant to forest biosecurity; and liaising with the Dothistroma Control Committee and the Stakeholders for Methyl Bromide Reduction on biosecurity problems associated with the log trade. No such committee exists in Australia.

In Australia, the recently formed Forest Health and Biosecurity Subcommittee under the AFPA Resources Chamber fills some of these roles, providing a focal point for forest health and biosecurity issues. The NZ forest industry also have a designated Biosecurity Manager — funded by the industry — who spends 25% of his time managing biosecurity matters, including forest health surveillance, research strategy and implementation, and liaison with government biosecurity agencies. No such position exists in Australia.

Key Findings

- NZ has a nationally coordinated and consistent forest health and biosecurity surveillance program. This assists in national reporting on forest health and biosecurity, including determination of Pest Area Freedom, which is vital for export markets. The NZ program has a greater focus on biosecurity than forest health, though.
- This contrasts with Australia's program, which is focused mainly on forest health, inadequately covers biosecurity, and has no national coordination nor consistency in methods, data capture nor reporting.
- In NZ the forest industry is actively involved and engaged in biosecurity, including senior forest (CEO level) representatives on biosecurity and R&D committees. NZ has a Forest Biosecurity manager, funded by industry, who manages national forest health surveillance, research strategy and implementation, and liaison with government biosecurity agencies.
- In Australia, much of the forestry biosecurity issues are pushed by technical experts within the States, and liaison with government etc. conducted, unofficially, mostly by individual technical experts or the Chair of FHaB.
- The NZ forest industry, as a whole, fund forest biosecurity surveillance and R&D.
- NZ is increasing its cohort of technical expertise, while this is diminishing in Australia.

Analysis of data to reveal how resources are distributed and identify any gaps in Australia's "forest health and biosecurity" system

Here we synthesise the preceding sections to reveal how resources and programs for forest health and biosecurity are distributed in Australia and identify any gaps in Australia's ability to adequately manage the risks posed by exotic threats to forestry. We first conduct a SWOT analysis (Table 4).

Table 4: SWOT analysis

Strengths	Weaknesses
Internationally recognised forest health & biosecurity expertise Good networking amongst forest health practitioners Good links to overseas knowledge base (e.g. via IUFRO plantation health working party) Many large growers conduct FHS 20-year history of FHS Good relationship between industry and forest health practitioners Good relationship between forest health practitioners and state/federal biosecurity agencies Effective systems in place for plant biosecurity (e.g. EPPRD, Plant Health Committee and its subcommittees) Good industry collaboration and cooperation already exists (e.g. herbicide consortium)	Ageing cohort of forest health practitioners No succession planning Only a proportion of plantation estate covered under FHS Negligible surveillance of commercial and conservation native forests Poor coverage of forestry in (agri-centric) government biosecurity surveillance programs No national coordination of FHS or biosecurity surveillance Lack of industry leadership of biosecurity Disparate forestry related diagnostic expertise; reliant on informal networking Forest health surveillance expertise lies mainly within the commercial forest health surveillance units, not in agricultural or environmental agencies No clear pathway to training and increasing the expertise in forest health and biosecurity
Opportunities	**Threats**
New owners/managers prepared to invest in risk management Heightened awareness and interest in biosecurity due to recent pest incursions Influence of CEOs who are already including biosecurity in their risk mitigation considerations Model for industry involvement in forest health and biosecurity already developed in NZ to benchmark Greater cross-industry collaboration with respect to expertise Increased ability to lobby for/facilitate training in forest health and biosecurity	Neither industry nor government take responsibility for succession planning No body (industry or government) acts to bring about national coordination of FHS Forest health surveillance is outsourced, thus reducing Australia's internal expertise and capacity to respond to emergencies Emergency response to giant pine scale fails, thus negatively affecting industry's faith in the biosecurity system Plant biosecurity agencies neglect forestry in state and federal considerations Pest incursion(s) not detected early enough to be able to eradicate

Forest Health Surveillance - Gaps

- Although there is relatively good coverage of the plantation estate with some sort of forest health surveillance activity, there are inconsistencies in methodology and the area being surveyed. This means that a proportion of the plantation estate is not adequately

surveyed, with risks of pest outbreaks (including new biosecurity pests) going undetected in these areas.
- There is no national coordination of surveillance activities, nor a mechanism to ensure consistency in data capture. This restricts the ability to collate data and report at a regional or national level, including on Pest Area Freedom status, which is important for international trade.
- Pest and disease issues identified during routine operational activities that growers conduct, such as inventory plot assessments and establishment surveys, are not adequately captured in overall forest health status reporting. Therefore, data on potential emerging issues, or the lack thereof, are potentially not captured at a national level.
- Forest health surveillance methodologies are designed to detect and map the extent and severity of established or endemic pests, not biosecurity threats. Thus, the data captured, and the time and resources spent conducting such surveys, may not be able to be used for biosecurity purposes, such as declaration of Pest Area Freedom.
- There is little structured surveillance in native forests.

Biosecurity - Gaps

- Forestry pests are inadequately surveyed for in post-border biosecurity surveillance programs in Australia, with no nationally coordinated program and only one forestry pest surveyed for nationally. This increases the chance that exotic incursions will become established and spread into production forests before being detected.
- General surveillance (i.e. the general public) is not consistently or well harnessed nationally. Utilising general surveillance increases the chance that new incursions are detected in urban and peri-urban environments, increasing the chance of — and reducing the cost of — eradication.
- There is a lack of transparency in what activities the federal government is conducting in biosecurity at the border. A greater understanding of these activities will allow risk assessments to be made about resource allocation for post-border surveillance.

Technical expertise and training - Gaps

- There has been a gradual decline in the number of technical experts actively working on forest health and biosecurity in Australia, with no body (industry or government) taking responsibility for succession planning. Within five years, the cohort of experienced technical experts will effectively be halved due to natural attrition.
- Training of industry is *ad hoc* and not consistent nor coordinated, and there is no nationally recognised course. This reduces the ability of this large work force from effectively being able to detect new pests and disease issues, including incursions, during their normal duties.

Industry engagement - Gaps

- There is a lack of industry leadership in biosecurity issues at a national level, with this generally being left to motivated technical experts. This has the potential for biosecurity issues to not be taken seriously by industry, or government to not take seriously forest industry needs in this arena.

Key Findings

- Lack of coordination of forest health surveillance activities and lack of consistency in data capture hinders our ability to report on the status of forest health and biosecurity nationally.
- Post-border forest biosecurity is not adequately covered, increasing the risk of pest incursions establishing.
- There is an uncertain future for sustainability of access to technical experts.
- Poor use of the forest workforce due to lack of coordinated and national training results in an over-reliance on pest detection by a small cohort of technical experts (in-house and consultants).
- Forest industry is relying too heavily on motivated technical experts to lead forest biosecurity at a state and national level.

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3. Costs and benefits of managing Chrysomelid leaf beetles by Forestry Tasmania.

Summary

Forest health and biosecurity programs rarely capture sufficient data to enable thorough cost-benefit analysis to occur. One notable exception has been Forestry Tasmania's research and control program on the leaf beetle *Paropsisterna* (=*Chrysophtharta*) *bimaculata*. For this program we were able to capture all major costs and benefits in monetary terms to allow analysis of a 'control' and a 'no control' option. The analysis provided insight into the economic drivers of applied forest health research and informed understanding of the risks and rewards of this type of investment.

Key Findings

- Above-threshold leaf beetle populations (that cause severe defoliation if uncontrolled) could be described by relationships with: (i) plantation age (likelihood of above-threshold populations peak at age 4-5 years and decline to a low value by age 12 years); (ii) site leaf beetle risk class (sites of low leaf beetle risk have fewer above threshold populations between years 3-12 years than sites of medium or high leaf beetle risk).

- Simulations of above-threshold leaf beetle populations in Forestry Tasmania's plantation estate between 2003-2034 found that the leaf beetle IPM, though controlling above-threshold populations, averted losses of 1.7M m^3 of merchantable wood volume (all products), equating to 7.7% of the total merchantable wood volume.

- The IPM program has been a 'break-even' proposition for Forestry Tasmania, generating a net benefit of (+) $476K (NPV @7.5%DR) when the cost of 'soft insecticide' research is excluded and a net cost of (-) $375K (NPV@7.5%DR) when 'soft insecticide' research is included.

- The benefits of the IPM program took many years to be realised operating for 20 years before achieving a positive cash-flow. Now that the program is well established it is generating a high level of ongoing net benefits.

- The time value of money was found to be a key driver of the IPM program's financial performance. This finding highlights the importance of minimising the time between the initiation of research and the operational implementation of management arising from that research.

- Having high fixed research costs made the scale of the program important. Programs with high fixed costs such as this one lend themselves to be undertaken on scale through cooperative arrangements.

- Investment in 'soft insecticide' research did not yield any financial returns. If 'soft insecticide' research can be applied in the future, it will enable certification by the Forest Stewardship Council (FSC). FSC certification is likely to generate 'social licence' and timber marketing benefits.

Part 1. Modelling the wood volume outcomes of using the Leaf Beetle IPM in eucalypt plantations in Tasmania's Permanent Timber Production Zone

1. The history of leaf beetle management by Forestry Tasmania

1.1 Integrated Pest Management for leaf beetles

More than 750 species of beetle from the family Chrysomelidae are native to Australia, with the majority feeding on the leaves of trees and shrubs of three genera – *Eucalyptus*, *Corymbia* and *Acacia* (Read 2006). A small number of species from the sub-tribe Paropsina (paropsine leaf beetles) have the potential to develop populations that cause significant damage in eucalypts, both in native forest and plantations. One such species, *Paropsisterna bimaculata* – a Tasmanian endemic – has been long known to be a significant defoliator of the ash group of eucalypts (Monocalyptus) in Tasmanian native forest (Greaves 1966, de Little 1979). The potential of this species to cause severe damage in plantations was then realised in early attempts to establish eucalypt plantations in Tasmania – initially the ash species, particularly *E. regnans*, (Candy *et al.* 1992), and then the non-native *E. nitens* (de Little 1989). Effective management of this leaf beetle would be needed if a viable eucalypt plantation estate was to be established in Tasmania (Elliott *et al.* 1992).

The biology of *P. bimaculata* and its suite of natural enemies was documented during research in the 1970s and 80s (Elliott and de Little 1980, de Little 1983, de Little *et al.* 1990). The impact of defoliation by *P. bimaculata* on the growth of plantation eucalypts was documented from research done in the 1980s and 1990s, initially on *E. regnans* (Candy *et al.* 1992, Elliott *et al.* 1993) and then *E. nitens* (Elek 1997, Candy 2000). Importantly, the research on the impact of *P. bimaculata* on eucalypt growth also documented the relationships between insect populations, levels of defoliation and subsequent tree growth (Candy *et al.* 1992, Candy 2000).

This early phase of research culminated in Elliott *et al.* (1992) articulating the elements of an Integrated Pest Management (IPM) for *P. bimaculata*. Subsequent research by Steve Candy (Candy 1999, Candy 2000, Candy 2003) provided the basis for designing a method for monitoring egg and larval populations in young plantations; predicting subsequent damage from a given measured population; and determining economic injury thresholds to guide control decisions. Candy's models for relating the size of egg / larval population to growth reduction (if not managed) has been incorporated into the Stand Manager routine within Farm Forestry Toolbox (Private Forests Tasmania 2016). The critical elements of the IPM were the regular monitoring linked to a threshold for the size of egg and larval population that triggered a control decision. Once a control threshold was reached an additional monitoring was done before spraying to determine if the population had reduced naturally (through predation or dislodgement of larvae during strong wind or rain events) obviating the need for spraying.

Forestry Tasmania's leaf beetle IPM was tested experimentally in 1990-2 and progressively refined to incorporate advances in monitoring and economic injury thresholds. This culminated in a fully operational IPM by 1998-9. This coincided with the start of a rapid expansion of eucalypt plantation establishment by Forestry Tasmania, which continued for a decade by which time the plantation estate reached approximately 50,000 ha. The leaf beetle IPM was used with little modification throughout this period of rapid plantation expansion.

The IPM was initially restricted to plantations between the ages of 3-6 years as these ages met the two conditions: vigorous trees had transitioned to adult foliage (favoured by *P. bimaculata*) and the shoots were accessible for sampling to measure egg and larval populations (Candy 1999). Despite this, it was known that older plantations could suffer severe defoliation by *P. bimaculata* (de Little 1989) (Figure 1). Annual health surveillance of Forestry Tasmania's eucalypt plantations had detected moderate (25-50% crown loss), and occasionally severe (>50% crown loss) defoliation by leaf beetles for several years (Wardlaw *et al.* 2011). A detailed assessment of leaf beetle defoliation in 2010 found that moderate – severe defoliation was concentrated in older plantations that were outside the span of age-classes included in the IPM (Wardlaw *et al.* 2011).

Figure 1. An 11-years-old *E. nitens* plantation that had been completely defoliated by *P. bimaculata*.

At around the same time, a study was done to determine whether plantations with above-threshold leaf beetle populations could be better predicted (Edgar 2011). This research found that elevation (≥550 m) and proximity (≤10 km) to native grassland we the two best predictors of plantations likely to have an above-threshold leaf beetle population. This finding, together with the evidence of under-protection from leaf beetles in older plantations was used to refocus the leaf beetle IPM to a risk-based targeting (Wardlaw *et al.* 2011): plantations in areas at lower risk of supporting above-threshold leaf beetle populations were excluded from the IPM and older plantations (up to age 12 years) in areas at higher likelihood of supporting above-threshold populations were included in the IPM. This change aimed to detect more above-threshold populations using a similar monitoring effort previously directed towards all younger plantations. The change accepted that some plantations in low risk areas would suffer significant damage from unmanaged leaf beetle populations. Annual health surveillance of the plantations (Wotherspoon 2008) detects such damage and affected plantations are included in the IPM the following season to guard against significant defoliation in consecutive years, which is known to have serious consequences, including mortality (Candy *et al.* 1992). Forestry Tasmania introduced the risk-based leaf beetle IPM in 2012. The original and the risk-based IPM are summarised in Table 1.

Table 1: Comparison of the key elements of the original and risk-based leaf beetle IPMs.

	Original leaf beetle IPM	Risk-based IPM
Target plantations	All plantations between 3-6 y.o.	Plantations between 4-12 y.o. in areas rated Medium or High leaf beetle risk Plantations suffering severe defoliation in the previous season
Monitoring period	Fortnightly between late November - February	Fortnightly between late November - February
Monitoring method	Two-stage: Satge 1: Roadside count of occupied (egg/larvae present) trees (OT). If > 3 OT, then do stage 2. Stage 2: Sample 6 shoots from each of 20 trees and count number of occupied leaves on each shoot (OLPS)	Roadside count of the number of occupied shoots / tree (OSPT) based on a sample of six shoots from each of 15 trees.
Population threshold for control	Initially OLPS > 0.3, increased to OLPS > 0.6 in 2009 (corresponds with populations causing >25% and >50% defoliation of current season foliage, respectively)	OSPT > 2.4 (corresponds with population causing >50% defoliation of current seasons foliage)

1.2 The search for softer control options

From the time the leaf beetle IPM was first conceived there was a strong focus on finding softer control options than broad-spectrum insecticides such as synthetic pyrethroids (Elliott *et al.* 1992). Initially the reasons for this were to avoid disrupting the high level of natural control of leaf beetle populations, particularly from egg predation (Elliott *et al.* 1992) and the high toxicity of the synthetic pyrethroids to aquatic animals (de Little 1989). More recently, the desire by many forest managers to seek certification under Forest Stewardship Council standards has become an important driver: α-cypermethrin is rated as highly hazardous by FSC (Forest Stewardship Council, 2015) and forest managers must seek a temporary derogation to use it while attempts are made to find ways to reduce reliance on the use of hazardous chemicals (Forest Stewardship Council 2007).

The initial focus of Forestry Tasmania's search for alternatives to broad-spectrum insecticides was on *Bacillus thuringiensis* var. *tenebrionis* (*Btt*) (Elliott *et al.* 1992). Laboratory trials showed *Btt* was non-toxic to the soldier beetle (*Chauliognathus lugubris*), one of the main egg predators of *P. bimaculata* (Beveridge and Elek 1999a). However, the toxicity of *Btt* to *P. bimaculata* was limited to first instar larvae (Elek and Beveridge 1999), and was lower when sprayed on *E. nitens* foliage than on *E. regnans* foliage (Beveridge and Elek 1999b). The limited spectrum of activity of *Btt* against *P. bimaculata* coupled with reduced effectiveness when applied under operational conditions (compared with results in the laboratory) prompted a decision in 1998 to discontinue research on this insecticide by Forestry Tasmania.

Between 1999-2003 Forestry Tasmania collaborated with Dow Agrosciences to conduct laboratory and field studies that evaluated the effectiveness of the product Success™, one of

the spinosyn group of biological insecticides. Like *Btt*, Success had little effect on non-target insects (Elek *et al.* 2004) and was not toxic to late instar larvae or adult leaf beetles. Success was however, sufficiently effective against young *P. bimaculata* larvae (1st and 2nd instars) when applied under operational conditions to allow registration of Success to control leaf beetles in *Eucalyptus* plantations by the Australian Pesticides and Veterinary Medicines Authority in 2003. Success was used operationally by Forestry Tasmania between 2003-11, with peak use (44% of area sprayed) in 2004. However, its use over that period progressively declined because of its greater cost and operational complexity compared with α-cypermethrin. The operational complexity was further compounded with the switch to the risk-based IPM, which extended coverage to older plantations in which the stage of development of the larval population could not be easily determined from monitoring.
The difficulties experienced in finding viable options for less toxic insecticides prompted a comprehensive review of management options and evaluating the range of options by several experts in forest insect pest management (Elek and Wardlaw 2013). Of the options for controlling outbreaks the review gave the highest rating (for economic, environmental and social outcomes) to an attract-and-kill approach. The Lethal Trap-tree Project, done though the CRC for Forestry, was used as a proof of concept for attract-and-kill. While lethal trap trees - blocks plantings of insecticide-treated *E. regnans* or *E. delegatensis* trap trees (attractive to *P. bimaculata*) within *E. nitens* plantations – did attract and kill *P. bimaculata* beetles from the surrounding *E. nitens* trees the reduction in beetle damage to the *E. nitens* was modest (Elek *et al.* 2011). This marked the end-point of Forestry Tasmania's research program to develop softer options for managing leaf beetles.

The full history of Forestry Tasmania's leaf beetle research program and costs associated with that research is chronicled in Appendix 1. These research costs were used in the analysis of costs and benefits of the leaf beetle IPM presented in Part 2 of this chapter.

2. Modelling the changes in wood yields from Forestry Tasmania's eucalypt plantation estate through using the leaf beetle IPM.

Wardlaw *et al.* (2010) did a detailed evaluation of the effectiveness and financial outcomes from the leaf beetle IPM in the 2009-10 leaf beetle season. That analysis concluded the IPM was largely effective in protecting plantations from severe defoliation by above-threshold populations and provided a financial benefit of $1.76 for each dollar spent in monitoring and control in that season. However, to understand the overall benefit of Forestry Tasmania's leaf beetle IPM the full costs (including research) and benefits (value of higher wood yields from protecting plantations from severe defoliation) need to be evaluated over a longer period.
Wood yields from Forestry Tasmania's eucalypt plantation estate, with and without management using the leaf beetle IPM, were calculated between the period 2003-2034. The 2003 starting point was used because that was the first year that the IPM was applied operationally throughout the whole plantation estate: before then some leaf beetle control operations were still being done for research to test softer insecticides. The 2034 end year was chosen because virtually all (98.5%) of the plantation estate had completed one full rotation by then.

The modelling is described in four parts: (i) assembling data to describe the plantation estate; (ii) developing a model to simulate above-threshold leaf beetle populations across a rotation; (iii) developing models to predict the reductions in plantation growth for a give sized leaf beetle population; (iv) modelling the wood yields with and without management of the simulated above-threshold leaf beetle populations.

2.1 Describing the plantation estate

Methods

Forestry Tasmania's eucalypt plantation estate model assembled for wood-flow modelling and sustained yield calculation was used to generate a list of all coupes in the estate. Very old plantations (pre-1990), often of species other than *E. nitens* of *E. globulus*, and currently unplanted areas of previously harvested plantations were excluded from the estate list. The total area of these excluded plantations was 1,227 ha and 1,486 ha for the old plantations and currently unplanted areas, respectively. For all other coupes in the estate model list values for the following attributes were obtained:

the regime (pruned or pulpwood) assigned to the coupe;
the year the coupe was planted;
the species planted;
the area planted; and,
the site index (mean height of dominant trees at age 15 years) based on either inventory plot data or calculated from LiDAR[3]. Precedence was given to site index values calculated from inventory plots – LiDAR-imputed site index was used when no inventory plots were located within the coupe.

For those coupes (or sections within coupe) that had been pruned, records of the average final pruned height and average number of pruned stems / ha were extracted from Forestry Tasmania's Forest Operations Database (FOD).

Estate data were analysed to describe the estate in terms of species mix, site index by regime, average pruned height (for each of 1, 2 and 3-lift pruning treatments) and average number of pruned stems per hectare. These calculations were used to specify the regimes for subsequent modelling in Farm Forestry Toolbox (in *Modelling wood yields*).

Results

Forestry Tasmania's 52,000 ha (approximately) eucalypt plantation estate is dominated by *E. nitens* in both the pruned and unpruned (pulpwood) parts of the estate (Table 2). Of the pruned plantations, those receiving three pruning lifts predominated (Table 2).

[3] LiDAR was collected for Forestry Tasmania's entire Permanent Timber Production Zone between 2011-14. Using ARC GIS, the mapped coupe boundary (PASPLUS data layer) was overlaid on the LiDAR data layer (including the LiDAR-derived digital elevation model) and the maximum height in each 25 x 25 m pixel within the mapped coupe boundary was extracted. The mean maximum height (surrogate for mean dominant height) for the coupe was calculated using all 25 x 25 m pixel records after clipping the extreme 10% of height records from the data. This tended to exclude data from misalignments of the coupe boundary with the LiDAR, e.g. when a slither of the coupe boundary extended into adjoining unlogged native forest.

Table 2: Area of Forestry Tasmania's eucalypt plantation estate partitioned by species and regime. Numbers in parentheses show the area for the indicated species (within a regime) as a percentage of the total area of the indicated regime.

Species	Pruned			Total pruned	Unpruned (pulpwood)
	1-lift	2-lifts	3-lifts		
E. nitens	1,729 (61.5)	3,785 (68.9)	19,931 (84.6)	25,445 (79.8)	15,610 (77.7)
E. globulus	935 (33.2)	1,180 (21.5)	3,135 (13.3)	5,249 (16.5%)	3,023 (15.0)
Other species	148 (5.3)	527 (9.6)	498 (2.1)	1,173 (3.7)	1,463 (7.3)
Total	2,811	5,492	23,564	31,867	20,097

To simplify modelling in Farm Forestry Toolbox (FFT) the estate needed to be segregated into site index classes. Four classes were considered manageable - the average site index value of each class would be used to represent the site index of the class in FFT. The site indexes of unpruned plantations were significantly lower than the pruned plantations ($F_{1,1841}$ = 201; MSE = 15.3; P<0.001). Because of this, calculations of interquartile ranges (used to classify each plantation into one of four site index classes) were done separately for the pruned and unpruned plantations (Table 3). NB. There were also significant differences in site index among the three pruned regimes (3-lift > 2-lift > 1-lift), but it was decided not to do separate site index classifications for the three pruning lift classes because of the low number of plantations in the 1- and 2-lift regime groups compared with the 3-lift group (Table 2).

The plantation estate developed slowly until 1998 when planting rates increased sharply (Figure 2a). High planting rates were maintained for the next decade, then fell away sharply. Thus by 2010 Forestry Tasmania's eucalypt plantation estate had largely reached its final extent (Figure 2b).

Table 3: Site index classification for pruned and unpruned plantations based on interquartile range values of site index. Average site index for each quartile class are shown in parentheses.

Regime	1st quartile	2nd quartile	3rd quartile	4th quartile
Pruned	<25 (22.6)	25 - <27 (25.6)	27 - < 29 (27.5)	≥29 (30.6)
Unpruned	<21 (17.4)	21 - <22 (21)	22 - <25 (22.8)	≥25(27.3)

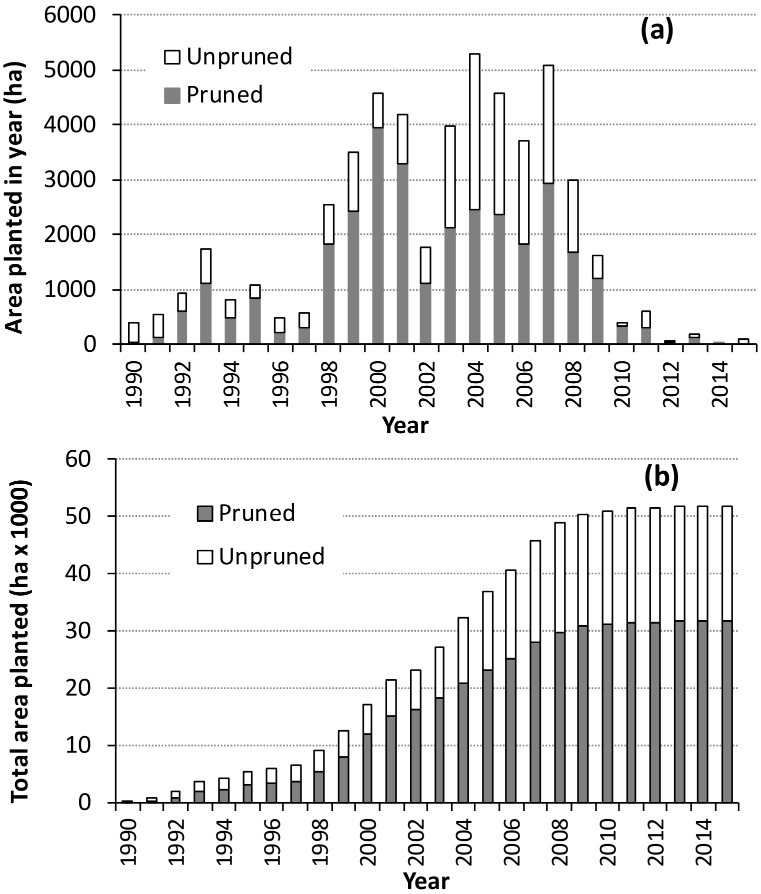

Figure 2: Age-class distribution of Forestry Tasmania's pruned and unpruned eucalypt plantation shown as (a) area planted by year and (b) cumulative area planted be year.

Coupes in both the 1- and 2-lift pruning regimes showed quite wide spread in pruning heights compared with coupes pruned to 3-lifts (Figure 3). Simple averages of pruning height characterise the 3-lift regime better than the 1- and 2-lift regimes. Given the dominance of the 3-lift regime in the pruned plantation estate, using a simple average of pruned height to characterise each of the three regimes was considered appropriate.

The number of pruned stems per hectare showed a wide spread of values for each of the three pruning lift regimes (Figure 4). As for pruning height, a simple average was a better characterisation of the 3-lift regime than the two lower lift regimes and for the reason of the 3-lift regime dominating the pruned estate was used for each of the three pruning lift regimes of the purposes of specifying the regimes used for modelling future yields.

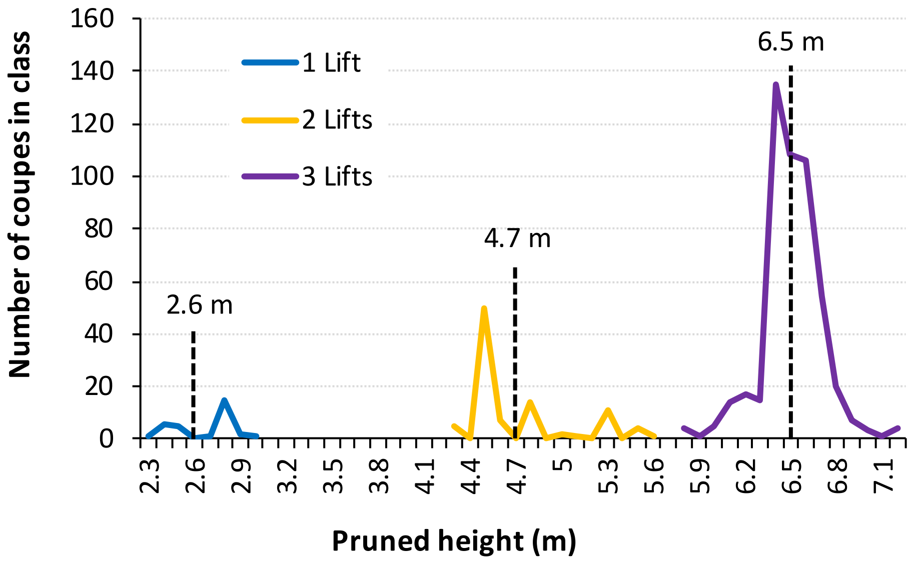

Figure 3: Frequency histogram of pruned height results for the three pruning regimes. Average pruned heights for the three pruning regimes are show by vertical dashed lines.

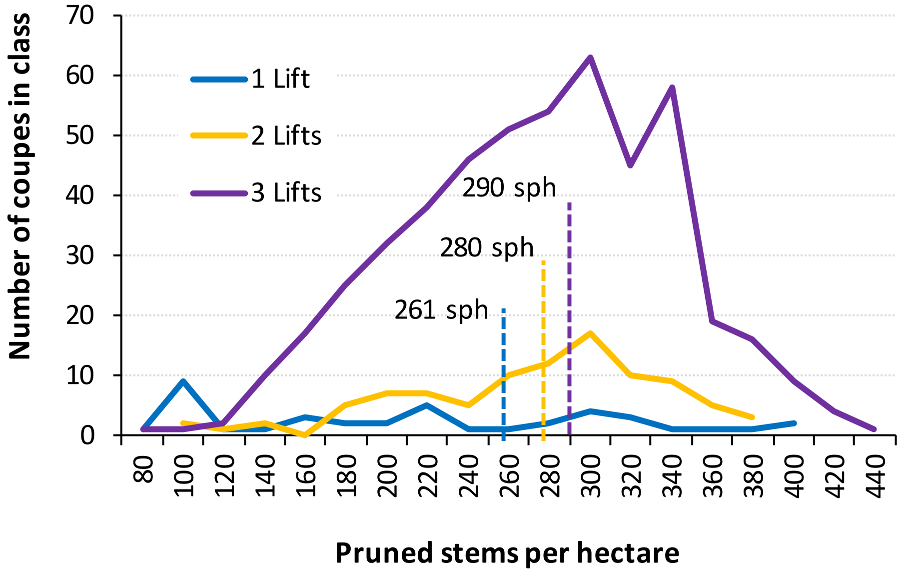

Figure 4: Frequency histogram of pruned stocking (stems/ha) for the three pruning regimes. Average pruned stocking for the three pruning regimes are shown by the vertical dashed lines.

To summarise, the specifications for the regimes for FFT modelling purposes are shown in Table 4.

Table 4: Specifications of growth model and silvicultural regimes for Farm Forestry Toolbox modelling.

Growth model: *E. nitens* (dominance of this species in the estate)
Site index: separate site index classification for pruned and unpruned (pulpwood plantations):
Pruned - <25 (22.6); 25 - <27 (25.6); 27 - < 29 (27.5); ≥29 (30.6)
Unpruned - <21 (17.4); 21 - <22 (21); 22 - <25 (22.8); ≥25(27.3)
Pruned heights: 3 lifts – 6.5 m; 2 lifts – 4.7 m; 1 lift 2.6 m
Pruned stems per hectare – 290

2.2 Modelling above-threshold leaf beetle populations

Methods

Forestry Tasmania bases decisions on the need to control a leaf beetle population on the measured size of the egg population assessed by sampling a number of trees (15-20), and shoots within trees (6), from within the plantation (Elliott *et al.* 1992, Candy 2000). Monitoring visits are done fortnightly between late November and early March. Up until 2011 monitoring was done in all plantations aged between 3- 9 (approximately) years. After 2011 the focus for monitoring changed to a risk-based targeting of coupes (described below) whereby coupes classified as low leaf beetle risk were not monitored, while those classified as medium and high risk were monitored if they were between the ages of 4-12 years. Records of leaf beetle population monitoring were extracted from the Forest Operations Database into an Excel spreadsheet. Fields extracted included:

Coupe name;
Planting year;
Date of leaf beetle survey;
Type of survey - occupied trees (OT); occupied leaves per shoot (OLPS); or occupied shoots per tree (OSPT) – as described in Table 1;
Measured size of the leaf beetle population;

The data for each monitoring season (November – March), comprising several fortnightly monitoring visits to each coupe, were reduced to a single record for each coupe – the maximum population size reached during the season. A total of 4158 coupe records of maximum population size were obtained for the nine seasons between 2007/2008 – 2015/2016. Each maximum population size record was assessed against the population threshold that triggers a control operation. The population threshold for control equates to a population that would cause >50% defoliation of current season's foliage. This equates to an occupied leaves per shoot value (OLPS) of 0.6 or an occupied shoots per tree (OSPT) value of 2.4. This is a higher threshold for population size than the original OLPS threshold value of 0.3, which approximated the economic injury level calculated by Candy (1999). Those records that exceeded the population threshold were assigned a rating of "above-threshold", while those records that did not exceed the threshold were assigned a rating of "below-threshold".

The age of each coupe in the season of monitoring was calculated by subtracting planting year from year when the monitoring was done. Each coupe was also classified into one of three classes of leaf beetle population risk – low, medium or high. These risk classes were assigned at the forest block level (the first two alphanumeric digits in the coupe name) according to criteria based on the study of Edgar (2011). Forest blocks assigned a high risk were ≥550 m elevation AND within 10 km of native grassland. Forest blocks assigned a medium risk were ≥550 m elevation OR within 10 km of native grassland. Forest Blocks assigned a low risk were below 550 m elevation AND further than 10 km from native grassland.

To model the impact of leaf beetle population on wood volume growth over a rotation requires knowledge of how many above-threshold populations a coupe is likely to experience and at what stage of the rotation those above-threshold populations occur. A total of 326 coupes, which had been monitored for leaf beetle populations over five of more seasons, were used to describe the frequency at which above-threshold populations recur. Quantile plots of the proportion of years monitored that an individual coupe experienced above-threshold populations (frequency of recurrence) were produced. Separate plots were produced for each of the three leaf beetle risk classes. From the quantile plots the proportion of coupes in a risk class that experienced above-threshold populations at differing frequencies of recurrence (from 0 – 100% of years monitored) were calculated.

A relative frequency histogram of above-threshold leaf beetle population by plantation age was generated using all records of above-threshold populations. This enabled the relative contribution of each plantation age group (between the ages of 3-12) to all above-threshold records to be calculated.

Results

The quantile plot of the proportion of years that coupes experience above-threshold populations clearly separate the low from the medium and high leaf beetle risk coupes (Figure 5). Coupes in the medium and high leaf beetle risk groups showed similar frequency of recurrence of above-threshold populations.

Sixty percent of coupes in the low leaf beetle risk group did not experience any above-threshold leaf beetle populations – double the proportion of the medium and high leaf beetle risk groups (Table 5). Recurrent (2 or more years in 10) above-threshold populations were recorded in more than 60% of coupes in the medium / leaf beetle risk groups, double the rate of the low risk group (Table 5).

Above-threshold leaf beetle populations were concentrated in the younger age-groups (Figure 6). While the monitored populations were also more concentrated in the younger age groups, the strong concentration of above-threshold populations in the younger age groups represented a significant departure from independent assortment ($\chi^2_2 = 188$; P<0.001).

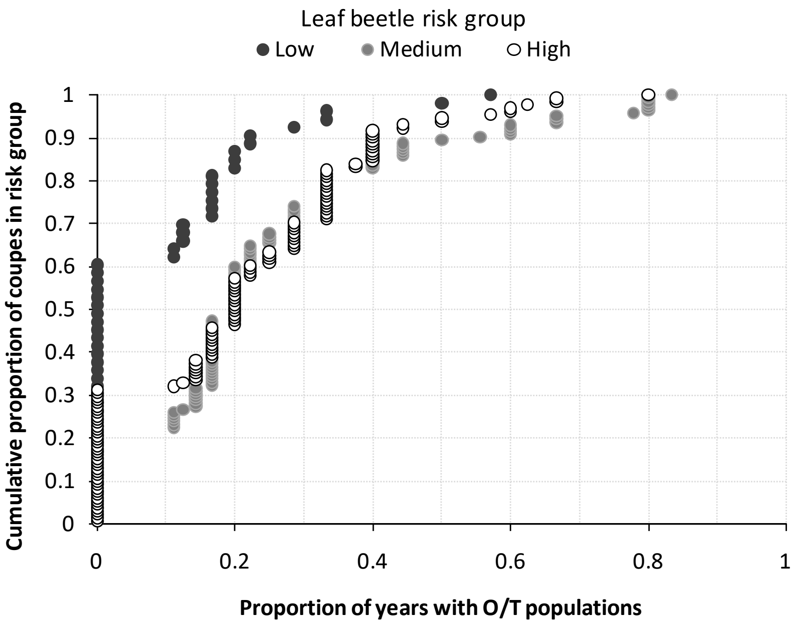

Figure 5: Quantile plot showing the cumulative proportion of coupes in low, medium and high leaf beetle risk groups plotted against the proportion of years the coupes experience above-threshold leaf beetle populations.

Table 5: Proportion of coupes in classes of increasing frequency of recurrence of above-threshold leaf beetle populations in low and medium / high leaf beetle risk groups.

Leaf beetle risk group	Years in 10 that stands experience over-threshold populations							
	0	1	2	3	4	5	6	8
Low	60	10	20	5		5		
Medium & high	26	8	28	20	8		5	5

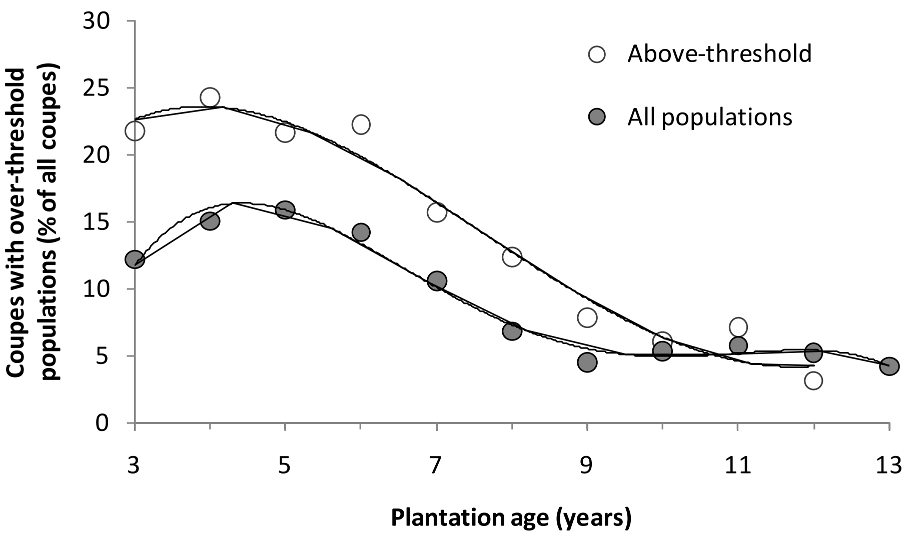

Figure 6: Frequency distribution of all monitored leaf beetle populations and above-threshold populations by plantation age.

2.3 Development of scenarios for above-threshold leaf beetle populations for plantations between the ages of 3-12 years.

Scenarios for modelling the impact of above-threshold leaf beetle populations on the plantation growth rates need to capture the patterns observed in the recurrence of above-threshold populations in individual coupes and the distribution of those above-threshold populations among age classes. This was done in two steps. The first step allocated each of the coupes, grouped according to their leaf beetle risk, into one of eight classes with each class representing the number of above-threshold populations experienced between the years 3-12 years. The number of coupes in each of those recurrence classes was based on the proportions calculated from the quantile plots and tabulated in Table 5. The number of coupes allocated to each recurrence class in this manner is shown in Table 6.

The second step involved allocating each above-threshold event represented in a recurrence class to an age between 3-12 years when that above-threshold event occurred. This was done manually and adjusted such that the proportion of coupes experiencing an above-threshold event in a particular age group was comparable with that measured in the frequency distribution of above-threshold populations by age-class shown in Figure 6. The allocation of above-threshold events to age groups for each of the eight recurrence groups is shown in Table 7 and the frequency distribution of above-threshold populations by age group of the model allocation compared with the actual frequency distribution is shown in Figure 7.

Table 6: Number of coupes in the three leaf beetle risk groups distributed according to the proportional representation of coupes in groups of differing frequencies of recurrence of above-threshold leaf beetle populations (shown as the number of above-threshold populations between years 3-12).

		Frequency of recurrence of above-threshold populations							
Risk group	No coupes	0	1	2	3	4	5	6	8
Low	323	194	32	65	16		16		
Medium	301	78	24	84	60	24	0	15	15
High	228	59	18	64	46	18	0	11	11

Table 7: Number of coupes in each of eight scenarios (recurrence of above-threshold populations between ages 3-12 years) and the ages at which the above-threshold populations occur.

Age (years)	Scenarios (recurrence of above-threshold populations)							
	0	1	2	3	4	5	6	8
3		75		122			26	
4			213			16		26
5			213			16		26
6				122	42	16	26	26
7				122		16	26	26
8					42	16	26	26
9					42		26	26
10					42			26
11								26
12							26	

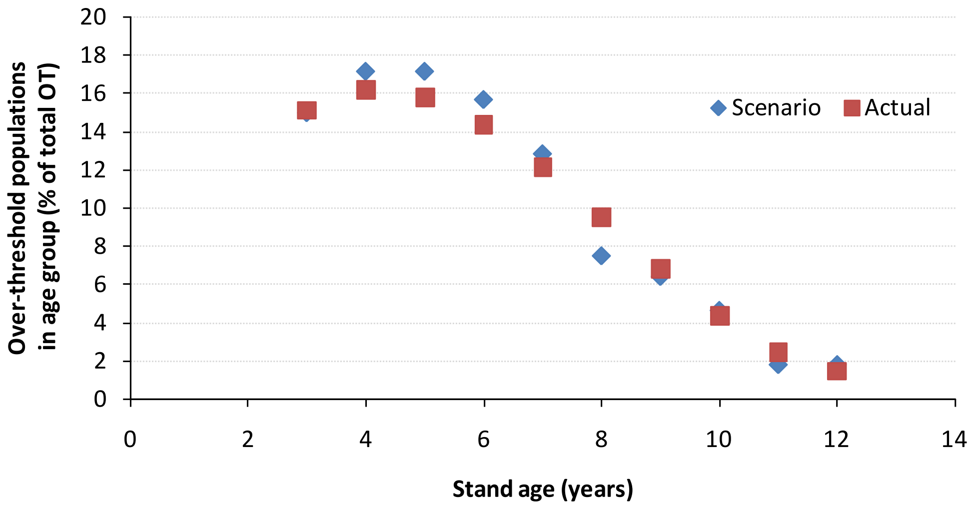

Figure 7: Frequency distribution of above-threshold populations by plantation age based on the allocation of coupes to the eight scenarios compared with the numbers actually recorded.

2.4 Modelling the impact of defoliation on plantation growth

The work by Steve Candy (Candy 1999) was used to model the impact of defoliation on plantation growth. Candy used a two-stage process to develop a leaf beetle population impact model. The first involved establishing the relationship between differing-sized populations (number of leaves per shoot occupied by egg-batches) and the amount of foliage consumed using caged shoot experiments. The second involved measuring the impact of a known amount of defoliation on growth using artificial defoliation studies. The model thus developed predicts a growth impact for a given-sized population in a form that can be applied in the Stand Manager routine of Farm Forestry Toolbox (Private Forests Tasmania, 2015). The population – growth impact models were developed separately for early (November-early January) and late (late January – March) leaf beetle populations of the egg and larval stages. The majority (71%) of spray operations done in response to above-threshold populations were for early season populations (analysis of records from the Forest Operations Database). However, the late season growth impact model was chosen for this analysis because the impact models only considered larval feeding and our experience is that both early and late season larval populations result in late season damage from feeding by adult beetles emerging after pupation.

The model developed by Steve Candy only provided data relating leaf beetle populations (and defoliation) to growth reduction for plantation ages of 2-6 years (Figure 8). To extend these relationships to older plantation ages, the slope and regression coefficients for the defoliation versus growth reduction models in Figure 8 were separately regressed against plantation age to develop models of these two regression parameters with age (Figure 9). This allowed the prediction of the slope and intercept values for the defoliation ~ growth reduction regressions for older plantations. The parameterised regressions of the defoliation ~ growth reduction models for all ages between 3-12 years were used to predict the reduction in growth for 75% defoliation of current-seasons foliage – the mid-point of the severe defoliation class. These values of growth reduction were used for the calculation of values for percent reduction in current season's volume growth corresponding to 75% defoliation for each year between 3-12 years (Table 2). The value of 75% defoliation was chosen because it was close to the level of defoliation predicted by the median value of population size (1.16) of all of the above-threshold populations.

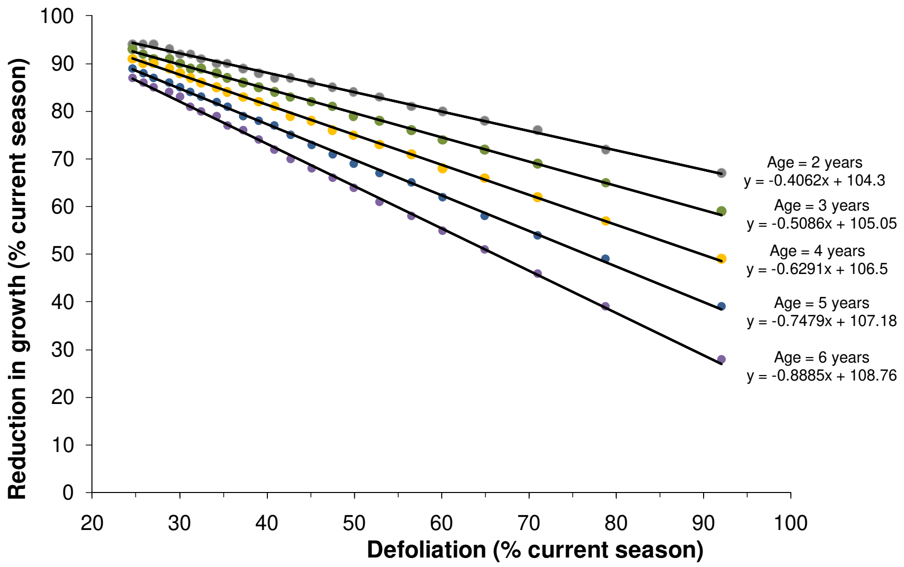

Figure 8: Linear regressions relating late-season defoliation by leaf beetles with reduction in tree volume growth for plantations aged between 6 – 6 years using models in Candy (1999).

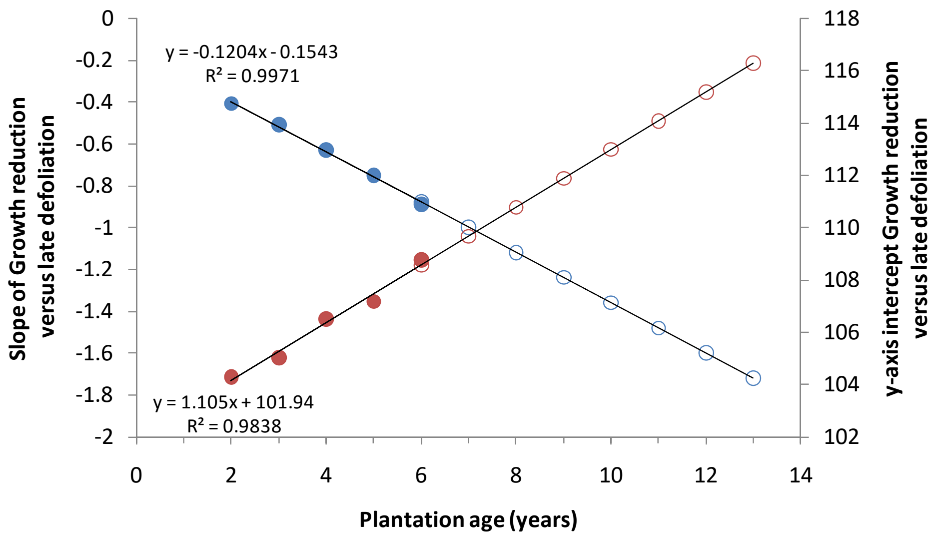

Figure 9: Parameter estimates of the slope (blue circles) and y-axis intercept (red circles) of the % defoliation versus % growth reduction regressions plotted against the plantation age corresponding to those estimates. The fitted linear regressions for the age vs slope and age vs y-axis intercept are shown. Extrapolation of those regressions was used to predict values of the slope and y-axis intercept values for ages above six years.

Table 8: Age-specific linear regression models predicting the percentage reduction in current annual increment (CAI) for a given level of defoliation of current season's foliage and the predicted reduction in CAI at 75% defoliation of current season's foliage. Parameter estimates for ages 7-12 were based on predictions shown in Figure 9.

Plantation age (years)	Regression model CAI reduction = α + β(Defoliation)	Predicted reduction in CAI at 75% defoliation (%)
3	105.05 – 0.509(Defol)	33
4	106.5 – 0.629(Defol)	41
5	107.18 – 0.748(Defol)	49
6	108.76 – 0.889(Defol)	58
7	109.68 – 0.997(Defol)	65
8	110.78 – 1.118(Defol)	73
9	111.89 – 1.238(Defol)	81
10	112.99 – 1.358(Defol)	89
11	114.10 – 1.479(Defol)	97
12	116.31 – 1.720(Defol)	100

2.5 Modelling wood yields with and without leaf beetle management

The Stand Manager Tool in Farm Forestry Toolbox (FFT) Version 5.3.2 (Private Forests Tasmania 2014) was used to predict future harvest yields based on a suite of scenarios that reflect "typical" specifications for silvicultural interventions to produce either a pruned sawlog crop or an unpruned pulpwood crop. The key specifications for the estate that were captured in the FFT regimes were site index, crop type, pruning height / pruned stocking (Table 4); the frequency and timing of above-threshold leaf beetle population events that are either controlled or not (Table 7); and the growth reduction resulting from unmanaged above-threshold populations (Table 8). The settings applied in the Stand Manager Tool of the silvicultural regimes and their specifications for the pruned and unpruned crops are show in Table 9, and the specifications for the log grades in Table 10. Initial FFT simulations of the yields from pulpwood crops managed on a uniform 15-year rotation were considered too low on lower quality sites (site index <22). As a result, the rotation length for pulpwood crops on low quality sites was extended to 20 years.

Table 9: Description of the silvicultural operations setting in the Regime Editor of Farm Forestry Toolbox for the four modelled regimes. Key silvicultural operations, their timing and their specifications are shown in shaded cells.

Age (years)	Pruned regimes			Pulpwood regime	
	1 lift	2 lifts	3 lifts	Site index ≥22	Site index <22
0	Pre-plant weed control Cultivation Browsing mammal control Seedlings Planting: 1008 sph – 95% survival				
0.3	Primary fertilization				
1	Browsing mammal control				
5	Pruning (lift 1): 290 stems/ ha to 2.6 m				
6		Pruning (lift 2) 290 stems / ha to 4.7 m			
7			Pruning (lift 3): 290 stems / ha to 6.5 m		
11.5	Forest Practices Plan				
12	Commercial thinning (5th tree outrow – 400 sph residual)				
14.5				Forest Practices Plan	
15				Clearfell	
19.5					Forest Practices Plan
20					Clearfell
24.5	Forest Practices Plan				
25	Clearfell				

Table 10: Specifications for the log grades used in Farm Forestry Toolbox modelling.

Log grade	Minimum length (m)	Maximum length (m)	Minimum small-end diameter (cm)
Pruned sawlog	2.5	11	30
Unpruned sawlog	2.5	5.5	20
Pulp log	2.4	11	8
Waste	0	0	0

The eight scenarios for above-threshold leaf beetle population events were modelled in FFT as follows:

i) A "no control" situation in which above-threshold populations are left unmanaged and cause growth impacts associated with severe (>50% defoliation of current seasons foliage) in each year between ages 3-12 that those populations occur in the plantation (Table 7). The growth impact of an unmanaged above-threshold population in a given year is modelled in FFT as a % of current CAI as shown in Table 11, with the growth effect extending over four years as recommended by Candy (1999), i.e. growth effect commences in the year of the above threshold population and progressively recovers to normal growth over the following three years.

Table 11: Matrix of leaf beetle scenario and plantation age (between 3-12 years) showing a value of the growth reduction (as a % of current CAI) in each year an above-threshold population occurs in a given scenario. Shaded columns indicate scenarios that apply for low, medium and high leaf beetle risk groups. Unshaded columns apply only for medium and high leaf beetle risk groups.

Age (years)	Leaf beetle population scenarios							
	0	1	2	3	4	5	6	8
3		67		67			67	
4			59			59		59
5			51			51		51
6				42	42	42	42	42
7				35		35	35	35
8					27	27	27	27
9					19		19	19
10					11			11
11								3
12							0	

ii) A mirror "IPM" for each of the "no control" scenarios. This is modelled differently for coupes assigned a LOW leaf beetle risk and coupes assigned either a MEDIUM or HIGH leaf beetle risk.

a. For coupes assigned a MEDIUM or HIGH leaf beetle risk the IPM mirror of each "no control" scenario involves monitoring to detect above threshold populations and controlling each of the above threshold populations when detected. This is modelled as a monitoring cost in each of the years between 3-12 and a control operation in each year that an above-threshold population occurs (as shown in Table 7 and mirrored in Table 10 as growth reductions if not controlled).

b. For coupes assigned a LOW leaf beetle risk, monitoring is not done routinely between years 3-12. Instead, monitoring is triggered by severe defoliation events to protected against a severe defoliation event in the following year. This is reflected in the FFT model as a growth reduction commencing in the first year an above-threshold population event occurs in the scenario; a monitoring event in the year after the above-threshold population; and, a control event in that following year if the scenario specifies an above-threshold population in that year. Monitoring continues into the following year if an above-threshold population occurs in the year after the defoliation from the initial above-threshold population. Monitoring ceases in the following year if an above-threshold population does not occur. Thus for scenario 3 monitoring is done at age four (triggered by severe defoliation at age 3); is not done in years five or six because no above-threshold population occurred in preceding year; the above-threshold event in year six was not detected and severe defoliation occurred triggering monitoring in year seven coinciding with the next above-threshold population which triggered a control operation.

A summary of how the leaf beetle scenarios were applied to the IPM and no IPM cases according to the leaf beetle risk groupings is given in Table 12. A total of 11 distinct leaf beetle scenarios were required to fully capture the IPM and no IPM cases for the three leaf beetle risk groups.

Table 12: Summary of the application of all leaf beetle scenarios for modelling yields with and without the leaf beetle IPM.

Leaf beetle scenario	IPM	No IPM
0: No above-threshold populations (all risk groups)	X	X
All above-threshold populations controlled (medium / high beetle risk groups)	X	
1: One above-threshold population not controlled (all beetle risk groups)		X
One above threshold population not detected and not controlled (low leaf beetle risk group)	X	
2: Two above-threshold populations not controlled (all beetle risk groups)		X
2a: Two above-threshold populations – first undetected and not controlled, second detected and controlled (low beetle risk groups)	X	
3: Three above-threshold populations not controlled (all beetle risk groups)		X
3a: Three above threshold populations: 1st and 2nd not detected and not controlled; 3rd detected and controlled (low beetle risk group)	X	
4: Four above threshold populations not controlled (medium and high beetle risk groups)		X
5: Five above-threshold populations not controlled (all beetle risk groups)		X
5a: Five above-threshold populations: 1st not detected or controlled, following four detected and controlled (low risk group)	X	
6: Six above-threshold populations not controlled (medium and high leaf beetle risk groups)		X
8: Eight above threshold populations not controlled (medium and high leaf beetle risk groups)		X

A number of simplifying assumptions were made with respect to the leaf beetle IPM:

i) Each above-threshold population at a particular age caused the same effect on growth regardless of prior history of above-threshold population events in the plantation;
ii) Control operations were 100% effective;
iii) No natural reduction of above-threshold leaf beetle populations occurred.

The validity and possible consequences of these simplifying assumptions are considered in the discussion.

Successive runs of FFT were run to calculate per hectare yields of the different wood products (as specified in Table 10) for each combination of leaf beetle scenario (as summarised in Table 12), site index class (as summarised in Table 4) and silvicultural regime (pruned – 1, 2 and 3 lifts; unpruned). A total of 176 separate runs of FFT were required to capture all combinations of leaf beetle scenario, site index class and silvicultural regime. Four yield tables were populated through this process – one for each of the four silvicultural regimes.

2.6 Applying wood yield tables and leaf beetle management schedule to the plantation estate

Excel spreadsheets were constructed for each of the four silvicultural listing all coupes managed under that regime. Each of the coupes within a regime was identified according to their planting year, site index class and leaf beetle risk group. Coupes within a common leaf beetle risk group were randomly assigned a leaf beetle scenario with the number of coupes assigned to a particular scenario based on numbers shown in Table 7. For each regime spreadsheet, a matrix of coupe x year spanning the 32-year period 2003-2035 was constructed and the age of each coupe in each year of the 32-year period was calculated. Where a coupe reached harvest age for the particular regime (15 or 20 years for pulpwood, 25 years for the three pruned regimes) within the 2003-2035 period, the next rotation (year 0) commenced the year after harvest.

The yield tables populated with FFT modelled data were then applied to each coupe[4] in the plantation estate and multiplied by the area of the coupe to provide predictions of harvest volumes for each year between 2003 and 2035. Two values of harvest volume for each wood product were generated for each coupe – volumes for the ***no IPM*** case of a given leaf beetle scenario and volumes for ***IPM*** case of the same scenario (as shown in Table 12). The process of randomly allocating leaf beetle scenarios within a leaf beetle risk group x site index group combination was repeated 25 times and the annual harvest yields of each wood product generated from each of those 25 randomisations were averaged and the 95% confidence intervals around those annual averages calculated.

A set of Excel spreadsheets mirroring those created to assign harvest yields to each coupe managed under each of the four regimes were created to capture values of coupe area monitored for leaf beetles and coupe area sprayed to control above-threshold populations. A look-up parameter for each coupe was created by concatenating beetle risk group, site index class, leaf beetle scenario and age of the coupe in a given year (between years 2003-2034). A spreadsheet containing a look-up table of values (0's or 1's) for monitoring and control operations for each unique combination of the look-up parameter was created. For coupes in the medium and high leaf beetle risk groups, monitoring events (monitoring value =1in look-up table) were assigned if their age in a given year was between 3-12 years. Control events (control values =1 in look-up table) for coupes in the medium and high leaf beetle risk groups were assigned in a given year if the coupe age in that year matched an above-threshold event occurring as determined by the leaf beetle scenario assigned to that coupe (as shown in Table 7). For coupe assigned a low leaf beetle risk, monitoring and control events for particular leaf beetle scenarios in are as shown in Table 13.

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[4] Each coupe within a regime was identified by site index class and leaf beetle scenario for both the IPM and no IPM cases. These identifiers were used to look up the appropriate yield value of a particular wood product in the yield table constructed for that regime.

Table 13: Timing (between years 3-12) of above-threshold leaf beetle populations ("X") and allocation of monitoring (shaded cells) and control (shaded "X" cells) events to each of the leaf beetle scenarios in coupes with a low leaf beetle risk rating.

Leaf beetle scenario	Plantation age (Years)									
	3	4	5	6	7	8	9	10	11	12
0										
1	X									
2a		X	X							
3a	X			X	X					
5a		X	X	X	X	X				

The value (0 or 1) assigned to each cell in the coupe x year matrix for monitoring or control events was multiplied by the area of the particular coupe. Thus a value of 1 (monitoring or control even took place) gave a value of the area (in hectares) that were monitored or controlled in a coupe in that year. The total area monitored or controlled in each year between 2003 and 2034 for each of the four regimes was obtained by summation.

3. Predicted wood yields and management effort

Predictions of wood yields with and without leaf beetle management (Figure 10 b and a) from Forestry Tasmania 52,000 ha eucalypt plantation estate found that the leaf beetle IPM averted losses of 86,100 m^3 of pruned sawlogs, 690,200 m^3 of unpruned peeler logs and 1,020,000 m^3 of pulpwood between 2003-2034 (Figure 10 c). This equates to a total of 1,796,000 m^3 in averted losses (equivalent to 34.5 m^3/ha). These averted losses represent 3.9, 6.4 and 9.9% of the total predicted harvest volumes of pruned sawlogs, unpruned peeler logs and pulpwood, respectively.

Variation wood yield estimates due to the random allocation of leaf beetle scenarios to coupes was small beyond 2017 when harvest yields climbed sharply. In the "No IPM" case, beyond 2017 the 95% confidence intervals were all <5% of yield mean values with the majority <1% of yields mean values. In the "beetle IPM" case variation in yield estimates due to randomisation was an order of magnitude lower than the variation measured in the "No IPM" case.

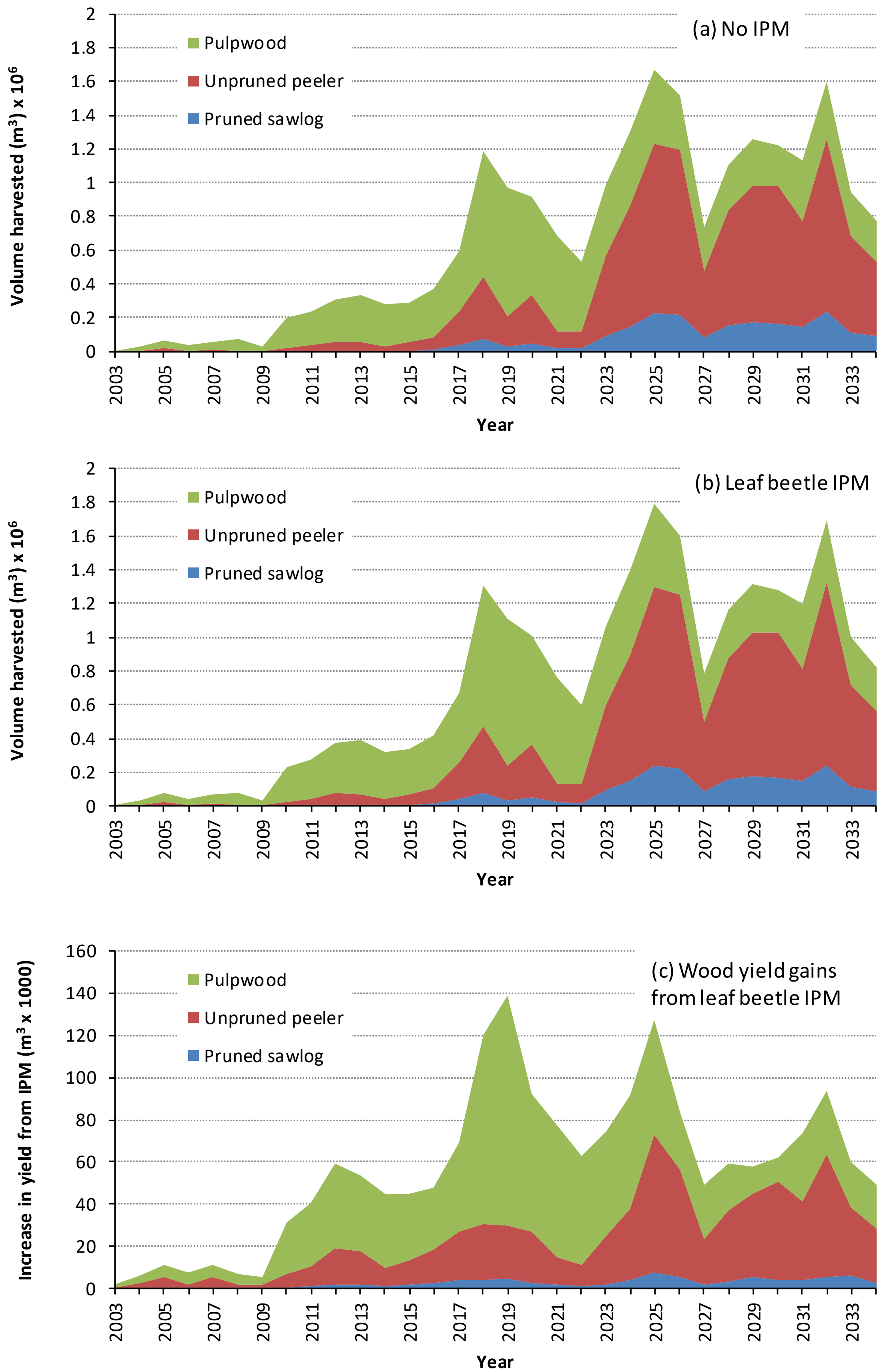

Figure 10: Predicted annual harvest volumes (by product type) between 2003-2034 from Forestry Tasmania's eucalypt plantation estate based on (a) no leaf beetle management, (b) using the leaf beetle IPM, (c) volume gains from using the IPM.

The total volume (all merchantable wood products) of averted losses through applying the leaf beetle IPM translate to per hectare values of between 10-42 m^3/ha (mean 21.5) across the total area harvested each year (Figure 11).

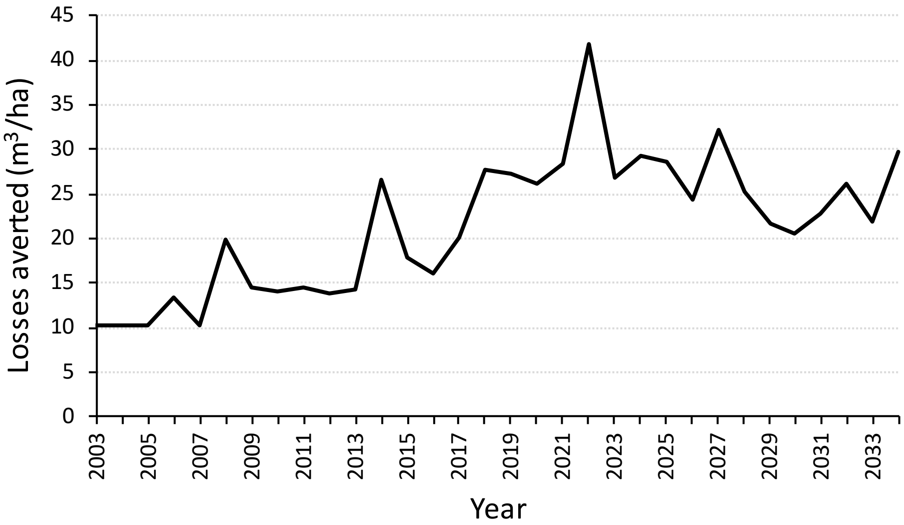

Figure 11: Annual per hectare losses in harvested wood volumes that were averted by the adoption of the leaf beetle IPM on Forestry Tasmania's eucalypt plantation estate.

The leaf beetle scenarios predict a progressive rise in management effort with the increasing area of plantation established, peaking in 2011 – three years after the end of the main period of rapid plantation establishment (Figure 12). Management effort declines over the next decade as increasing proportions of the plantation estate move into older age classes that are beyond the age when the IPM is applied. Manage effort begins to increase again in the mid-2020s as increasing an increasing proportion of the estate moves into the next rotation. Actual management effort in using the IPM between 2003-14 shows a moderate correspondence with the simulation although the peak effort appeared a year earlier and declined more sharply following that peak (Figure 11).

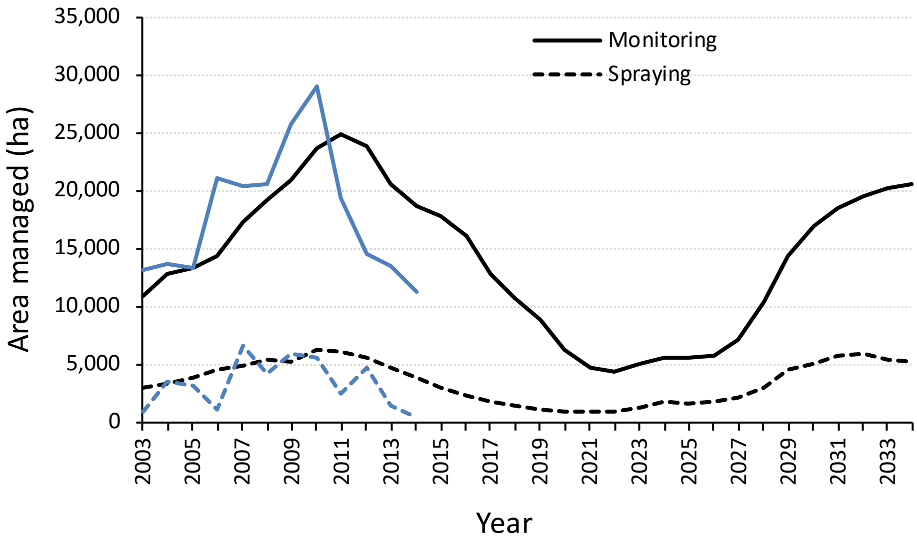

Figure 12: Area of Forestry Tasmania's eucalypt plantation estate managed annually between 2003-2034 for leaf beetles. Black lines show management effort based on the leaf beetle scenarios and blue lines show the actual management effort.

Discussion

We predicted gains in wood yields from the leaf beetle IPM of between 3.9 – 9.9% (depending of product), representing a total of 1,796,000 m^3 in averted losses from Forestry Tasmania's 52,000 (equivalent to 34.5 m^3/ha) ha plantation estate between 2003-2034. These gains through averted losses seem plausible and are comparable with other studies that forecast impacts across large scales of space and time. MacLean *et al.* (2001) forecast losses from severe defoliation by spruce budworm equating to 37 m^3/ha over a 30-year period in a 450,000 ha New Brunswick forest estate. May and Carlyle (2003) estimated annual wood volume losses of 2-6% based on three annual measurements in ten *P. radiata* stands suffering defoliation from *Essigella californica* and extrapolating to a whole estate based on the (undemonstrated) assumption the measured stands were representative of the whole estate. In New Zealand, Bulman (1993) predicted whole of rotation losses in wood volume from *Cyclaneusma* needle-cast disease in *Pinus radiata* plantations of 71m^3/ha. However, this prediction took no account of compensatory growth of trees that were unaffected by the disease. Straw (1996) measured whole of rotation volume losses of 5.6% from intermittent outbreaks of the pine looper moth (*Bupalus piniaria*) causing defoliation in *P. sylvestris*. However, in both of these latter two studies, losses were based on measurements restricted to affected tree / stands rather than a whole estate, where damage levels will vary more widely.

The unique aspect of our analysis was the model to simulate the frequency and timing of above-threshold populations. This model was informed by data accumulated from over 4,000 coupe-years of beetle population measurements. Examples of large-scale spatio-temporal modelling of forest insect pest outbreaks is largely restricted to outbreak-waves – outbreaks that develop from epicentres that enlarge over time – such as mountain pine beetle (Aukema *et al.* 2006) and spruce budworm (Gray *et al.* 2000). In contrast, chrysomelid population outbreaks in Tasmania show no evidence of expanding spread from epicentres (Grimbacher *et al.* 2011). Instead high populations tend to be associated with features of the landscape (Edgar 2011) that can be best captured as site-based risks. Further, this study has shown a strong effect of plantation age on the likelihood of high leaf beetle populations. De Little and Hingston (2008) also showed a peak in the occurrence of leaf beetles at age 5-6 years but had no data beyond age 7 and so did not detect a decline with age.

A critical aspect to the modelling done in this study was the translation of pest size to a growth effect. The relationship between population size and defoliation was established from studies done in young plantations (Candy *et al.* 1992, Candy 1999). The validity of extrapolating the "apparent" linear increase in growth reduction with age, beyond age 6 is untested. However, a limited number of growth measurements done in 9-12 y.o. plantations suffering severe defoliation gave values that were comparable with those predicted by extrapolating the growth reduction – age relationship in younger plantations (Wardlaw *et al.* 2011).

Another critical assumption made in the study was the effects of repeated severe defoliation over successive years. This study modelled growth reductions due to each defoliation event independent of any preceding defoliation. We know from studies in young plantations that severe defoliation in two successive seasons causes high levels of mortality (Candy *et al.* 1992). Older plantations may be less likely to suffer mortality from severe defoliation over successive years. Monitoring mid-rotation *E. nitens* plantations that had severe (>50%) defoliation over successive years recorded no mortality, although growth effectively ceased (Wardlaw *et al.* 2011). Despite this apparent older-age resilience (as survival) to repeated severe defoliation, simple independent growth reductions from each successive defoliation event is likely to underestimate impacts of repeated defoliation.

When calculating gains in wood volume from leaf beetle management, the modelling assumed that every above-threshold population was managed and the management was effective. Very clear the data shown in Figure 12 shows actual area sprayed was sometimes less than the area predicted to be above-threshold. This reflect two possibilities: (i) above-threshold populations declined to below threshold naturally (predation or weather events); (ii) spraying of above-threshold populations was not due to operational reasons, e.g. unfavourable weather, helicopters were unavailable or very costly operations (small, isolated areas). Over the past 12 years an average of nearly 1/3 of above-threshold populations were not sprayed. More detailed analysis in recent years indicate about half of the unsprayed above-threshold results were due to natural reductions of initially above-threshold populations. For these, the analysis of the costs and benefits will over-estimate the costs by an amount equivalent to the cost of the spray operation. A large proportion of the remainder of the above-threshold populations that were not sprayed occurred during periods of financial stress. While financial stress is a good reason for avoiding expenditure, losses incurred from not spraying should not be considered in the analysis of costs and benefits of management, because the interest is in the value of the control decision, not the ability to pay for it – that needs to be weighed against the value of expenditure for other purposes.

The analysis assumed all spray operations were completely effective. That is rarely the case. Wardlaw *et al.* (2011) reported 6% of sprayed coupes still suffered moderate or severe defoliation. While accounting for ineffective spraying could have been done incorporated into the modelling, to do so would have added additional complexity. The alternative is to incorporate a sensitivity analysis to understand the consequences of uncertainty surrounding actual yield changes due to management in the analysis of costs and benefits.

Finally, the modelling assumed notional harvest ages of 15 (or 20) and 25 years for pulpwood and sawlog crops, respectively. For the no leaf beetle management scenario, trees in affected stands would be smaller at these notional harvest ages than unaffected stands and might justify delaying harvest. Such a delay would be expected to further decrease the value of the no leaf beetle IPM relative to the value with the leaf beetle IPM. While the option of delayed harvest could be modelled it would add considerable complexity and is unwarranted given many other factors also dictate harvest age (e.g. management of wood supply, market fluctuations).

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Appendix 1. History of leaf beetle research activities and costs

Year	Research activities	Expenditure ($)
1974-75	Establish Florentine artificial defoliation trial	2,560
1975-76	Document life history of *P. bimaculata*. First survey work to sample natural enemies.	4,000
1976-77	Defoliation trials in Florentine (*E. regnans*) and Southern Forests (*E. obliqua*). Predation and parasitism studies in Florentine Valley.	2,300
1977-78	Monitoring natural predation by ladybirds (Florentine)	2,600
1978-79	Final (year-4) measurement of growth impact study (artificial defoliation)	720
1979-80	Population monitoring to develop life table for *P. bimaculata.*	6,000
1980-81	Documenting past research (life table, growth impact)	6,100
1981-82	Establishment of Esperance study (artificial defoliation) to measure impact of defoliation on growth of plantation *E. regnans*.	6,000
1982-83	Year-2 treatment of Esperance study (artificial defoliation) to measure impact of defoliation on growth of plantation *E. regnans*.	5,000
1983-84	Ongoing growth measurement of Esperance defoliation study	5,300
1984-85	Final measurement of Esperance defoliation study	5,700
1985-86	Write-up Esperance trial)	600
1986-87	Establishment of insecticide spraying trial at Goulds Country	3,300
1987-88	Goulds Country Spray Trial. Trial leaf beetle IPM in the Florentine Valley.	18,500
1988-89	Establish Westfield Road Exclusion Trial. Travel overseas to look at operational use of Bt for control.	30,000
1989-90:	IPM implemented in two plantations. Development of field monitoring system to measure populations. Relationship between population and damage. Insecticide trials – initial focus on *B.t.t.* versus α-cypermethrin: Field trials: Westfield 100, Smiths Plains (intensively-sampled small-scale trial – to measure efficacy vs dose); Lab trials effects on natural enemies	120,000
1990-91	Growth impact studies – impact of adult feeding demonstrated. Finalise lab studies on effects of insecticides on natural enemies. Further refinements to aerial application methods.	100,000
1991-92	Commencement of funding through the Intensive Forest Management Program: State-wide use of IPM (natural enemies sufficient in most plantations). Smith's Plains - α-cypermethrin reduced potential damage of 45% to 10%. Further field trials to test effectiveness of *Btt*. Leaf beetle populations in thinned versus unthinned native forest.	142,857
1992-93	CRC Temperate Hardwood Forestry Commences. Growth impact: Exclusion trial remeasurement (*E. regnans*), Continuation of growth impact studies – *E. regnans* (4th year remeasurement), *E. nitens* established. Impact of leaf beetles on growth of thinned stands. Establishment of Fingal trap tree study	142,857

1993-94	Data for developing population-impact model: artificial defoliation trial established; caged shoot study (foliage consumed x population size). Growth impact: Exclusion trial remeasurement, remeasurement of trap-tree study. Canopy penetration by insecticide. Monitoring of natural enemy populations (with CRC THF). Lab study of life history of *P. agricola* on *E. ni*tens	142,857
1994-95	Refinement of aerial spraying technology for *Btt* - control of droplet-size; dose-response (4 vs 6 l/ha *Btt*). Growth impact: continue *E. regnans* Exclusion trials; Second year of manual defoliation treatments. Start analysis for population impact model	142,857
1995-96	Refinement of field monitoring system (sampling efficiency for taller trees). Growth impact: continue *E. regnans* Exclusion trials, new *E. nitens* trial Exclusion trial; remeasure initial manual defoliation trial, establish new trial comparing early versus late season defoliation. Laboratory study – leaf consumption through life cycle. Insecticide application – evaluation of ULV application methods for *Btt* and effect on leaf beetle larval stages	142,857
1996-7	Refinement to monitoring – within plantation sampling, duration of monitoring. Remeasure exclusion and artificial defoliation trials, defoliation in 10 y.o. *E. nitens* (stem injection trial). Impact of natural enemies in field populations. Further evaluation of efficacy of *Btt* used operationally	142,857
1997-98	Incorporated leaf beetle impact into *E. nitens* growth model. Evaluation of insecticides – acephate capsules, highlighted issues with reliability of *Btt*. Enhancing natural enemies (with CRC THF) – inundative release of ladybirds.	142,857
1998-99	Roll-out of refined monitoring method (OLPS). Establishment of additional four trap-tree trials. Commence evaluating Spinosad (Success) and fipronil (Regent). Monitoring field populations of natural enemies, study on inundative release of ladybirds finalised.	195,200
1999-2000	Laboratory and field trials of Success, another field trial of *Btt.* Understorey plants as hosts for natural enemies. Publication of IPM Manual, incorporation of Leaf beetle IPM into Farm Forestry Toolbox.	227,000
2000-01	Impact of defoliation on 1-year-old *E. nitens* / *E. globulus*. Lab and field trials of dose response of Success on leaf beetles and natural enemies. Long-term exclusion trial – protection of previously defoliated trees	209,000
2001-02	Impact of defoliation on 1-year-old *E. nitens* / *E. globulus*. Field trial to compare natural enemy population after spraying with Success and α-cypermethrin. Lab and field trials – predicting dates of emergence from overwintering and commencement egg-laying	114,100
2002-03	Field trial comparing recolonisation by leaf beetles – Success vs α-cypermethrin. Collate results of lab and field studies with Success to support label registration. Registration of Success.	131,700
2003-04	Late season defoliation study completed. Study tour of Canada / US on operational use of biological insecticides. Lethal trap trees –	85,200

	commence field and lab studies of dose-response of imidacloprid / thiocloprid.	
2004-05	Investigate / refine 2-stage monitoring. Initial screening to detect response by *P. bimaculata* to kairomones / pheromones. Develop method for dose-response studies (imidacloprid). Develop methods for tree injection (imidacloprid).	147,600
2005-06	Lethal trap trees: evaluate alternative formulations and delivery methods; commenced choice experiments	134,295
2006-07	Lethal trap trees: Establish first set of trap tree plantings; Protocols for stem injection with imidacloprid; Choice experiments; Dose-response study. Helped Bass District with introduction of “blocking” to reduce monitoring effort.	93,300
2007-08	Lethal trap trees: Establish further seven trap tree plantations; Stem injection studies – radial movement, bioassay experiments; Choice experiments. Investigate decline in use of Success.	122,300
2008-09	Lethal trap trees; Stem injection studies continue – high volume infusions vs concentrates; Support pilot study to screen volatile compounds from eucalypt leaves for sensory response in leaf beetles; Transferred leaf beetle IPM co-ordination to FHS team	96,000
2009-10	Lethal trap trees: First field evaluation of trap trees made lethal with systemic insecticide. Evaluate effectiveness of leaf beetle IPM: FHS assesses defoliation in all plantations. Impact of defoliation in mid-rotation plantations – establish CABALA plots	107,500
2010-11	Lethal trap trees: Documented results from year-1 field trial; Second field evaluation of trap trees made lethal with systemic insecticide; Submitted manuscript reviewing options for managing leaf beetles. Evaluate effectiveness of leaf beetle IPM: Financial analysis of leaf beetle; Supported UTas honours study to predict leaf beetle populations; Document refinements to IPM – propose risk-based targeting; Impact of defoliation in mid-rotation plantations – remeasure CABALA plots	120,000
2011-12	Lethal trap trees: Document lethal trap tree study. Evaluate effectiveness of leaf beetle IPM	110,000
2012-13	Introduced changes to IPM – risk-based targeting; extension into older age-classes, revise monitoring method. Impact of defoliation in mid-rotation plantations – remeasure CABALA plots	51,000
2013-14	Shoot / leaf damage phenology study in mid-rotation plantations	30,000
2014-15	Co-ordination of IPM	10,000
2015-16	Co-ordination of IPM	10,000

Part 2: Cost-Benefit Analysis of Leaf Beetle Pest Control in Tasmania

Background

Chrysomelid leaf beetles have caused extensive defoliation and growth losses in eucalypt plantations in Australia and have prevented the large-scale establishment of eucalypt plantations in New Zealand. The establishment of an ongoing Integrated Pest Management (IPM) system for this pest in Tasmania began over 40 years ago (Greaves 1966, Candy *et al.* 1992, Elliott *et al.* 1992, Elliott *et al.* 1993, Elek 1997). Research on the leaf beetle was chiefly predicated on studies which confirmed that the pest was having a significant economic impact on plantation productivity (Candy *et al.* 1992, Elliott *et al.* 1993, Elek 1997). The IPM system which arose from this research established beetle population economic injury thresholds.

In this case study we were able to capture the costs of Commonwealth and Forestry Tasmania funded leaf beetle research dating back to 1975 and the associated costs of a broad-scale state forest monitoring and control program which began in 2003. This was 5 years after the operational IPM first started and corresponded with the period of rapid plantation expansion by Forestry Tasmania (Figure 1). The IPM modelled through until 2034 by which stage virtually all (98.4%) of the plantations had completed one full rotation. The gains of the leaf beetle program were quantified by modelling the growth differences between a 'control' and 'no control' option.

Key Terms

- ***NPV*** - Net present value reported in 2015 dollars
- ***IRR*** - Internal rate of return reported as a %
- ***BCR*** - Benefit-cost ratio reported as a number.
- ***Conventional insecticide*** - α-cypermethrin a synthetic pyrethroid effective against a wide range of pests
- ***Soft insecticide*** - insecticide that has minimal adverse environmental impacts
- ***Monitoring*** - leaf beetle egg count sampling and monitoring leaf instar larvae levels
- ***Spraying*** - aerial spraying of plantations that have above threshold levels of eggs and instar larvae

Plantation Description

Our cost-benefit analysis case study was applied to Forestry Tasmania's 52,000 ha hardwood eucalypt plantation. A detailed description of this estate is provided in Part 1 of this chapter. 60% of the estate is managed under a sawlog regimes and 40% is managed under a pulpwood regime. Of the plantations grown for sawlog on average 9% are pruned once (1 lift), 17% are pruned twice (2 lifts) and 74% are pruned three times (3 lifts) (Figure 1). *E. nitens* makes up approximately 80% of the plantation estate and the balance is *E. globulus.* The majority of this plantation estate was established between 1998-2008 (Figure 2). Approximately 2,500 ha of older plantations (planted before 1990) of primarily ash species (*E. regnans*, *E. delegatensis* and *E. obliqua*), and 1500 ha of plantations harvested but not yet replanted were excluded from the analysis.

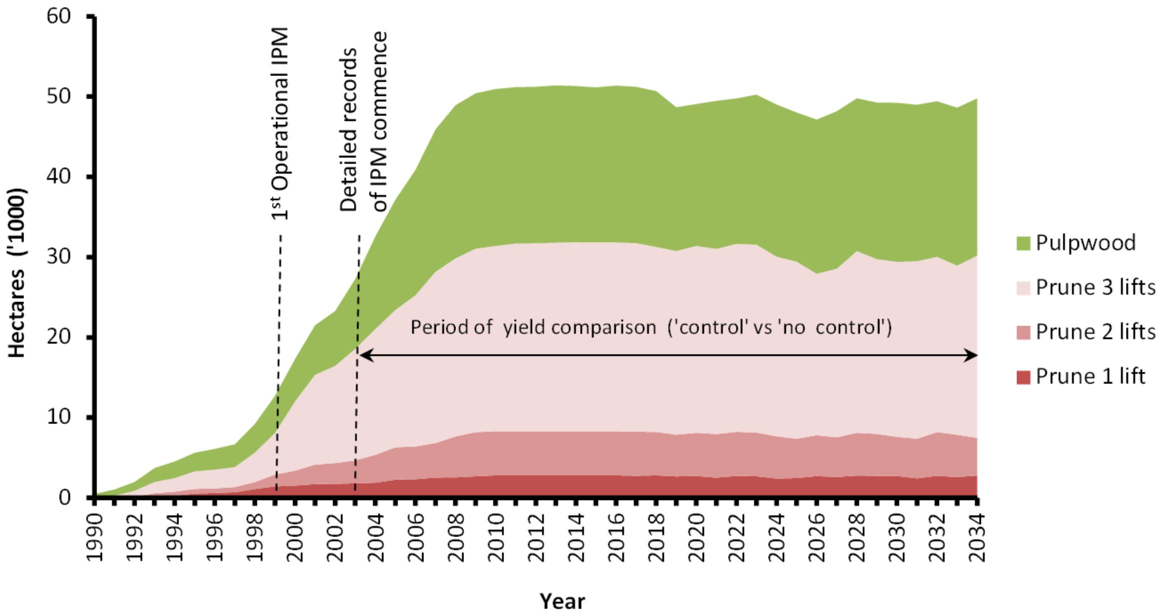

Figure 1: Area of hardwood plantation by management regime that was the subject of this case study.

The age class distribution of the current plantation estate is shown at Figure 2. The great majority (85%) of the pruned plantation estate is in plantations that were established during the period 1998-2008.

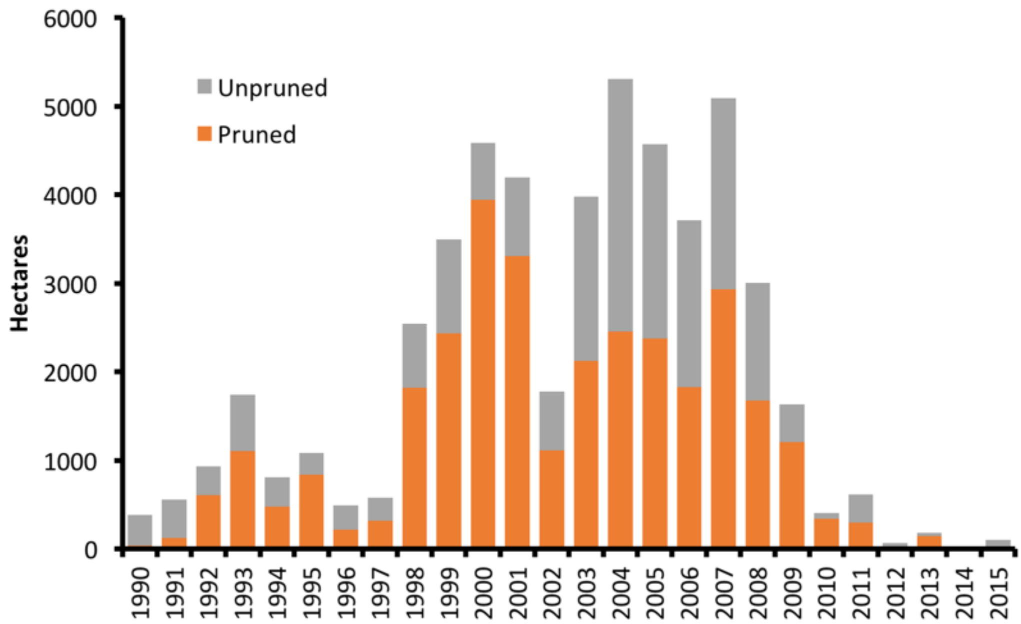

Figure 2: Current area of hardwood plantations by planting year and management regime

Methodology

The cost-benefit analysis was applied to predicted harvest volumes each year of pruned sawlogs, unpruned peeler logs and pulpwood from the plantation estate based on two scenarios; no leaf beetle management and, leaf beetles managed using the IPM. The yield difference between these two scenarios is shown in Figure 3. The details of the modelling for the managed and unmanaged scenarios are described in Part 1 of this chapter.

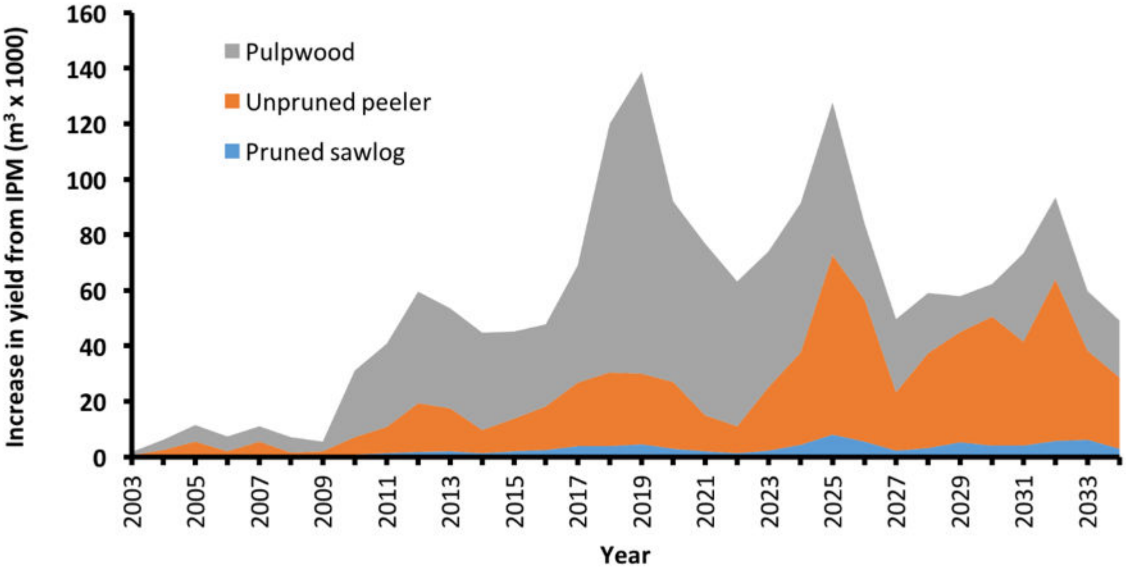

Figure 3: Predicted increase in yield from IPM Program by log category.

Costs and benefits were valued at the specific time at which they occurred. As historic and future costs and benefits had to be accounted for together it was necessary to have all values in today dollars (2015$s) before any discounting could be applied. Historic costs (costs prior to 2015) were converted to 2015$s using an 'All Groups-Consumer Price Index' published by the Australian Bureau of Statistics. All future costs and benefits were all also recorded in $2015s.

Discounting future costs and benefits to a present value was undertaken to account for the fact that a dollar now is worth more than a dollar next year. A discount rate of 7.5% was applied using a standard net present value formula:

$$\mathrm{NPV}(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

NPV = Net present value
i = the discount rate
N = the total number of periods
t = the time of the cash flow
R = net cash flow

To allow independent consideration of the appropriateness of a 7.5% discount rate we also calculated the program's internal rate of return (IRR). The IRR is the discount rate (expressed as a %) that makes the net present value of all cash flows equal to zero.

For our net present values analysis, we used 1990 as the base date for discounting which is when the research program commenced in earnest with annual investment exceeding $100,000. Leaf beetle research that occurred prior to this date (1975-1990) primarily considered the biology of the insect and was done in native forest (with only one trial to measure growth impacts in an *E. regnans* plantation).

To assess the sensitivity of choosing 1990 as the base date we also ran NPV analysis using 1975, 2003 and 2015 as 'alternative' base dates for discounting. 1975 was used as this was the first year that leaf beetle research occurred. 2003 was the year that broad-scale operational monitoring and control commenced and 2015 was used to allow evaluation of the program going forward (treating historic costs as sunk costs).

Cashflows that occurred prior to the base date for discounting were treated as sunk costs. To assess the sensitivity of this decision we also ran a scenario where costs prior to the base date for discounting were included. This occurred by converting all costs to $2015s and then summing them.

The benefit-cost ratio (BCR) of the program was calculated for the scenarios specified above using two different formulae.

1. **BCR = present value benefits / present value costs**
2. **BCR = present value net recurrent costs / present value capital (research) costs**

For a program to be acceptable the BCR should have a value greater than one.
Key forest management cost and revenue input assumptions used in our model are reproduced in Table 1.

Table 1: Key modelling input assumptions.

Product /Service	Rate
Pruned sawlog ($\$/m^3$)	$40.00
Unpruned sawlog ($\$/m^3$)	$20.00
Pulpwood ($\$/m^3$)	$15.00
Leaf beetle monitoring Cost ($/ha)	$3.80
Leaf beetle Spraying Cost ($/ha)	$55.75

Sensitivity analysis was undertaken on the benefits arising from the leaf beetle control program by modelling timber yield at 20% above and 20% below the expected yield values.

Research costs were classified into two groups:

'conventional insecticide' research

'soft (environmentally friendly) insecticide' research

We modelled two research scenarios, one with both research types included and the other with 'soft insecticide' research costs excluded.

Results

The net cash-flow of the leaf beetle program is shown at figure 4. It reveals that cash-flow remained negative for 20 years (1990-2009) before becoming strongly positive from 2010 onward as a greater proportion of the estate reached harvest age (Figure 3).

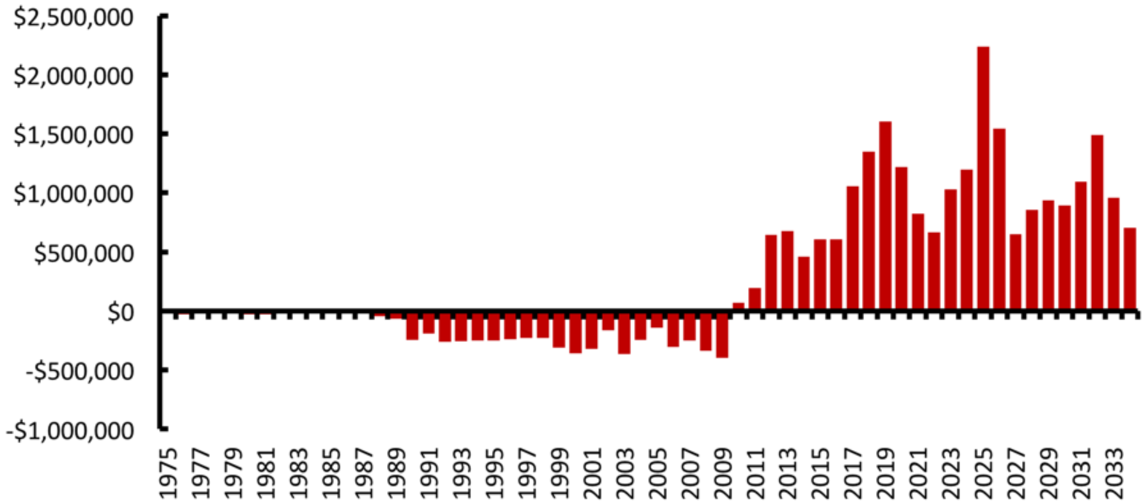

Figure 4: Net cash-flow of costs and benefits of the leaf beetle program ($2015s).

The costs that were incurred under the leaf beetle program are shown by category at Figure 5. Investment in 'conventional insecticide' research occurred first followed by 'soft insecticide' research and then on-ground management (monitoring and spraying) from 2003. The total of the expenditure was $5.08M between 1975 and 2015, with the majority ($4.5M) occurring after 1990.

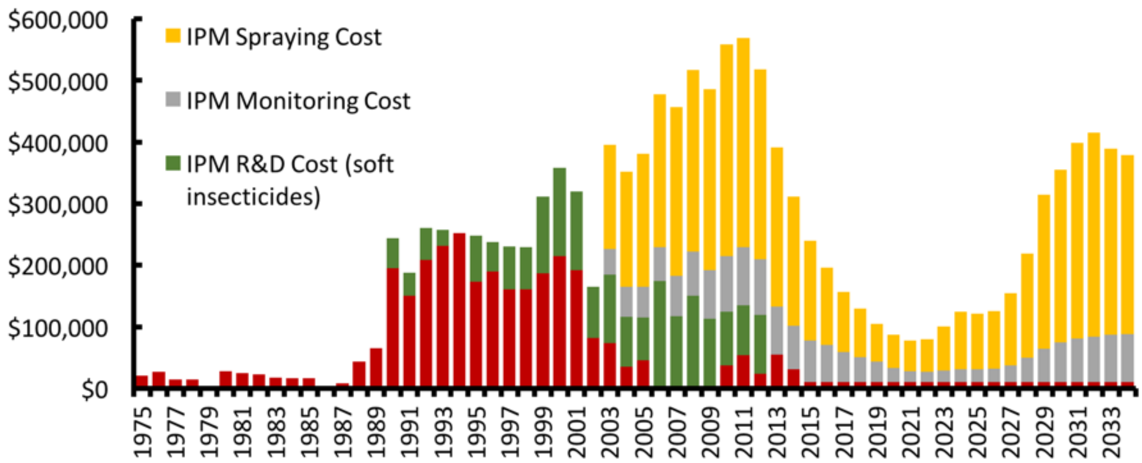

Figure 5: Expenditure on leaf beetle research and management by cost category.

The cost of the IPM program in Table 2 details the net present value of each cost category. Research was the largest cost accounting for 66% of total expenditure while monitoring was the smallest representing only 7%. On average, over the life of the program (2003-2034), 27.8% of the plantation estate was subject to monitoring and 6.9% was subject to spraying.

Table 2: Net present values of leaf beetle program costs (1990- 2034).

Expenditure Category	NPV $2015s *	%
Research - conventional insecticides	$1,761,111	45%
Research - soft insecticides	$851,368	22%
Monitoring	$289,476	7%
Spraying	$1,054,325	27%
Total Cost	$3,956,280	100%

* 1990 base year for discounting @ 7.5%DR

The modelled benefits of the leaf beetle program took the form of additional timber yield (figure 3) which translated to additional timber revenue (figure 6). Additional timber revenues first arose in 2003 but were not fully realised until after 2010. A comparison of graph scales used in figures 5 and 6 reveals the dollar value difference between costs and benefits (additional timber revenue). In general, benefits were between double and four times higher than cost (before taking account of the time value of money).

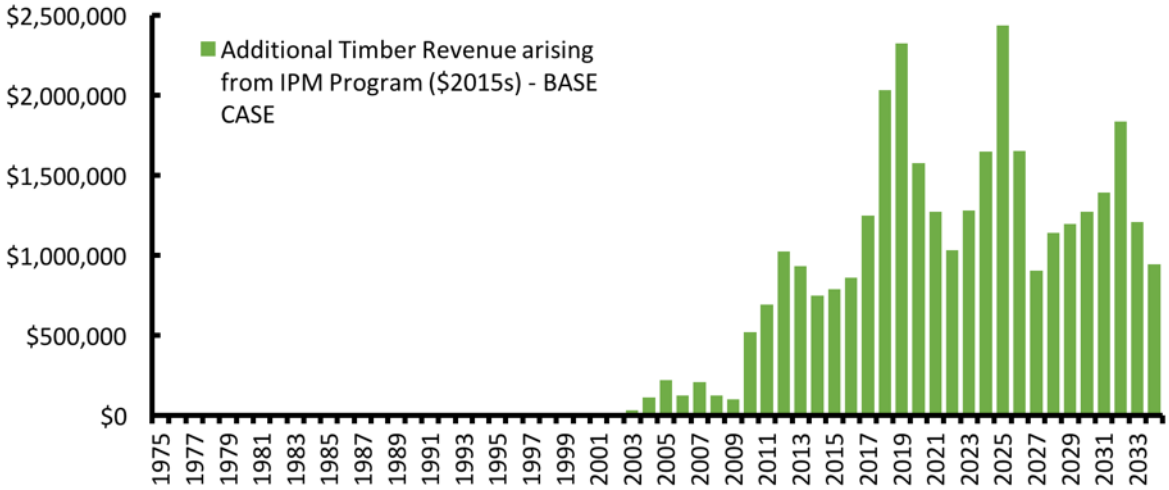

Figure 6: Modelled value of the additional timber generated by the leaf beetle program.

Figure 7 and Tables 3-6 show how the adjustment of timber yield affected the value of the additional timber revenue. They reveal that NPV was far more sensitive to a lower yield gain that it was to a higher yield gain.

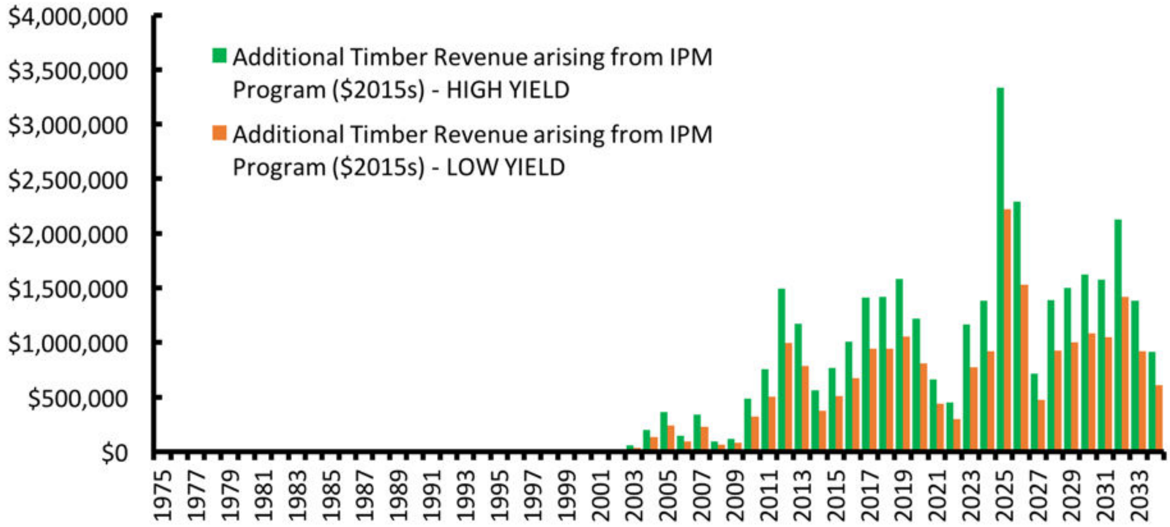

Figure 7: Modelled value of the additional timber generated by the leaf beetle program under a 'high yield (+20%) and low yield (-20%) scenario.

The results of financial and cost-benefit analysis are summarised in Tables 3 and 4. Table 3 results have all research costs included (i.e. both 'conventional' and 'soft insecticides') while Table 4 results exclude 'soft insecticide' costs. The results for the base case (1990) are respectively highlighted in each table.

Table 3: Results of cost-benefit analysis with all leaf beetle research included.

	Base Year for Discounting			
	1975	**1990**	**2003**	**2015**
Financial Analysis				
NPV base case	-$318,462	-$374,884	$4,631,823	$13,339,697
NPV sensitivity to higher yield gain	-$278,694	-$257,216	$4,933,102	$12,515,846
NPV sensitivity to lower yield gain	-$695,413	-$1,490,237	$1,776,057	$7,687,758
IRR base case	6.2%	6.9%	17.9%	
IRR sensivitiy to higher yield gain	6.3%	7.1%	20.4%	
IRR sensitivity to lower yield gain	3.8%	4.3%	12.5%	
Cost-Benefit Analysis				
BCR (PV benefits/PV costs)	0.81	0.91	2.02	7.78
BCR sensivity to higher yield gain	0.84	0.93	2.09	7.36
BCR sensivity to lower yield gain	0.56	0.62	1.39	4.91
BCR (PV net recurrent costs /PV capital costs)	0.70	0.86	5.22	130.31

Table 4: Results of cost-benefit analysis with soft insecticide research costs excluded.

	Base Year for Discounting			
	1975	1990	2003	2015
Financial Analysis				
NPV base case	-$30,728	$476,485	$5,431,221	$13,339,697
NPV sensitivity to higher yield gain	$9,040	$594,153	$5,732,500	$12,515,846
NPV sensitivity to lower yield gain	-$407,680	-$638,869	$2,575,456	$7,687,758
IRR base case	7.4%	8.4%	22.9%	
IRR sensitivitiy to higher yield gain	7.5%	8.7%	28.2%	
IRR sensitivity to lower yield gain	5.1%	5.9%	16.9%	
Cost-Benefit Analysis				
BCR (PV benefits/PV costs)	1.00	1.15	2.45	7.78
BCR sensivity to higher yield gain	1.03	1.19	2.53	7.36
BCR sensivity to lower yield gain	0.69	0.79	1.69	4.91
BCR (PV net recurrent costs /PV capital costs)	0.96	1.27	19.23	130.31

Tables 5 and 6 replicate the results in Tables 3 and 4 but with historic costs (costs incurred prior to the base year for discounting) included.

Table 5: Results of analysis with hard and soft insecticide research included (incorporating historic costs).

	Base Year for Discounting			
	1975	1990	2003	2015
Financial Analysis				
NPV base case	-$318,462	-$697,910	$1,007,410	$9,112,809
NPV sensitivity to higher yield gain	-$278,694	-$580,242	$1,308,689	$9,266,913
NPV sensitivity to lower yield gain	-$695,413	-$1,813,263	-$1,848,355	$2,508,437
IRR base case	6.2%			
IRR sensitivitiy to higher yield gain	6.3%			
IRR sensitivity to lower yield gain	3.8%			
Cost-Benefit Analysis				
BCR (PV benefits/PV costs)	0.81	0.84	1.12	2.86
BCR sensivity to higher yield gain	0.84	0.86	1.16	2.89
BCR sensivity to lower yield gain	0.56	0.58	0.77	1.92
BCR (PV net recurrent costs /PV capital costs)	0.70	0.76	1.21	2.76

Table 6: Results of cost-benefit analysis with soft insecticide research costs excluded (incorporating historic costs).

	Base Year for Discounting			
	1975	1990	2003	2015
Financial Analysis				
NPV base case	-$30,728	$153,459	$2,708,970	$11,093,604
NPV sensitivity to higher yield gain	$9,040	$271,127	$3,010,249	$11,247,708
NPV sensitivity to lower yield gain	-$407,680	-$961,895	-$146,795	$4,489,233
IRR base case	7.4%			
IRR sensivitiy to higher yield gain	7.5%			
IRR sensitivity to lower yield gain	5.1%			
Cost-Benefit Analysis				
BCR (PV benefits/PV costs)	1.00	1.04	1.42	3.99
BCR sensivity to higher yield gain	1.03	1.08	1.47	4.02
BCR sensivity to lower yield gain	0.69	0.72	0.98	2.68
BCR (PV net recurrent costs /PV capital costs)	0.96	1.07	1.90	4.48

Discussion

The leaf beetle IPM program has been a major investment by Forestry Tasmania, with $4.5M ($2015s) expended since 1990.

The benefits of the IPM program have taken many years to be realised with 20 years elapsing (1990-2010) before a positive cash-flow was achieved. This is the consequence of the majority of the research needed to develop the IPM being done before large-scale planting of the current hardwood estate commenced. In this case, leaf beetles were a known existing threat (Greaves 1966, de Little 1979, Elliott et al. 1993) and a successful plantation venture would require effective management to be developed before that venture started. In addition, prior to 1994 Forestry Tasmania was a government agency with a wider industry responsibility.

Once the cash-flow of the program became positive its value was shown to be substantial with additional timber revenue valued at $3.7M (NPV @ 7.5%DR) using 1990 as the base year for discounting and $14.5M (NPV @ 7.5%DR) using 2015 as the base year.
When the yield gain from the IPM program was reduced by 20% this reduced the overall IRR by 2.5%. The sensitivity of the program to a lower yield gain highlights the need for special care when estimating the yield gains that arise from this and other comparable programs. Overall the IPM program may be viewed as a 'break-even' proposition for Forestry Tasmania, generating a net benefit of $476K (NPV@7.5%DR) when the cost of 'soft insecticide' research is excluded and a net cost of $375K (NPV@7.5%DR) when it is included.

Analysis of the investment in 'soft insecticide' research reveals that it has been a risky, high-cost venture that has not yet provided any financial return. However, the need to find viable control options alternative to broad-spectrum insecticides like α-cypermethrin remains a priority for Forestry Tasmania who aspires to obtain certification under Forest Stewardship Council (FSC). For Forestry Tasmania, FSC certification is likely to generate both 'social licence' and timber marketing benefits.

The outlook for the IPM program is very positive with a BCR of 7.78 and an NPV of $13M (using 2015 as the base year for discounting). Although not quantified, we may also assume that the scientific knowledge arising from Forestry Tasmania's research is also benefitting other Tasmanian hardwood plantation growers.

Sensitivity analysis around the discount rate revealed that the time value of money has a strong bearing on the program's financial success. For example, reducing the value of 'time' by using a discount rate of 5.0% increased the NPV of the program to over $2.5M. This finding highlights the importance of minimising the time between the initiation of research and the operational implementation of management arising from that research. In the case of the IPM program 14 years of research elapsed (1990-2003) before broad-scale monitoring and control commenced. As stated previously, research to develop an IPM commenced well before the plantation estate was fully established. Now that the plantation estate has been established, any need to undertake research in the future to manage a new pest will not have such a delay in estate-wide implementation of research-driven management.

Our finding that 66% of the IPM program's costs were incurred as fixed research costs was significant. A consequence of having high fixed costs is that the net benefits of the program are dependent of its scale. Forestry Tasmania's 50,000 plantation hardwood estate may be considered to be of average size with most hardwood estates within Australia ranging between 15,000 hectares and 140,000 hectares. Had Forestry Tasmania's estate been either larger or smaller the findings of the cost-benefit analysis would have been very different. We may conclude from this that; when it comes to managing forest biosecurity risk, cooperative arrangements are likely to yield a much higher return to individual growers than if they choose to manage their risks independently.

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4. An analysis of pest risk and potential economic impact of pinewood nematode, *Bursaphelenchus xylophilus*, and its vector, *Monochamus alternatus,* to softwood plantations in Australia

Summary

Pine wilt disease, caused by the pinewood nematode (*Bursaphelenchus xylophilus*), has caused extensive damage to *Pinus* forests where it has invaded countries with susceptible hosts and with native co-occurring *Monochamus* (Coleoptera: Cerambycidae) species. Northern American *Pinus* species are believed to be resistant, or only mildly susceptible (due to co-evolution of pest and host), although questions still remain as to whether this resistance is retained when species are planted outside their native range, and subject to heat and drought stress and bred for long periods in the absence of the disease. Pinewood nematode has killed tens of millions of trees in invaded countries (Japan, China and Portugal) and cost tens of millions of dollars in lost wood production and control programs. It has also caused financial losses due to export restrictions on countries with the nematode established.

We conducted a Pest Risk Assessment (following Plant Health Australia guidelines) of the likelihood of pinewood nematode and its primary vector, *M. alternatus* (Japanese pine sawyer beetle), arriving, establishing and spreading in Australia. Both *Monochamus* and *Bursaphelenchus* species regularly arrive at Australian ports (intercepted by quarantine authorities); *Bursaphelenchus* species have breached the border on at least three occasions, but no *Monochamus* species has yet been known to have breached the border. Australia does not have an established primary vector (*Monochamus* sp.) for pinewood nematode, and there are no known records of *Monochamus* spp. establishing outside their native range, although secondary vectors are established in Australia (e.g. *Arhopalus* spp.). We believe *Pinus* spp. planted in Australia are likely to be susceptible to pine wilt disease under drought and heat stress. Subtropical and Mediterranean climates in Australia are moderately-to-highly likely to be suitable for *M. alternatus* (based on CLIMEX analysis). Thus, the likelihood of pinewood nematode and Japanese pine sawyer beetle arriving in Australia is *high*; the likelihood of these pests establishing and spreading in Australia is *low*; but the likelihood of impact of pine wilt disease on softwood species if they *do* establish and spread is *medium*.

Here we present a scenario where pinewood nematode and Japanese pine sawyer beetle enter Australia via wood packaging material at the Port of Brisbane and are immediately transported to a container holding facility at Caboolture, where goods are stored and inspected before further distribution. Adult beetles, infected with pinewood nematode, emerge from wooden pallets and disperse into surrounding amenity *Pinus* trees. Some also eventually make the 5 km journey to the commercial softwood plantations at Beerburrum State Forest. Once there, they mate and multiply, and spread through the plantation at a rate of 1 km or 2 km per year (based on two likely spread rate scenarios).

The economic analysis presented here revealed substantial expected present value of damage costs due to pine wilt disease, even at low probabilities of establishment, and low rates of spread and mortality. This translates into high expected benefits from biosecurity programs. Our results indicate that it would be economically efficient to spend up to $0.35 M/y on biosecurity to keep pine wilt disease from establishing at Beerburrum. In addition, the expected value of the estate modelled here would be increased with increased forest pest

biosecurity. Consequently, economically sound biosecurity policy would encourage cooperative control programs with the estate managers.

Introduction

The increasing spread of invasive pests and pathogens threatens global forests, plantations and ecosystem (Pimentel et al. 2000; Levine and D'Antonio 2003; Hulme 2009; Fisher et al. 2012; Wingfield et al. 2015). Pine wilt disease, caused by the pinewood nematode, *Bursaphelenchus xylophilus*, is one of the most significant and devastating invasive diseases affecting *Pinus* spp. worldwide (Mota and Vieira 2008; Zhao et al. 2008). These microscopic nematodes require an effective primary vector, which have so far all been proven to be cerambycid beetles in the genus *Monochamus* (Evans et al. 1996; Akbult and Stamps 2012). *Bursaphelenchus xylophilus* is native to Northern America where it is considered a secondary pest of weakened trees (Bergdahl 1988; Wingfield et al. 1984). *Bursaphelenchus xylophilus* was detected in Japan in 1905 (Mamiya 1988), China in 1982 (Cheng et al. 1983), Taiwan in 1983 (Tzean and Jan 1985), South Korea in 1988 (Choi and Moon 1989; Enda 1989), Portugal in 1999 (Mota et al. 1999) and Spain in 2010 (Abelleira et al. 2011; Robertson et al. 2011). Severe mortality to endemic *Pinus* spp. has occurred in all countries where the pinewood nematode has invaded and where an efficient vector has been present. In Northern America, severe damage has only occurred to exotic species, and often when these are under some form of stress (Harman et al. 1986; Rutherford and Webster 1987).

The lifecycle of the pinewood nematode and its vectors have been detailed previously (Wingfield et al. 1982, 1984; Kobayashi et al. 1984; Wingfield 1987; Linit 1988; Evans et al. 1996; Togashi and Shigesada 2006). During spring to summer, *Monochamus* beetles emerge from trees infected and killed the previous year, carrying pinewood nematodes in their tracheal system. They fly to healthy pine trees and feed on young shoots and twig bark (maturation feeding, required to be able to reproduce). Nematodes are transmitted to the tree via beetle-feeding wounds, rapidly multiple, and move throughout the tree via resin ducts where they feed on parenchyma and epithelial cells, as well as wood-infesting fungi. This is the primary mode of transmission of pinewood nematode, where nematodes are transferred to healthy trees. Susceptible trees eventually wilt and die, often rapidly (within 2–3 months); symptoms typical of pine wilt disease. Water stress and high temperatures are consistently associated with expression of pine wilt disease (Rutherford and Webster 1987; Sathyapala 2004; Futai 2008; Naves et al. 2016), especially where mean air temperatures exceed 20° C for long periods. The mode of tree death is believed to be via cambial destruction resulting in xylem embolism, which interferes with water translocation and photosynthesis (Myers 1986; Fukuda 1997). Beetles are then attracted to these dying trees and oviposit eggs into the bark, also transmitting nematodes. This is the secondary mode of transmission, where nematodes are transferred to stressed or dying trees. The developing beetle larvae feed on phloem and cambium, construct a pupal chamber in the sapwood during autumn, and await spring to mature and emerge. During this period, nematodes within the tree migrate to the pupal chamber and enter the beetle's tracheal system prior to beetle emergence. The pinewood nematodes are thus transmitted to another tree when the beetles emerge in spring and search for new trees for maturation feeding and oviposition.

Pine wilt disease has resulted in extensive timber losses and management costs following invasion of new countries. The annual timber loss in Japan increased from 30,000 m^3 to 1.2 million m^3 in the 1930s to 1940, and peaked in the late 1970s at 2.4 million m^3 (Mamiya 1988). Annual timber losses still average 1 million m^3 annually (Suzuki 2002), with over 46 million m^3 lost since the 1950s (Zhao et al. 2008). Annual tree deaths over this period were in the order of 5–10 million (Mamiya 1983). It is common for greater than 50% of trees in a stand to be killed by pine wilt disease (Kishi 1980; Shibata 1981; Futai 2008), and in some areas in Japan, whole forests have been destroyed and are now replaced with broadleaved species. In China, annual tree deaths reached 2.3 million trees just in a single county (Robinet et al. 2009), with over 1 million trees killed annually across China from 1995 to 2006, including 5 million each year from 1998 to 2002 (Zhao 2008). In Korea, infection in highly susceptible *P. densiflora* stands generally reaches 100% within two years (Shin 2008), with a steady increase in the annual number of trees infected with pine wilt disease — and subsequently felled — from approximately 300,000 in 2000 to over 1 million in 2005–2006 (Fig. I.11, Shin 2008). Predicted losses in wood production in the European Union from the spread and damage from pinewood nematode was estimated at €22 billion over 22 years, with losses in standing volume in Portugal and Spain greater than 80% (Soliman et al. 2012).

A substantial amount of money and effort has been spent on trying to reduce the spread of pinewood nematode or mitigating its impact. This has included trying to control the vector beetle through aerial and ground spraying of insecticides, and destroying infected trees by felling and chipping, fumigating or burning, including small branches (Mamiya 1988; Yoshimura et al. 1999; Shin 2008; Zhao 2008; Naves et al. 2016). In the 1980s, an average of 123,000 ha were sprayed annually with insecticides in Japan, and the Japanese government spent over ¥6 billion annually in control programs (Mamiya 1988). Despite extensive control efforts (~US$30 million annually), pinewood nematode continued to expand (Yoshimura et al. 1999). In Korea, the average annual cost of disease management is US$8 million, and this is increasing (Shin 2008). Furthermore, Korea has already spent over US$6 million on pine wilt disease research (Shin 2008). In Portugal, the primary control strategy is to detect and destroy infected trees while *Monochamus* beetles are still inside such trees (Rodrigues 2008; Sousa et al. 2011). In 2007, in response to continued expansion of pinewood nematode in Portugal, nearly 5 million healthy pine trees were cut down to establish a host-free "buffer" zone 3 km wide (Rodrigues 2008; Sousa et al. 2011). A similar method was used in China, with all pine trees felled within a 4 km wide, 100 km long buffer to protect a World Natural and Cultural Heritage site (Zhao 2008).

A delay in detection due to lack of surveillance can result in substantial increases in control costs (European Commission 2013). By the time pinewood nematode was detected in Portugal, over 500,000 ha were affected, and €38 million was granted for an eradication campaign, which ultimately failed. In contrast, three isolated outbreaks of pinewood nematode in Spain were detected early and eradicated with expenditures of less than €5 million.

Pinewood nematode also causes impact due to loss of export markets and import restrictions (Dwinell and Nickle 1989; Robinet et al. 2011). European import restrictions due to pinewood nematode have the potential to cause losses of US$150 million annually in the United States and $700 million in Canada. The presence of pinewood nematode in a country can result in considerable costs associated with surveillance and containment, and activities to enable declaration of regional area freedom to enable ongoing export, both domestic and international, of coniferous timber (OEPP/EPPO 2012). These measures are a significant extra cost to those already resulting from timber losses (Mallez et al. 2015).

There are many examples of invasive species that have caused extensive damage to forests and ecosystems worldwide, including chestnut blight (Anagnostakis 1987), gypsy moth (Davidson et al. 1999; Sharov et al. 2002) and sudden oak death (Grünwald et al 2008), as well as commercial plantations (e.g. sirex wood wasp [Slippers et al 2012]). The majority of species that invade, however, are not successful and do not establish, let alone become pests (Williamson and Fitter 1996). The success of an invasive species depends on three factors: arrival, establishment and spread (Liebhold et al. 1995). A new pest can arrive via anthropogenic assistance, such as on cargo or solid wood packaging material, or via natural means such as wind. The pest then needs to establish a local population in this new habitat (e.g. amenity trees around a port) and persist for several generations. Once established, the pest needs to increase numbers and expand into adjoining areas (e.g. forests); thus spread.

Here we present a Pest Risk Assessment (PHA 2013) of the likelihood of arrival, establishment and spread of pinewood nematode and its primary vector, *M. alternatus*, to Australia, and the likelihood of impact to softwood plantations if these invasive pests established.

Likelihood of arrival of pinewood nematode and vectors to Australia

Bursaphelenchus xylophilus and its *Monochamus* vectors are known to be able to survive transport in solid wood packaging material and arrive at new ports following shipment. Tomiczek et al. (2003) reported that 78% of inspected consignments of coniferous wood packaging from China arriving into Austria had either insects or nematodes or evidence of insect attack (galleries), including live *Monochamus* and *Bursaphelenchus* species. Inspections of solid wood packaging material arriving in China revealed that over 5% contained live *Bursaphelenchus* species, including *B. xylophilus* (Gu et al. 2003). A large proportion of these were from countries where pinewood nematode is a primary pest (Japan, Taiwan, Korea and Spain). In Australia, 9% of ~20,000 crates inspected in Sydney, Brisbane and Melbourne during 2005 had "something of quarantine concern", such as bark, fungi, live insects or frass, including *M. alternatus* and *Bursaphelenchus mucronatus* (Zahid et al. 2008). A large proportion of these detections were on solid wood packaging from countries where pinewood nematode is present (China, Korea and the United States). These authors concluded that there are still major quarantine concerns despite ISPM-15 compliance, and that a large proportion (50%) of break-bulk cargo (i.e. goods that must be loaded individually, and not in intermodal containers, nor in bulk, as with oil or grain) contains untreated solid wood packaging material (Zahid et al. 2008).

Most overseas reports of interceptions use aggregated data, usually only presented down to family level (e.g. Haack 2006). However, Brockerhoff et al. (2014) estimated the interception frequency for a large number of individual bark beetle and cerambycid beetle species using long-term intercept and establishment data from the USA and New Zealand. They estimated the interception index frequency for *M. alternatus* as 16.6, which equates to a risk of establishment (estimated for cerambycid beetles as a group) of 15% over the next 100 years. Backing up the Australian intercept data (see below), *M. alternatus* would therefore appear to be a common intercept globally, and at a level with a relatively high probability of establishment.

Australia imports a large amount of wood packaging material from countries where pinewood nematode is established, such as China and Japan. In chapter 1, we showed that, when we discounted for a single common intercept (burnt pine longicorn) from New Zealand, China and Japan accounted for 41% of exotic forest insect interceptions into Australia between 2000–2016, most linked to wood packaging and wood products. Much of this wood packaging is associated with imports of containers. In 2013–14, 3.5 million shipping containers were imported to Australia with only a very small percentage subject to biosecurity inspection. Container volume imported into Australia continues to increase yearly, illustrating that the wood packaging pathway for entry of pine wilt disease into Australia from our major trading partners that have the disease will continue to increase.

Analysis of inspection data at Australian ports reveals that vectors of *B. xylophilus* are detected relatively regularly. Since 2008, there have been 35 interceptions of *Monochamus* spp., the majority being *M. alternatus,* the primary vector of *B. xylophilus* in Asia, but also *M. galloprovincialis*, the primary vector in Portugal and Spain. Thirty of these interceptions were on material imported from countries where *B. xylophilus* is established, the vast majority from China. Half of these were intercepted in Brisbane. Despite these interceptions, there is no evidence that any beetles established. Unmated *M. alternatus* females are still able to transmit nematodes via oviposition of sterile eggs, thus allowing pinewood nematode to establish in a new region without *M. alternatus* necessarily establishing (Akbulut and Stamps 2012). Australia has exotic longicorn species known to be able to vector *Bursaphelenchus* species (Mamiya and Enda 1972; Mamiya 1976; Linit 1988), including species of *Arhopalus* (Webb and Eldridge 1997; Hodda et al. 2008). And *Bursaphelenchus* species have previously established in Australia (Carnegie et al. unpublished).

In 2000, a species of *Bursaphelenchus* was detected in dying *P. halepensis* trees near port facilities in Melbourne, Australia (Hodda et al. 2008; Smith et al. 2008). It was initially believed to be *B. xylophilus*, but later confirmed as *B. hunanensis*. Surveillance for dead trees and trapping for a vector began promptly. Trees confirmed with *B. hunanensis* were removed and destroyed, with 35 out 450 dead trees testing positive. No primary vector was found, but *Arhopalus rusticus* emerged from infected logs, and is a known secondary vector overseas. It is thus likely that *B. hunanensis* arrived via infected wood and transferred onshore by a primary vector (*Monochamus* sp.), which subsequently failed to establish, similar to that which occurred in Portugal (Sousa et al. 2011; Naves et al. 2016). *Bursaphelenchus hunanensis* is believed to have been eradicated, although *A. rusticus* established (Hodda et al. 2008; Smith et al. 2008).

In May 2014, live *M. alternatus* (as well as Asian longhorn beetle and brown mulberry longhorn beetle) were detected in wood packaging material from China at major Australian ports including Brisbane, Sydney and Melbourne (http://www.farmonline.com.au/news/agriculture/general/news/exotic-timber-pests-detected/2702213.aspx). The timber pallets had been stamped with the IPSM-15 mark. Panel traps were established within port facilities and a small number of live males and females were caught. Panel traps and monitoring of pine trees immediately outside port facilities in Brisbane, Sydney and Melbourne (from 2014 to 2016), however, has revealed no evidence of either of these beetles establishing. In 2014, during surveys associated with this interception, *B. sexdentati/vallesianus* was detected in a single pine tree in Brisbane. No obvious vector was found, and no other dead pine trees in the area were found to have the nematode. The tree has since been destroyed by biosecurity authorities.

In early 2016, *B. sexdentati/vallesianus* was detected in rapidly dying *P. radiata* in Sydney, not 5 km from the port facility where *M. alternatus* had been detected in 2014. Seven trees have been detected—and destroyed by biosecurity authorities—out of 1,500+ surveyed in the area. No primary vector has been found, but all infected trees had high numbers of *Arhopalus syriacus,* an exotic longicorn beetle long established in Sydney (Webb and Eldridge 1996). Species of *Arhopalus* are known secondary vectors of *Bursaphelenchus* spp. (Mamiya and Enda 1972; Mamiya 1976; Linit 1988). Similar to that which occurred in Portugal with *B. xylophilus* (Sousa et al. 2011; Naves et al. 2016) it is likely that a primary vector arrived in solid wood packaging into Port Botany (Sydney), transmitted *B. vallesianus* to stressed pine trees, but failed to establish (due to, for example, unfavourable climatic conditions and Allee effects [Stephens et al. 1999] – Allee effects occur when a population is at a level below a critical threshold where individuals are unable to find mates and reproduce). *Arhopalus syriacus* may now be vectoring the nematode to stressed and dying pine trees, as it is a secondary pest of stressed trees, and thus unable to be a primary vector of the nematode (i.e. unable to transfer the nematode to healthy trees). *B. vallesianus* is not considered a highly pathogenic nematode species, compared to *B. xylophilus.* UPDATE: pine trees infected with *B. sexdentati/vallesianus* have been found further afield in Sydney and in regional areas of NSW, and it has now been determined that this exotic nematode has established in Australia (Carnegie et al. unpublished).

The above examples raise several points. Firstly, the threat of *Monochamus* arriving into Australia is real, and such beetles have likely vectored *Bursaphelenchus* spp. across the border. However, the fact that there is no evidence of *Monochamus* spp. having established on a new continent (Bain and Hosking 1988), perhaps due to the Allee effect, suggests the chance of this occurring in Australia is negligible. *Bursaphelenchus xylophilus* has only invaded and established in countries where a native *Monochamus* species is already native, such as *M. alternatus* in Japan, China and Korea, and *M. galloprovincialis* in Portugal. The fact Australia does not have a native *Monochamus* sp., nor an exotic species currently established, means we have to have *Monochamus* arrive and establish, as well as *B. xylophilus* enter and establish. Bain and Hosking (1988) thought the chance of this was too small to worry about. Note that the invasions of pinewood nematode in both Japan and Portugal are thought to be only a single introduction event to each country, based on genetic diversity of the nematode (Mallez et al. 2015). This indicates how rare an invasion of pinewood nematode would be on a new continent such as Australia.

Likelihood of establishment and spread of pinewood nematode and vectors in Australia

Susceptible habitat (hosts)

To effectively establish, exotic pests require suitable hosts once they have arrived at a new location. There are ample *Pinus* trees planted around major ports in Australia, including Sydney and Brisbane. *Pinus* trees are planted throughout urban and peri-urban areas and have the potential to provide an effective pathway for spread of exotic pests into production forests. For example, there are major softwood plantations within 40 km from the Port of Brisbane, and these plantations are within 5 km from pallet/container depots at Caboolture, where containers (and wood packaging material) are sent before being inspected and later distributed. Many of these port-environ trees are under stress, and thus would be attractive to potential vectors and susceptible to nematode infection. All *Pinus* spp. planted in Australia have the potential to be hosts of *Monochamus* and *Bursaphelenchus* species. Many of these are under stress, and thus would be attractive to potential vectors and susceptible to nematode infection. There are also potential secondary vectors already established in Australia, including *A. rusticus, A. syriacus, Ips grandicollis, Hylurgus ligniperda* and *Hylastes ater.*

Suitable climate

A suitable climate is also required for both the beetle vector and nematode to survive, reproduce and expand its population. Climate-matching programs are commonly used to determine the potential climate suitability of exotic pests to a new region (e.g. MacLeod et al. 2002; Wharton and Kriticos 2004; Carnegie et a. 2006; Kriticos et al. 2013). For our analysis, we used CLIMEX (Kriticos et al. 2015) to investigate the potential climate suitability of Australia for pinewood nematode and its primary vector. We used the model developed by Song and Xu (2006) for *M. alternatus*, which was based on the distribution of *M. alternatus* in China. This included locations in provinces within the recognised natural distribution of *M. alternatus* (Makihara 2004), but also some provinces just outside the recognised native distribution, such as Hebei to the north and Hainan to the south (Figure 1). Noteworthy is their inclusion of Xinjiang and Tibet in their distribution of *M. alternatus,* which is listed by CABI (www.cabi.org/isc/datasheet/34719); but not recognised by others (Makihara 2004)[5]. They validated their model using the distribution of *M. alternatus* in Japan, illustrating the accuracy of the model (Figure 2). Song and Xu's (2006) model parameters (Table 1) indicated that cold stress would restrict the beetle's persistence south of 30° S, and that heat and dry stress would restrict its persistence in Northern Australia; the potential distribution of *M. alternatus* included eastern and southern Australia.

Table 1: Parameters used in the CLIMEX model (Song and Xu 2006)

DVO	Limiting low temperature	10.8°C
DV1	Lower optimal temperature	15.0°C
DV2	Upper optimal temperature	30.0°C
DV3	Initiating high temperature	33.0°C
PDD	Minimum degree-days above DVO necessary to complete a generation	1,690
TTCS	Cold stress temperature threshold	8°C
THCS	Cold stress temperature rate	0.00013
THCS	Heat temperature threshold	33°C
THCS	Heat stress temperature rate	0.0001
SMDS	Dry stress threshold	0.25
HDS	Dry stress rate	0.001
SMWS	Wet stress threshold	4.0
HWS	Wet stress rate	0.0001

Figures 1–2 show the predicted range for *M. alternatus* in Asia (China, Japan and Korea), based on the CLIMEX model we used. This encompasses the natural distribution of *M. alternatus* in China and Japan (Makihara 2004), which is generally restricted to humid subtropical and humid continental climates in both countries. For China, the known distribution of pine wilt disease (Zhao 2008; Hu et al. 2013) is encompassed within the

[5] Due to this, the current authors are in the process of re-analysing the CLIMEX model with these anomalous data removed.

predictive model, but the model predicts only geographically patchy distribution in southern China, including unsuitable conditions around Hong Kong where pine wilt disease is common. For Japan, the predictive model closely matches the known distribution of pine wilt disease (Futai 2008) and the area of most severe epidemics in central and south-western Japan (Nakamura-Matori 2008), but pine wilt disease extends further into the cooler humid continental climate in northern Japan where the model predicted unsuitable climate. The invasion of *B. xylophilus* is likely to have increased the predictability of food resources for *M. alternatus* by producing more weakened and dying trees for larval development (Nakamura-Matori 2008) and this may have increased the expansion potential of the beetle vector. The distribution of pine wilt disease in Korea (Shin 2008) fits closely with the model predicting distribution of *M. alternatus.* This gives us confidence in the model and predictions of its potential climate suitability in Australia.

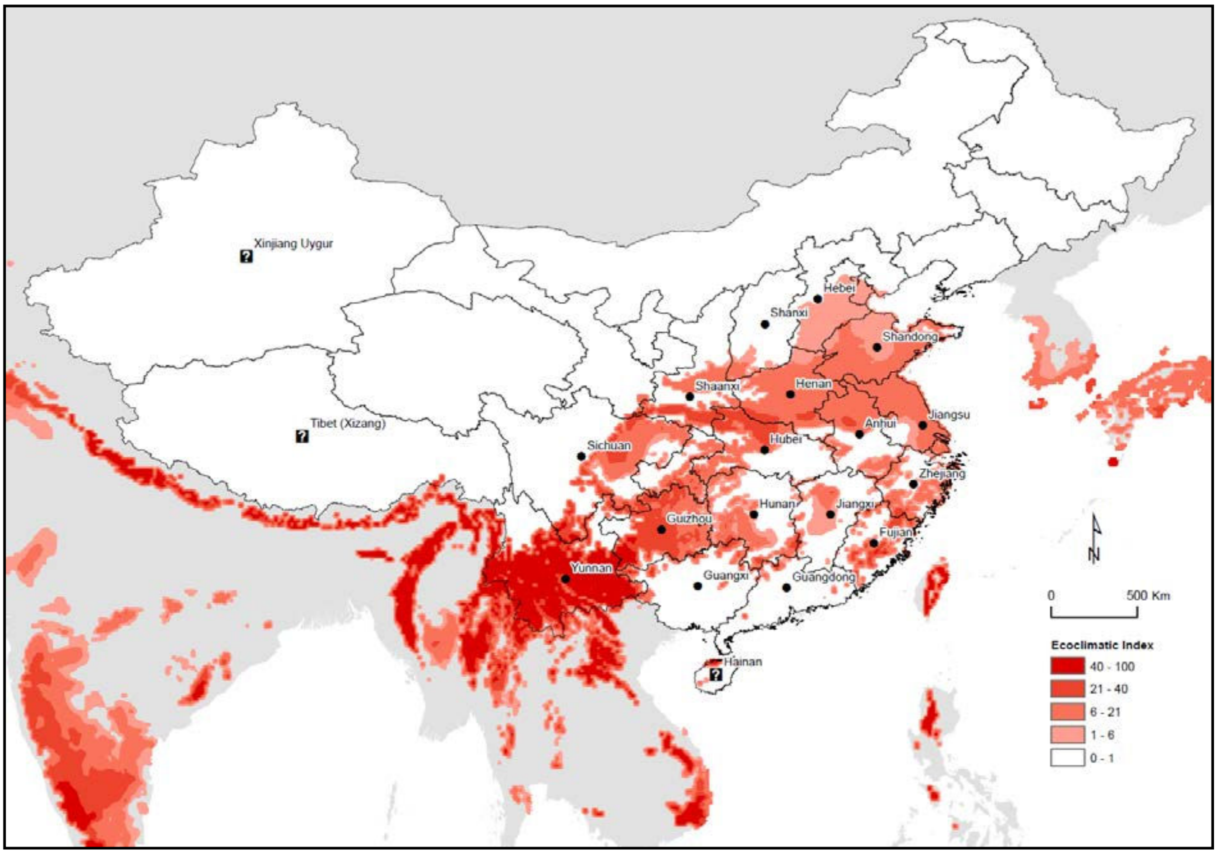


Figure 1: China showing known and potential range of occurrences of *Monochamus alternatus.* Black dots indicate provinces with known records of *M. alternatus* (Makihara 2004); modelled climatic suitability for *M. alternatus* under historical (1961–1990) climate averages as modelled using CLIMEX Ecoclimatic index (EI) with >40 optimal and <1 unsuitable; question marks indicate dubious distribution records used in the CLIMEX model by Song and Xu (2006); the current distribution of pine wilt disease (Zhao 2008; Hu et al. 2013) is captured by the black dots.

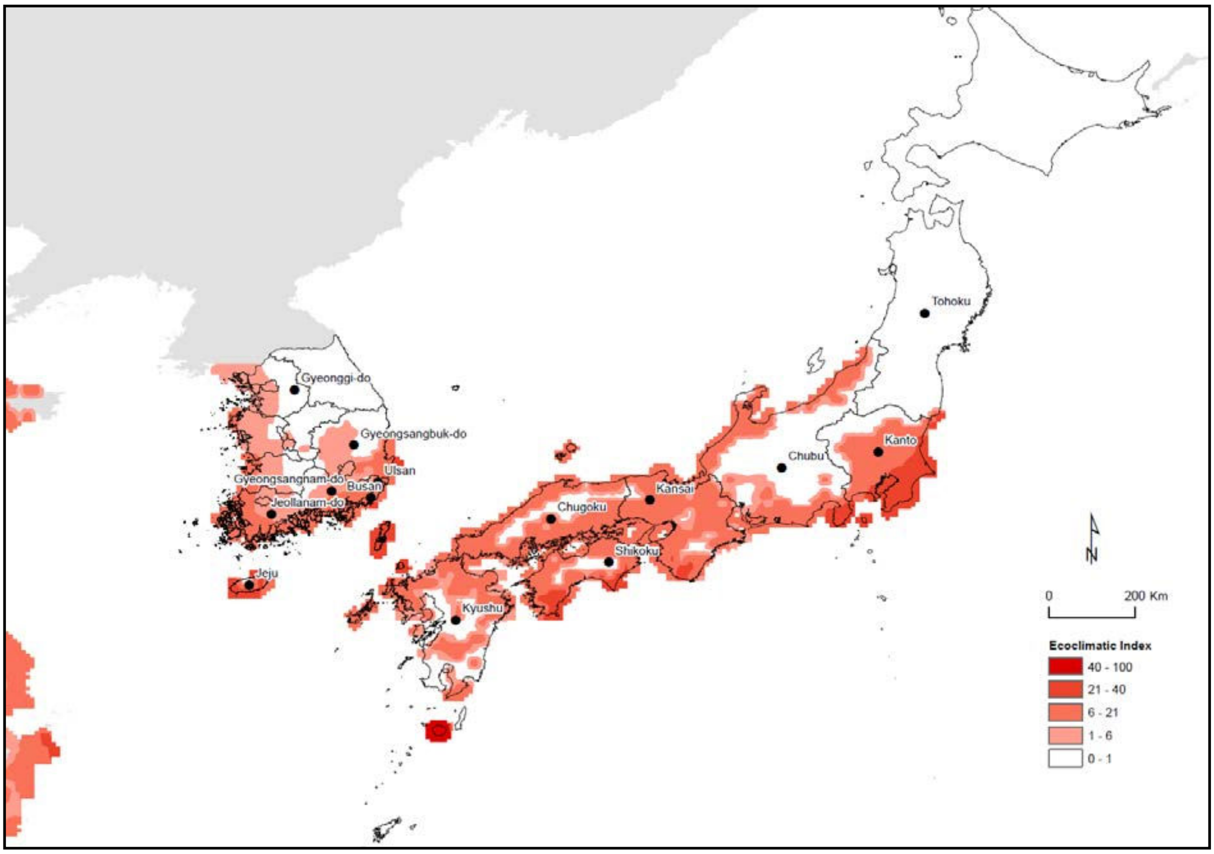


Figure 2: Japan and Korea showing known and potential range of occurrences of *Monochamus alternatus*. Black dots indicate provinces with known records of *M. alternatus* (Makihara 2004; Shin 2008); modelled climatic suitability for *M. alternatus* under historical (1961–1990) climate averages as modelled using CLIMEX Ecoclimatic index (EI) with >40 optimal and <1 unsuitable; the current distribution of pine wilt disease (Futai 2008; Shin 2008) is captured by the black dots.

The CLIMEX model for Australia showed highly suitable to optimal climate along the east coast—especially in subtropical climates—and Mediterranean climates in south-western Australia, with moderately suitable climates in the warm semi-arid climates of southern Australia (Figure 3). This encompasses the softwood plantations in Queensland (Figure 4) and northern NSW (Figure 5)—planted mainly with *P. eliottii, P. taeda* and *P. elliottii* × *caribaea* hybrids—and the *P. radiata* and *P. pinaster* plantations in Western Australia (Figure 6). Interestingly, a large part of the Australian plantation estate, planted with *P. radiata,* is predicted to be unsuitable for establishment of *M. alternatus* (Figure 3).

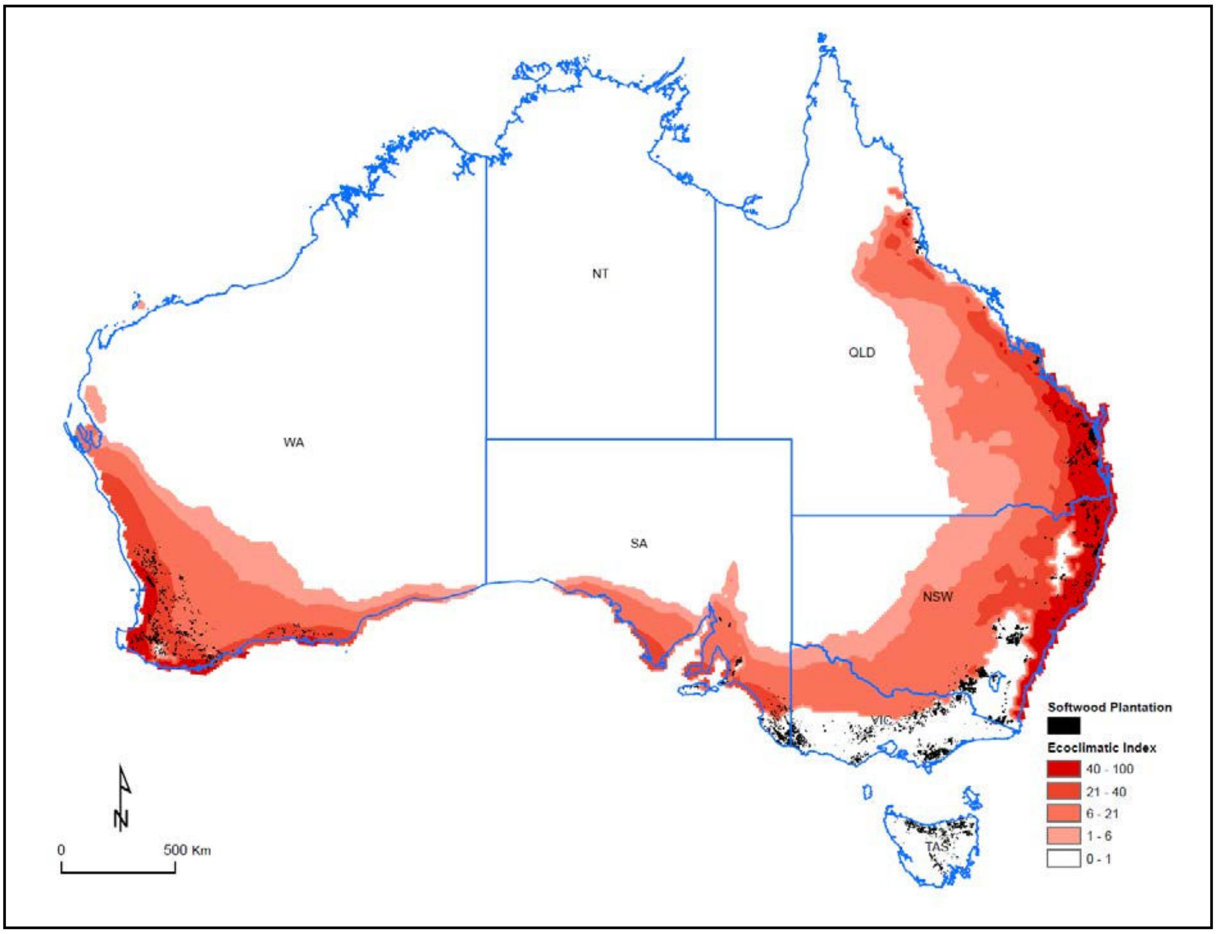


Figure 3: Australia showing potential range of *Monochamus alternatus,* and by association, pine wilt disease. Modelled climatic suitability for *M. alternatus* under historical (1961–1990) climate averages as modelled using CLIMEX Ecoclimatic index (EI) with >40 optimal and <1 unsuitable; softwood plantations (Data source: ABARES).

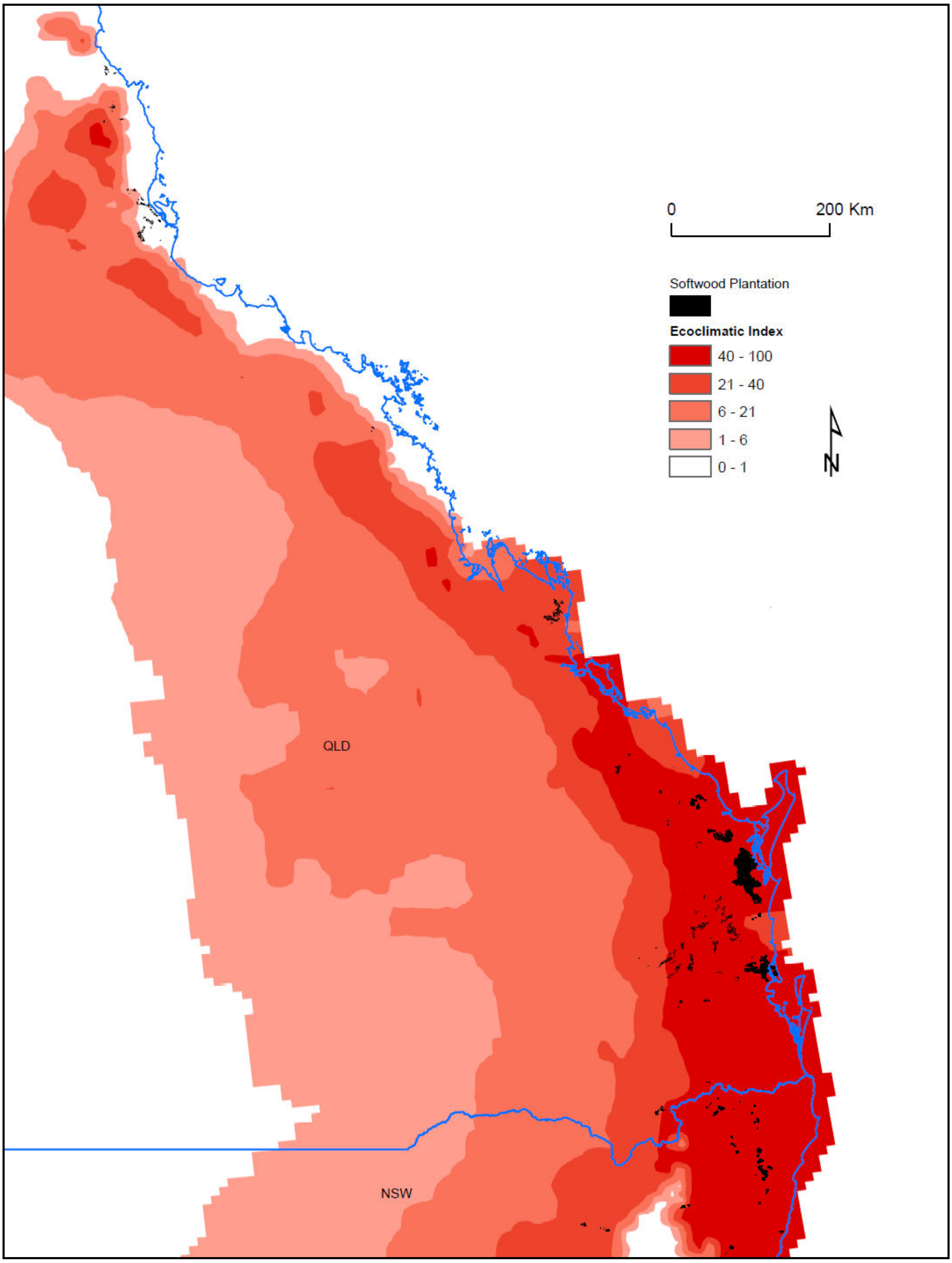


Figure 4: Queensland showing potential range of *Monochamus alternatus,* and by association, pine wilt disease. Modelled climatic suitability for *M. alternatus* under historical (1961–1990) climate averages as modelled using CLIMEX Ecoclimatic index (EI) with >40 optimal and <1 unsuitable; softwood plantations (Data source: HQPlantations and ABARES).

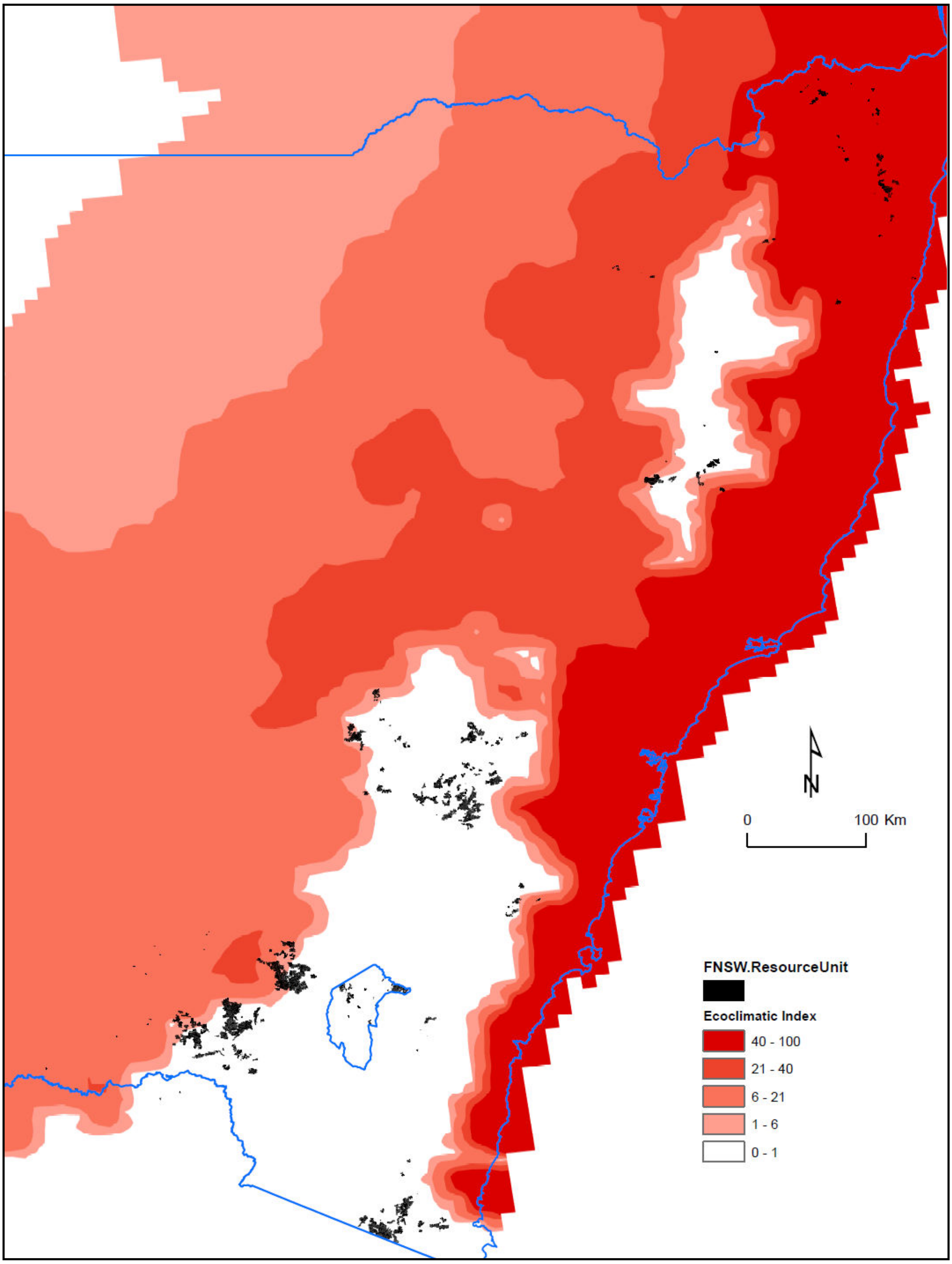


Figure 5: New South Wales showing potential range of *Monochamus alternatus,* and by association, pine wilt disease. Modelled climatic suitability for *M. alternatus* under historical (1961–1990) climate averages as modelled using CLIMEX Ecoclimatic index (EI) with >40 optimal and <1 unsuitable; softwood plantations (Data source: Forestry Corporation of NSW and ABARES).

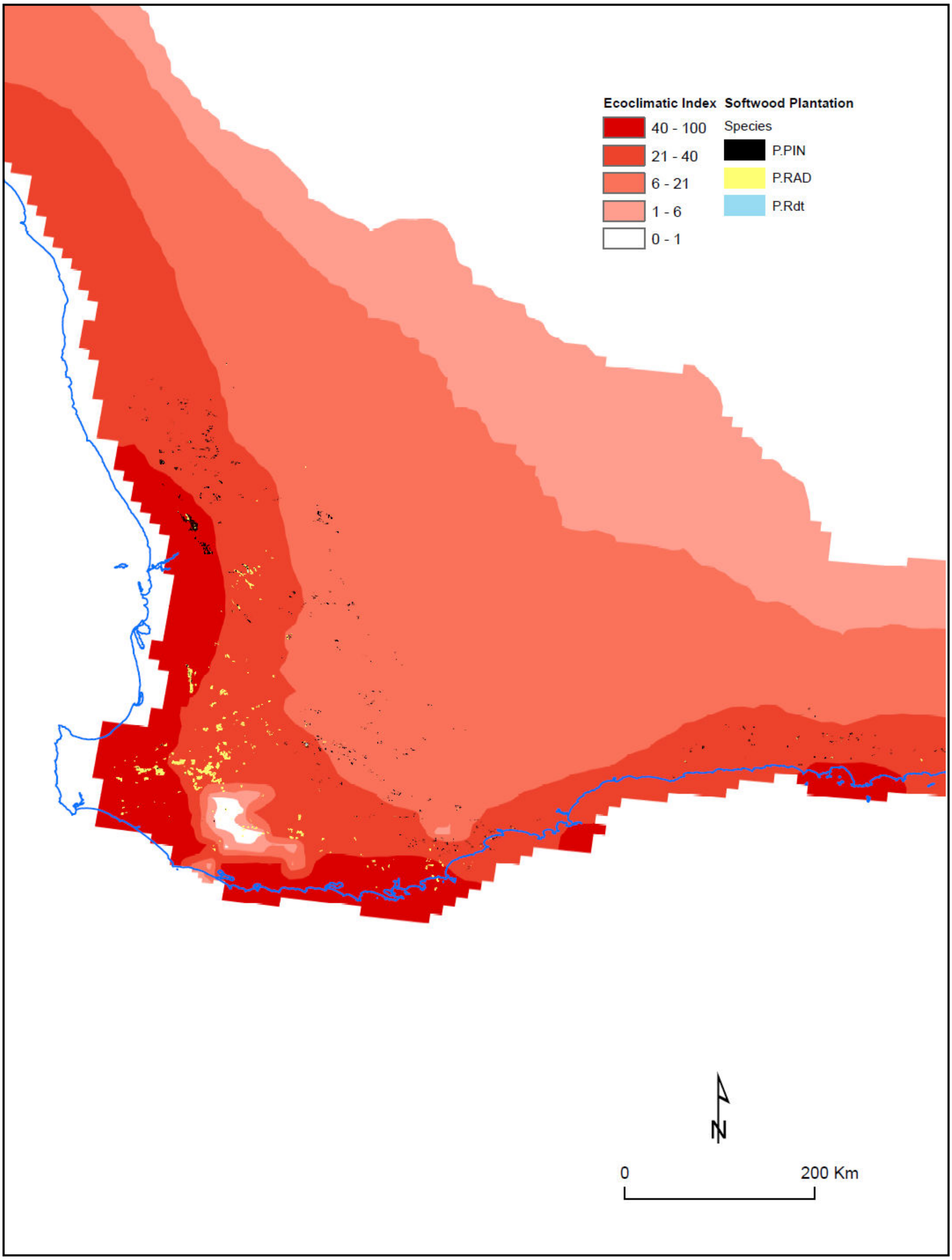


Figure 6: Western Australia showing potential range of *Monochamus alternatus,* and by association, pine wilt disease. Modelled climatic suitability for *M. alternatus* under historical (1961–1990) climate averages as modelled using CLIMEX Ecoclimatic index (EI) with >40 optimal and <1 unsuitable; softwood plantations (Data source: Forest Products Commission).

Spread

Numerous studies have reported or modelled spread rates for pinewood nematode following invasion of a new country (e.g. Yoshimura et al. 1999; Takasu et al. 2000; Togashi and Shigesada 2006; Robinet et al. 2009), which range from 2 to 15 km per year. Takasu et al. (2000) reported range expansion of pinewood nematode in Japan of 4.2 km per year based on long-term monitoring and modelling, with the majority of *M. alternatus* flying relatively short distances, but a small proportion (10%) long-range dispersers. They also concluded that beetle spread is faster in denser forests. Etxebeste et al. (2015) reported that the majority of *M. galloprovincialis* in Portugal disperse 250–500 m in contiguous pine stands, but a small proportion will disperse 2.5–3.5 km. In fragmented landscapes *M. galloprovincialis* generally disperse over longer distance (~2 km), and as far as 13.6 km. Sousa et al. (2011) reported that *Monochamus* spp. tend to fly further in open (sparse) stands than in uniform (dense) stands. Robinet et al. (2009) reported that *M. galloprovincialis* was responsible for short-distance spread in China of 7.5 km per year, but that human-assisted long distance spread could be over 300 km annually. Transportation of nematode-infested pine logs is the primary cause of long-range expansion of pinewood nematode in Japan (Togashi and Shigesada 2006) and China (Robinet et al. 2009).

So with ample susceptible hosts in peri-urban and plantation areas, *M. alternatus* and pinewood nematode are likely to spread, albeit slowly, through areas with conducive climates in Australia. Australia does not have a primary vector for pinewood nematode, so the slower rate of spread is based on the need for *M. alternatus* to spread into new areas and vector pinewood nematode. In Japan, China and Portugal, where primary vectors are native, spread was faster than what we would expect in Australia.

We predict spread of 5 km/year through peri-urban and rural areas where hosts are common, but fragmented; and 1 km/year through the plantation estate. This could double if *M. alternatus* has two generations per year, as is predicted under our model for much of the plantation estate (Fig 7).

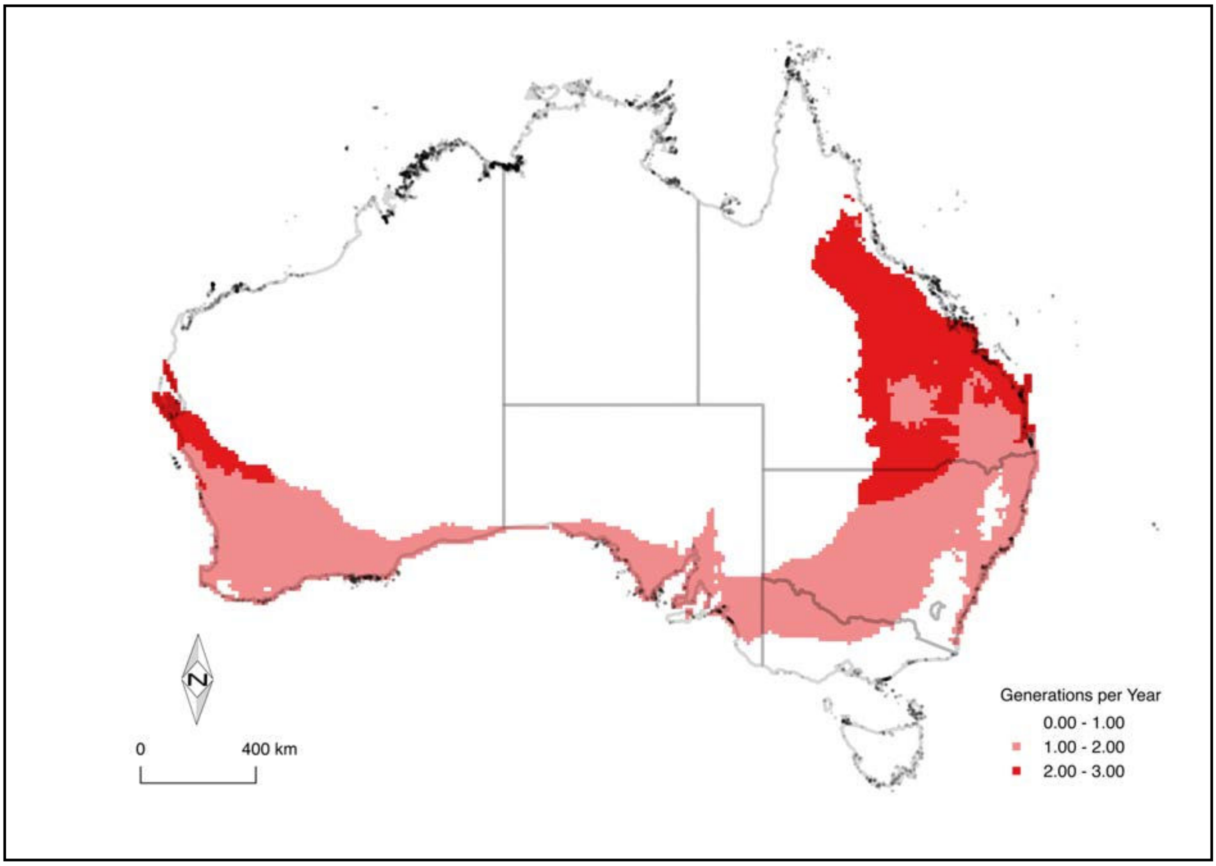


Figure 7: Australia showing predicted number of generations per year for *M. alternatus*. Data is integrated with ecoclimatic index such that for EI values less than one, no reproduction by *M. alternatus* is predicted.

Likely impact of pine wilt disease to softwood plantations in Australia

Susceptibility of *Pinus* species in Australia

Pinewood nematode has caused devastating damage to native *Pinus* where it has expanded its native range, including to *P. densiflora* and *P. thunbergii* in Japan (Mamiya 1988), *P. massoniana* in China (Zhao 2008) and *P. pinaster* in Portugal (Rodrigues 2008). In contrast, pine wilt nematode and its primary vectors are considered secondary pests in their native range in Northern America (Dopkin et al. 1981; Wingfield et al. 1986), likely due to co-evolution of a native pest with its hosts (Bain and Hosking 1988; Evans et al. 1996; Akbulut and Stamps 2012). Exotic species planted in Northern America (e.g. *P. sylvestris*) are, however, highly susceptible to pinewood nematode (Malek and Appleby 1984; Linit and Tamura 1987; Sikora and Malek 1991).

Bain and Hosking (1988) and Sopow et al. (2010) did not consider pinewood nematode a significant exotic threat to the large *P. radiata* plantations in New Zealand, due in part to *P. radiata* being native to Northern America and likely to thus be resistant under field conditions. Personal communication with J. Bain (May 2016) and M. J. Wingfield (May 2016) support and expand this view, that pinewood nematode is unlikely to be a significant threat to Australia's exotic *Pinus* estate because Australia plants species native to Northern

America (*P. radiata, P. elliottii, P. taeda*) where pinewood nematode is native. Dwinell and Nickle (1989) considered North American *Pinus* spp. to be either immune or highly resistant to pine wilt disease.

So the question arises, “is our softwood estate *really* at risk from pinewood nematode?”.

There are many contradictory and ambiguous results of host susceptibility for pinewood nematode in the literature. Over 35 *Pinus* species have been identified as hosts of pinewood nematode (Bergdahl 1988; CABI 2016), but there is wide variation in susceptibility within these (e.g. Mamiya 1983; Evans et al. 1996). *Pinus densiflora, P. thunbergia, P. luchensis, P. massoniana* and *P. pinaster* are unequivocal hosts, with extensive tree mortality in native and introduced stands of these species (Mamiya 1988; Zhao 2008; Sousa et al. 2008). Some of the contradictory results relate to differences in age of trees inoculated under trial conditions, often with trials using seedlings reporting high susceptibility, but those based on mature trees conflicting results for the same species (Mamiya 1983; Bain and Hosking 1988). Wingfield et al. (1984) illustrated this eloquently: inoculation with pinewood nematode killed seedlings of *P. banksiana, P. resinosa* and *P. nigra,* but failed to kill mature forest trees in the USA. As such, care is needed when interpreting results from seedling-inoculation trials. Susceptibility based on artificial inoculation of young trees or seedlings does not imply susceptibility of established trees (Mamiya 1983; Wingfield et al. 1986; Linit and Tamura 1987; Bain and Hosking 1988; Baoujun and Qouli 1989).

Based on the literature, the susceptibility of key Australian *Pinus* species is ambiguous. For *P. radiata,* Mamiya (1983) and CABI (2016) list it as “susceptible”, Evans et al. (1996) as “intermediate”, while Bain and Hosking (1988) found no evidence of infection during surveys of native stands of *P. radiata* in California. Futai and Furuno (1979) inoculated 7-year-old *P. radiata* trees (95–230 cm in height) in Japan and 1/3 died (note small sample size though). Furuno et al. (1993) on the other hand reported 80% mortality of mature (10–26 cm DBH, 6–13 m height) field-grown *P. radiata* under natural conditions of pinewood nematode in Japan (i.e. natural infection), 86% mortality for mature *P. pinaster* (18–28 cm DBH, 11–13 m height) and no mortality for mature *P. elliottii* (18–36 cm DBH, 15–25 m height). *Pinus elliottii* is generally considered to be “resistant” (Mamiya 1988; Evans et al. 1996). However, Yang and Wang (1986) reported 40% mortality of 3-year-old field-grown seedlings inoculated with nematodes in China, and Futai and Furuno (1979) reported 30% mortality (3/9) of 7-year-old (230–350 cm in height) nematode-inoculated trees in Japan. Moreover, Luzzi et al. (1984) were able to induce tree mortality (pine wilt disease) by subjecting 10-year-old healthy *P. elliottii* to feeding by nematode-infected *M. titillator* in Florida, USA. *Pinus taeda* is considered “resistant” (Mamiya 1988) to “intermediate” (Evans et al. 1996), with Yang and Wang (1986) reporting no mortality from inoculation trials and Futai and Furuno (1979) 1/14 trees dying. However, Ebine (1981, cited in Mamiya 1988) reported severe mortality of *P. taeda* (up to 70% mortality) adjacent to *P. densiflora* which had been decimated by pinewood nematode in Japan; it appears that once the *P. densiflora* resource had been destroyed, *M. alternatus* attacked the adjacent *P. taeda* in large numbers. Futai and Furuno (1979) noted that resistance also varied with inoculum level: hosts previously thought resistant became susceptible when inoculated with larger numbers of nematodes. *Pinus caribaea* is reported to be “resistant” (Mamiya 1988) to “intermediate” (Evans et al. 1996). *Pinus pinaster* is listed as “susceptible” (Mamiya 1988; Evans et al. 1996). Futai and Furuno (1979) reported almost 60% mortality of 7-year-old nematode-inoculated *P. pinaster* trees in Japan, and da Silva et al. (2015) showed it to be highly susceptible in inoculations trials of 3-

year-old plants in Portugal. It is the main species killed by pinewood nematode in Portugal (Naves et al. 2016). The only studies on *P. elliottii* × *P. caribaea* hybrids is of 12-month-old seedlings shipped from Australia to Japan and inoculated with nematodes (Lawson and Sathyapala 2008). They reported wide variation in susceptibility among hybrid clones, with some relatively resistant and others highly susceptible. In the same trials, *P. caribaea* was relatively resistant and *P. elliottii* highly susceptible. Note that care is needed when interpreting these results with reference to mature trees. There is little other data on the susceptibility of hybrids, but important to note that hybrids between susceptible parents can produce resistant hybrids, such as *P. thunbergii* × *P. massoniana* and *P. densiflora* × *P. nigra* subsp. *laricio* (Mamiya 1988; Evans et al. 1996).

It should be noted that the *Pinus* germplasm in Australia has been substantially altered — through extensive breeding programs — from that which occurs in native populations in Northern America. Furthermore, much of the regions where *Pinus* are planted are likely to be sub-optimal sites compared to the native distribution of these species, with drought and heat stress common events. *Pinus* spp. grown outside their native range have shown increased susceptibility to pinewood nematode (Myers 1988). *Pinus resinosa* is highly resistant to pinewood nematode in its native range in Minnesota, USA (Wingfield et al. 1986), but suffered high levels of infection and mortality in off-site plantings in Maryland, USA (Harman et al. 1986). Recent observations of high levels of natural infection by *B. xylophilus* of *P. radiata* plantations in Spain led Zamora et al. (2015) to declare that "*P. radiata* should be regarded as susceptible to pine wilt disease when planted out of its natural range". Numerous studies have reported that water stress (drought) and heat stress (high temperatures) increase tree susceptibility to pinewood nematode (Malek and Appelby 1984; Mamiya 1983; Sikora and Malek 1991; Fukuda 1997; Nakamura-Matori 2008). Tree mortality increased from 11–16% to 23–24% in *P. thunbergii* stands in Japan during below average rainfall years (Yoshimura et al. 1999). Moreover, tree mortality events, such as drought and forest fires, a common event in Australia, increase the food resource for *M. alternatus,* thereby potentially allowing *M. alternatus* to reach outbreak proportions (Nakamura-Matori 2008).

Thus, although the general consensus is that North American *Pinus* species are resistant to pine wilt disease, we have here taken the precautionary principle approach and determined that the breeds grown in Australia would be susceptible under Australian conditions.

Likely severity (incidence) of pine wilt disease in softwood plantations in Australia

Incidence of damage by pinewood nematode depends on susceptibility of the host and conducive climate. The majority of reports of tree mortality associated with pinewood nematode describe numbers of trees or lost wood volume; there is a paucity of data on the incidence within a pine stand. The annual loss of pine trees in Japan increased from 30,000 m^3 to 1.2 million m^3 in the 1930s to 1940, and peaked in the late 1970s at 2.4 million m^3 (Mamiya 1988). In some areas, whole forests were destroyed, and are now replaced with broadleaved species. In China, annual tree deaths have reached 2.3 million trees just in a single county (Robinet et al. 2009). Tree mortality from pinewood nematode can increase rapidly following initial invasion of a susceptible forest, with records from Japan showing an increase of over 10% within a single year, from 0.7% incidence to 8% incidence (Togashi and Shigesada 2006). To model the impact of pinewood nematode on pine forests in the EU, Soliman et al. (2012) used incidence figures ranging from 40% to 100%, depending on the age and susceptibility of likely hosts. Cumulative mortality in plantations of *P. densiflora* and *P. thunbergii* in Japan ranged from 33% to 94% over a five-year period (Ugawa and Fukuda

2008). Mamiya (1988) reported a loss of 10% of total growing stock within a single year in a 56,000 ha forest in Japan, and some stands were totally destroyed within four years. In Portugal, annual mortality of *P. pinaster* forests averaged 5% over four years in one stand, but only 2% over six years in another stand (PHRAME 2007).

The potential levels of tree mortality in Australian coniferous plantations if pinewood nematode established is impossible to predict from the available literature. However, we consider that levels are unlikely to be as high as seen for highly susceptible species in Japan and China. The combination of large contiguous plantations of a host planted outside its natural range in a region often experiencing drought and heat stress indicates mortality rates closer to that seen for *P. pinaster* in Portugal.

On this basis, we predict mortality rates of 10% per rotation is *highly* likely; mortality of 20% per rotation is *moderately* likely; mortality of 40% per rotation will be a rare event.

Pest Risk Assessment

Below are the underlying assumptions we have made in our analysis, and discussions regarding their validity.

ASSUMPTION	VALIDITY
Likelihood of arrival of pinewood nematode and vectors	
Monochamus alternatus and *Bursaphelenchus xylophilus* have a ***high*** chance of arriving in Australia	Interception records reveal both are regularly intercepted at Australian ports; literature indicates both are intercepted regularly at international ports, including New Zealand. ISPM-15 not effective at negating the chance of these species arriving in SWPM.
Likelihood of establishment of pinewood nematode and vectors	
Bursaphelenchus xylophilus has a ***moderate*** chance of establishing in Australia	Unequivocal evidence, with three recent examples of a *Bursaphelenchus* sp. establishing in port surrounds (Melbourne, Brisbane, Sydney). Secondary vectors of *Bursaphelenchus* (*Arhopalus* spp.) are established in Australia
Monochamus alternatus has a ***low*** chance of establishing in Australia	No previous evidence of *Monochamus* species having successfully invaded new countries, but evidence of spread within known countries of origin. Although probable that primary vectors of *Bursaphelenchus* spp. incursions (above) were *Monochamus,* none established.
Likelihood of spread of pinewood nematode and vectors	
Likely spread of pinewood nematode in Australia, <u>assuming *M. alternatus* established</u>, is ***medium***	*Pinus* species are common as amenity trees throughout urban and peri-urban environments; all species in Australia are known hosts of pinewood nematode, and likely to be stressed and thus attractive to vectors. These would act as “stepping stones” to commercial plantations, which similarly have susceptible species often under water and heat stress. CLIMEX modelling indicates south-east Queensland and north-east NSW, and south-west WA, highly suitable climate for *M. alternatus.*
Likelihood of significant impact to coniferous plantations	
Likelihood of significant impact to commercial plantations is ***medium***	*Pinus* species planted in Australia likely to be resistant or only mildly susceptible to pine wilt disease. However, there is ambiguity over how these species, bred for many decades in the absence of the disease, retain this resistance when planted outside their native range in areas where drought and heat stress are common.
Likelihood of *inter-state* trade restrictions impacting Australian producers is ***high***	Highly likely that a ban will be imposed on transport of logs from infested areas, either inter- or intra-state

Likelihood of *international* trade restrictions impacting Australian producers is ***high***	Several growers rely on export markets for either the majority of, or a proportion of, harvested logs from certain plantations.

Invasion Scenario – Costs of pine wilt disease establishing in the southeast Queensland *Pinus* plantation estate.

Pine wood often carries pinewood nematode or its vector beetles, and have acted as long-distance spread agents in Japan (Futai 2008), China (refs), Korea (Shin 2008) and Europe (Vicente et al. 2012). Below we report an analysis of the potential costs to a plantation estate of the invasion of the Japanese pine sawyer beetle, *M. alternatus,* vectoring pinewood nematode (and causing pine wilt disease) in an Australian region predicted to be highly suitable for the establishment and spread of the beetle.

Method for estimating the damage cost of establishment of pine wilt disease in southern Queensland

A discounted cash-flow analysis has been performed to estimate the expected present value of foregone timber revenue (in 2016 dollars) to HQPlantations in southern Queensland over a simulation period of 30 years.

Pine wilt disease probability of establishment, rate of spread and tree mortality scenarios

The scenarios examined assume timber pallets and dunnage used in shipping goods from countries with *Monochamus alternatus*/pinewood nematode are the pathway of entry to the port of Brisbane. Pallets are routinely transported from Brisbane to holding areas in Caboolture. Part of the Beerburrum exotic pine plantation estate managed by HQPlantations is close to the holding yard (<5 km), as are many wildling exotic pines and amenity plantings that would be suitable hosts for the disease.

The scenarios examine the potential for pine wilt disease to invade and establish around Caboolture, and then spread into the Beerburrum estate. Given the high volume of traffic (including HQPlantations and logging contractor vehicles and equipment) that travels the highway north from the Beerburrum estate through the Tuan-Toolara estate, the scenarios also examine the possibility that the disease is delivered from Beerburrum to Tuan-Toolara. Table 2 reports the levels adopted in the scenario analysis for the annual probability of establishment of pine wilt disease in the Beerburrum estate, the pest’s annual rate of spread, the annual probability that the pest is accidentally transported from Beerburrum to the Tuan-Toolara estate, and the level of tree mortality. Figures 8 and 9 illustrate the Beerburrum estate area and the Tuan-Toolara estate area examined in this study, respectively. The concentric circles are 1 km apart, representing a 1 km per year rate of spread from an assumed original establishment point within both estates.

Table 2: Pine wilt disease establishment and spread scenario parameters

Parameter	Levels examined
Annual probability of establishment of pine wilt disease in the Beerburrum estate	1%, 5% and 10%
Annual rate of spread	1 km and 2 km
Annual probability of establishment of pine wilt disease in Tuan-Toolara, given establishment in the Beerburrum estate	1%, 5% and 10%
Proportion of trees in invaded stands killed by the pine wilt disease	10%, 20% and 40%

Timber resource at risk and financial analysis parameters

To support analysis of the potential impact of pine wilt disease on their exotic pine estates at Beerburrum and Tuan-Toolara, HQPlantations supplied spatial data with planting area and planting year of all stands within the area defined by Figures 8 and 9. This represents 22,079 ha at Beerburrum and 67,171 ha at Tuan-Toolara. Figure 10 summarises the age class distribution of the estate area examined. Table 3 reports key financial analysis parameters.

The estate is managed on a 28-year rotation, and the analysis tracked the age of all stands throughout the 30-year simulation, harvesting them at age 28 and replanting in the same year. HQPlantations supplied a growth and yield table for an 'average' exotic pine stand to support estimation of timber revenues over time with and without pine wilt disease.

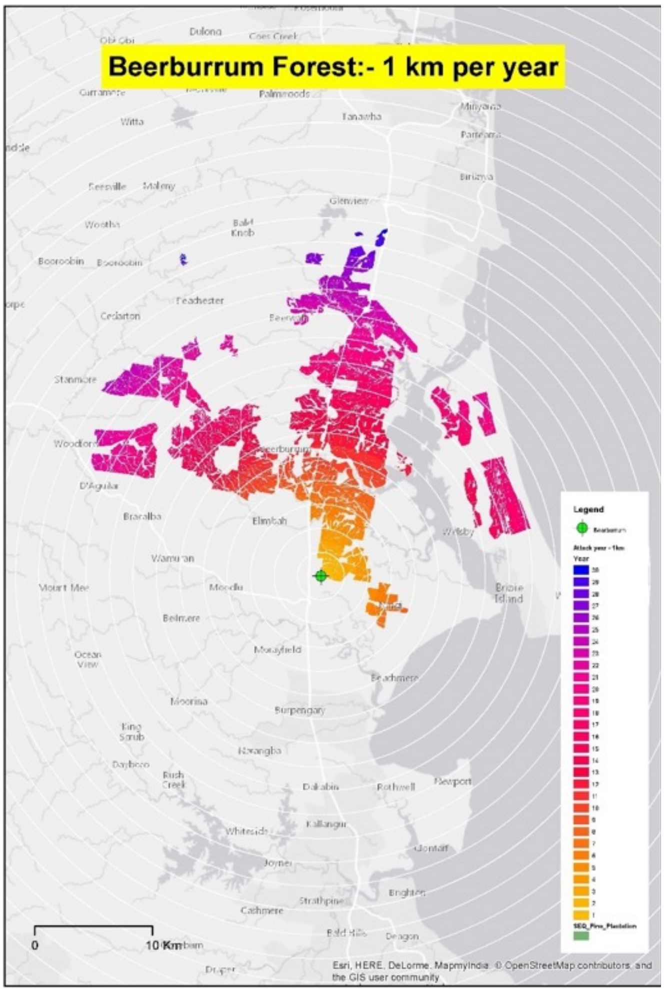


Figure 8: The Beerburrum plantation estate

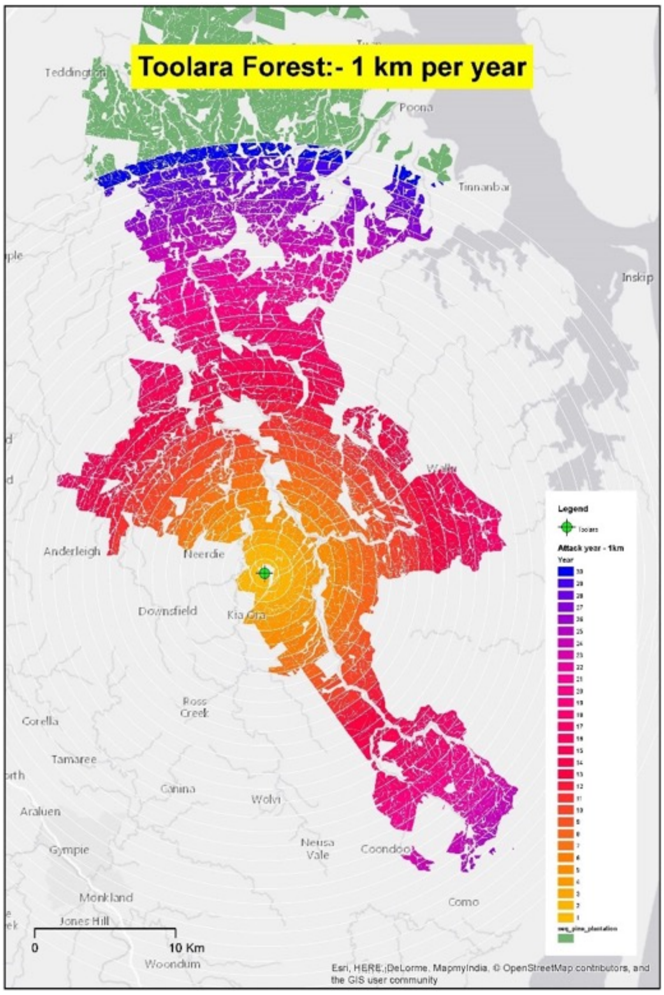


Figure 9: The Tuan-Toolara plantation estate

Figure 10: Age class distribution of the HQPlantations exotic pine estate in 2016

Table 3: Financial analysis parameters

Parameter	Level
Discount rate (%)	5 (3, 7)
Rotation length (Y) [1]	28
Average clearfall recoverable volume (m^3/ha) [1]	491
Average clearfall stumpage price for the domestic market (\$/m^3)	80.4

[1] Information supplied by HQPlantations

Growth and yield models developed by HQPlantations for their exotic pine plantation estate revealed insignificant growth responses in retained stems due to thinning at all plantation ages. Consistent with this observation, HQPlantation staff recommended that the impact of pine wilt disease on clearfall yield be estimated as follows. For all plantation stands, determine the age of the stand when pine wilt disease is simulated to invade. In the yield table provided by HQPlantations, find the standing volume for a plantation of that age. In the absence of published information about mortality over time, assume all tree death within a newly invaded stand occurs in the year of invasion. The volume lost is the proportion of trees killed (10%, 20% or 40%) multiplied by standing volume at the age of invasion. This volume lost is subtracted from the clearfall recoverable volume at age 28, as reported in Table 3, to give recoverable volume with invasion. In the financial analysis, the cost of invasion of a stand is realised when the stand is harvested with a lower recoverable volume at age 28.

The wood of trees killed by pine wilt disease is likely to become degraded within six months of tree death due to co-attack by the five-spined bark beetle, *Ips grandicollis*, which vectors bluestain fungi (*Ophiostoma ips*). *Diplodia sapinea,* another bluestain fungus, is also likely to colonise such trees. Bluestain is largely a cosmetic degrade agent and does not change wood properties significantly, but wood containing bluestain is generally not marketable. If killed trees are not salvaged within a reasonable time frame after death fungal rots (e.g. *Rigidoporus lineatus*) will also be introduced into timber and negatively impact on wood properties. Therefore, all trees killed by pine wilt disease are assumed to have zero commercial value.

All of the Tuan-Toolara estate logs and 80% of the Beerburrum estate logs are processed in southern Queensland. The only known effective treatment for wood already infected with *B. xylophilus* and its vectors is heat treatment in which all parts of the wood reach a temperature of 56 degrees Celsius for at least 30 minutes (Smith et al. 1997). Standard kiln drying practices with exotic pine producers in southern Queensland achieve this (McNaught and Gough 1995). Therefore, the analysis assumes wood from trees not killed by pine wilt disease can continue to be processed as usual.

For all stands, the expected present value in the absence of pine wilt disease is 491 m^3/ha multiplied by \$80.40, discounted by the number of years until the stand is harvested. For all stands, the present value of the stand with invasion of the disease is recoverable volume with invasion (as defined above) multiplied by \$80.40, discounted by the number of years until the stand is harvested. The expected damage cost of pine wilt disease for the exotic pine estate within the study area is the sum of the expected present value in the absence of pine wilt disease for all stands in the study area over the 30-year simulation period, less the sum of the expected present value of all stands in the study area over the 30-year simulation period given alternative probabilities of arrival and rate of spread.

Expected area invaded, damage costs and foregone export revenues due to pine wilt disease

Figure 11 illustrates the area invaded per annum for 1 km/y and 2 km/y spread rates, and the corresponding present value (2016 dollars, 5% discount rate) of damage costs under conditions of 10%, 20% and 40% tree mortality in the Beerburrum and Tuan-Toolara estates, given the pine wilt disease establishes in both estates today. The purpose of this figure is to highlight how rapidly the pest is likely to spread throughout the plantation estate after it establishes, and the high associated damage costs. Should pine wilt disease establish, these are the appropriate damage costs against which to compare the costs of an eradication program to determine the economic efficiency of eradication. The sum of the present value of annual damage costs over the 30-year simulation for Beerburrum and Tuan-Toolara in Figure 11 when tree mortality is 20% is $65 M when the spread rate is 1 km/y, and $106 M when the spread rate is 2 km/y. When new area invaded annually drops to zero in Figure 11, as it does in panels (a), (b) and (d), the entire estate has been invaded.

Given that arrival of the pine wilt disease to southern Queensland is not a certain event, *expected* present value of damage costs are more appropriate for biosecurity policy analysis. Table 4 reports the expected present value of damage costs of the disease to the Beerburrum estate by annual probability of establishment in Beerburrum for a 5% discount rate. For example, the expected present value of damage costs given 20% tree mortality and a 5% per annum chance of establishment at Beerburrum is $6.1 M.

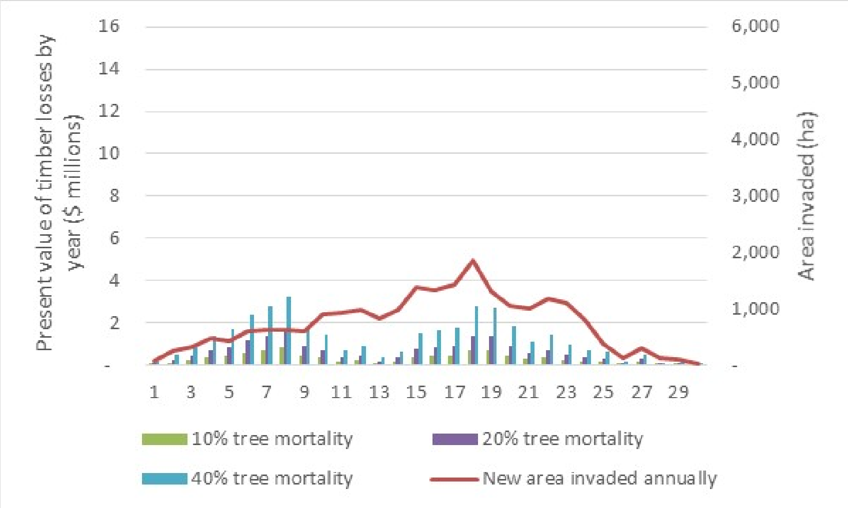
Damage costs in Tuan-Toolara are presented in Table 5, where they are reported by annual probability of pine wilt disease being accidentally transported from the Beerburrum estate, given a 5% per annum chance of arrival at Beerburrum. For example, if we accept a 5% chance per annum of accidental transport of the pine wilt disease, and 20% tree mortality, the expected present value of damage costs is $0.8 M.

Results presented in Tables 4 and 5 are cumulative. Thus, the expected present value of damage costs given 20% tree mortality, 1 km/y spread rate, 5% per annum chance of establishment at Beerburrum and 5% per annum chance of accidental transport to Tuan-Toolara is $6.9 M.

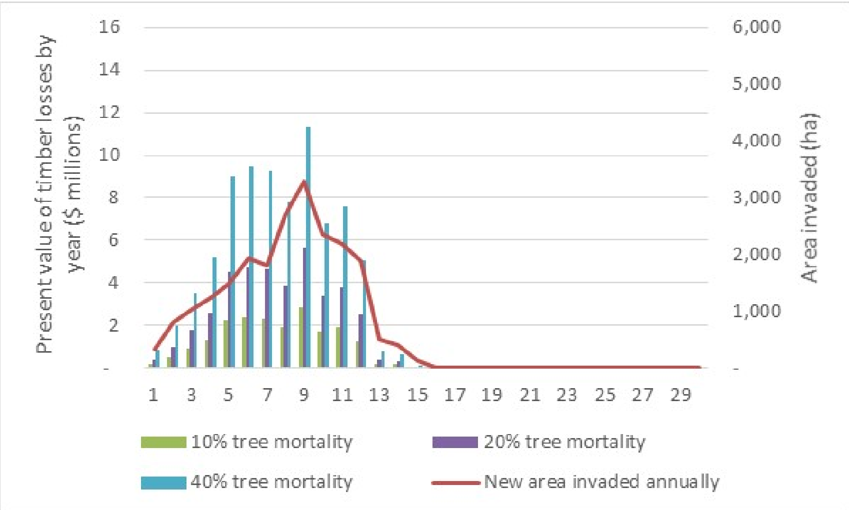
Results are sensitive to the stumpage price and discount rate. Since the damage cost estimates are foregone timber revenues, the sensitivity of damage costs to changes in average stumpage price are estimated by multiplying the damage costs by the percent change in stumpage price. For example, a 10% decrease in stumpage price will lead to a 10% decrease in the expected present value of damage costs. Figure 12 illustrates the sensitivity of expected damage costs to the discount rate for the case where there is a 5% per annum chance of establishment in Beerburrum and a 5% per annum chance of accidental transport to Tuan-Toolara.

Figure 11: Simulated area invaded and present value of damage costs in Beerburrum and Tuan-Toolara given arrival of pine wilt disease in both estates in year 1

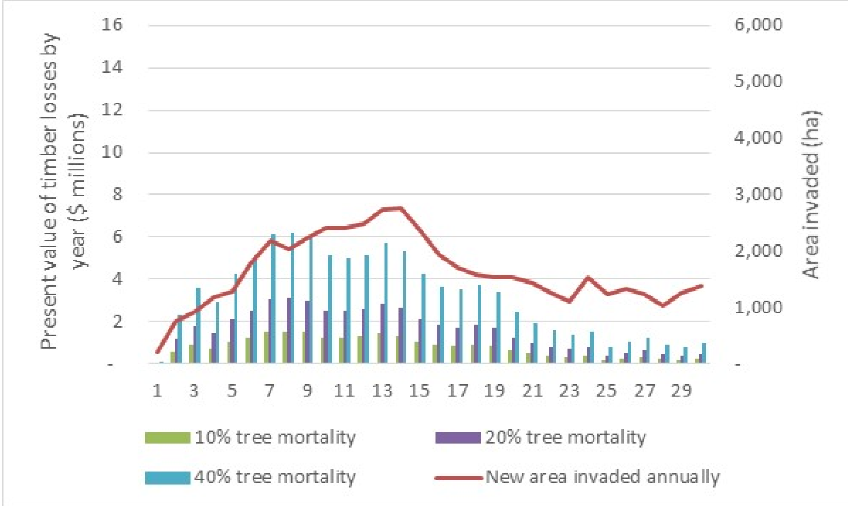
(a) Beerburrum 1km/y spread rate



(b) Beerburrum 2km/y spread rate



(c) Tuan-Toolara 1 km/y spread rate



(d) Tuan-Toolara 2 km/y spread rate

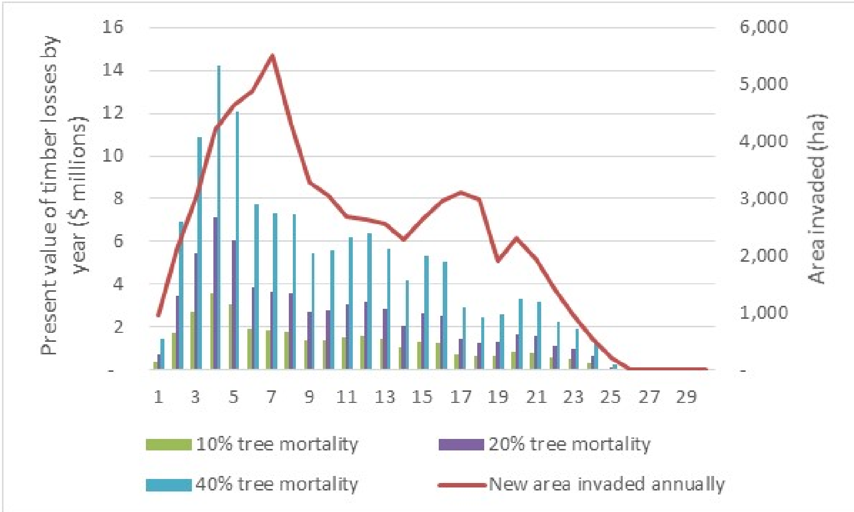


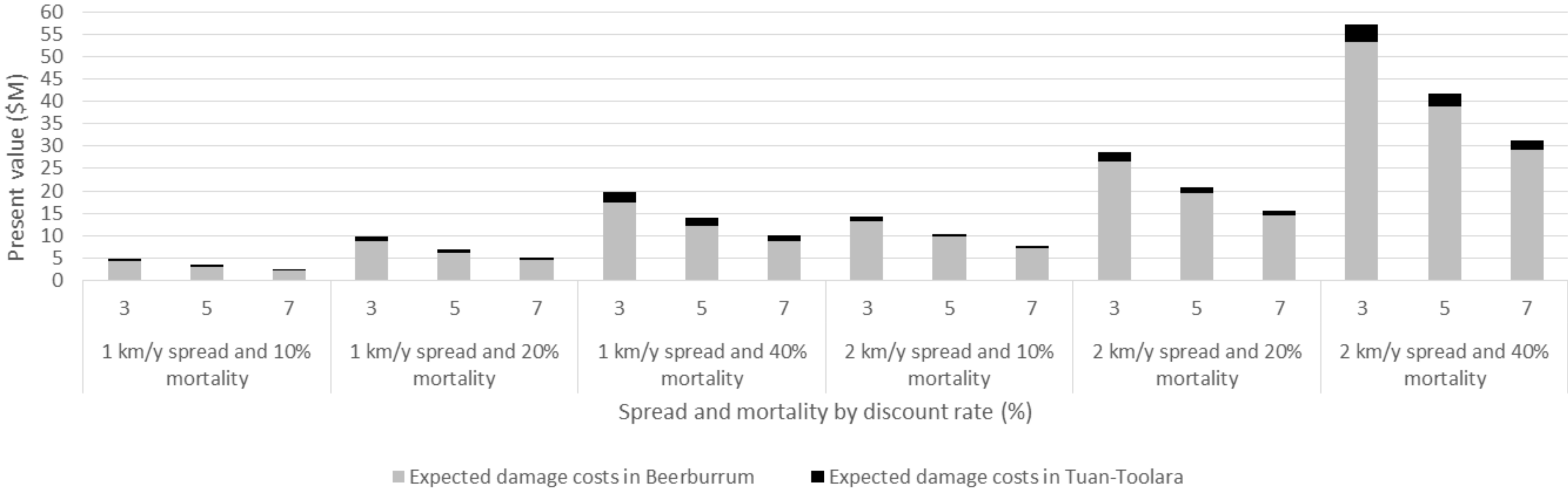
Table 4: Expected present value of damage costs in the Beerburrum estate by annual probability of establishment of pine wilt disease.

Spread rate (km/y)	Mortality rate (%)	Expected present value of timber damages ($ M) by annual probability of establishment		
		0.01	0.05	0.1
1	10	0.6	3.1	5.8
1	20	1.2	6.1	11.6
1	40	2.5	12.3	23.1
2	10	1.9	9.7	18.0
2	20	3.9	19.5	35.9
2	40	7.8	38.9	71.8

Table 5: Expected present value of timber damages in the Tuan-Toolara estate given a 5% per annum chance of establishment of pine wilt disease at Beerburrum

Spread rate (km/y)	Mortality rate (%)	Expected present value of timber damages in Tuan-Toolara ($ M) by annual probability of spread from Beerburrum		
		0.01	0.05	0.1
1	10	0.1	0.4	0.8
1	20	0.2	0.8	1.7
1	40	0.3	1.7	3.4
2	10	0.1	0.7	1.5
2	20	0.3	1.5	2.9
2	40	0.6	2.9	5.8

Figure 12: Sensitivity of present value of damage costs to the discount rate (3, 5 or 7%) for each spread rate given a 5% per annum chance of establishment in Beerburrum and a 5% per annum chance of accidental transport to Tuan-Toolara.



Discussion

The economic analysis revealed substantial expected present value of damage costs due to pine wilt disease, even at low probabilities of establishment, and low rates of spread and mortality. This translates into high expected benefits from biosecurity programs. For example, the expected present value of damage cost within the study area, given a 5% per annum chance of establishment at Beerburrum, a 5% per annum chance of accidental transport to Tuan-Toolara, 20% tree mortality, and a 1 km/y spread rate is $6.9 M. If the time value of money is 5%, this implies it is economically efficient to spend up to $0.35 M/y on biosecurity to keep pine wilt disease from establishing at Beerburrum.

In the event that pine wilt disease did establish at Beerburrum, and it was detected early due to a well-funded biosecurity program, eradication may be possible. The eradication program would need to remove and destroy all *Pinus* trees within about 5 km from the established population. In this study, we simulated an initial population in 82 ha located at the centre of the concentric circles in Figure 8. There are 2,181 ha of *Pinus* plantation within 5 km of this initial infestation and an unknown number of wildling and other planted *Pinus* trees scattered along roadsides, within patches of remnant native forest/riparian zones and on semi-rural properties. Contractor estimates provided by HQPlantations to push all plantation trees on these 2,181 ha over utilising scrub chains and blade pushers, heaping and burning amounted to $2.05 M. Contractor costs would be double if the trees had to be chipped because of air quality concerns with the burning. The cost to destroy wildling trees is unclear, but given their scattering over the landscape across multiple tenures, this cost is likely to be high.

For illustrative purposes, we assume burning is permitted and the total cost to destroy all trees (including wildlings) is $6 M. The present value of foregone timber revenues from the 2,181 ha of plantation that would be destroyed, even with the arrival of the disease (given 20% mortality and a spread rate of 1 km/y) is $24 M. Therefore, the total cost of eradication would be $30 M. The sum of the present value of annual damage costs over the 30-year simulation for Beerburrum and Tuan-Toolara when tree mortality is 20% and the spread rate is 1 km/y is $65 M when the pest arrives with certainty (Figure 11). Therefore, the eradication program described would be economically efficient even if the probability of success was only 50%.

The expected value of HQPlantations' estate is increased with increased forest pest biosecurity. Consequently, economically sound biosecurity policy would encourage cooperative control programs with HQPlantations. Of course, since the pest is lethal for many northern hemisphere coniferous species that may be grown outside commercial plantations, there are broader social benefits associated with keeping pine wilt disease out of southern Queensland, and a taxpayer-contribution to a biosecurity program would be justified, according to a cost-sharing arrangement decided by a categorisation for this pest.

A limitation of this analysis that will be addressed in future publications is that it did not account for the export market. If pine wilt disease does establish in southern Queensland, the export market will be lost. This market is worth approximately $4 M/y. The expected present value of losses arising from losing the export market (lost sales revenue) are likely to be high, because as soon as the pest establishes in Beerburrum, access to the export market would cease, and there is presently no demand from local wood processors for the logs that are presently exported.

Discussion

Our pest risk assessment revealed that there is a small but real chance of pine wilt disease establishing in Australia. *Monochamus* species and pinewood nematodes are common intercepts worldwide, although no *Monochamus* spp. have yet established outside of their native (country) ranges. *Monochamus* spp. have been intercepted 35 times in Australia since 2008, making them a frequent high-priority intercept, with the highest frequency of intercepts into the port of Brisbane. Three incursions of *Bursaphelenchus* spp. nematodes have occurred since 2000 in Australia, indicative of border breaches by *Monochamus* spp., but without beetle establishment. *Bursaphelenchus sexdentati/vallesianus* has established in NSW. Therefore, pine wilt disease has been and is likely to continue to be a threat to Australia's softwood plantation estate.

Here we examined a scenario with an introduction of *M. alternatus* carrying *B. xylophilus* through the port of Brisbane, with infested pallets transported to Caboolture and subsequent establishment on urban pine trees there and movement into the nearby Beerburrum plantation estate. Our estimate of spread rate, and subsequent impact, is conservative because of the likelihood of *M. alternatus* having multiple generations per year, based on the CLIMEX model (Figure 7). Thus, under our scenario, a spread rate of 1 km *per generation* would result in a 2 km per year geographical spread. In southern China, *M. alternatus* has 2–3 generations per year and two generations per year in Taiwan. In subtropical Okinawa, Japan, the beetle is thought to have a single generation per year. There is thus considerable plasticity in its lifecycle and ability to exploit favourable climates. Further modelling, using a process based predictive system such as DYMEX could clarify the likely voltinicity of *M. alternatus* in southeast Queensland and other at-risk regions.

Much of south-east Queensland experiences periodic extreme temperatures and drought (www.bom.gov.au). Queensland has experienced an increase in mean temperature above the long-term average over the past 35 years, and lengthy periods of below-average rainfall, generally running for 3–5 years. These are all conditions highly conducive for pine wilt disease outbreaks, and are likely to put the *Pinus* spp. planted in this region under extreme stress, increasing their susceptibility. Complicating our analysis is the unknown status of the susceptibility of *Pinus* germplasm to *B. xylophilus* in Australia generally, but more specifically the hybrids between *P. elliottii* and *P. caribaea* grown in southeast Queensland. Given the significant potential economic risk posed to by pine wilt disease to these plantations in particular, it is a matter of high priority to characterise host tree susceptibility, preferably using molecular genetic approaches that could identify genetic markers of resistance in current and future deployed germplasm.

We used relatively conservative estimates of impact for our economic analysis of the impact of pine wilt disease in south-east Queensland. These revealed significant financial costs of establishment of pine wilt disease. These damage costs are likely to be mirrored, in relative terms, if the disease spreads to softwood plantations in the high risk areas of northern NSW. Other costs associated with establishment of a new pest have not been modelled here, such as on-going management and research. Potential long-term management if pine wilt disease established in Australia could include biological control, with the parasitic wasp, *Scleroderma guani,* used operationally in China to control *M. alternatus*, being particularly effective in subtropical regions (Xu et al. 2002; Zhao 2008).

Our analysis revealed that a large proportion of the softwood estate in Australia is not at risk from pine wilt disease. While this was a positive outcome, it has the potential to downplay the ongoing risks of biosecurity threats to Australia. For example, growers in temperate regions not at risk from pine wilt disease may not see the need for increased biosecurity programs to reduce the risk of pine wilt disease as identified in this study. We therefore recommend further pest risk assessments and damage cost estimates be conducted on other high priority pests that would cover a broader range of both softwood and hardwood growers.

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5. Case Study - Sirex woodwasp (*Sirex noctilio* Fabricius [Hymenoptera: Siricidae])

Summary

The sirex wood wasp (*Sirex noctilio* Fabricius [Hymenoptera: Siricidae]) and its symbiotic fungus *Amylostereum areolatum* (Fr.) Boiden, cause the death of softwood trees through a combination of a phytotoxic mucus produced by the wasp and white rot induced by the fungus (Neumann et al. 1987).

This study sought to detail the spread of sirex within Australia and quantify and evaluate the investment made in its control over a 62-year period. We estimate that there is around 366,000 hectares of *Pinus* plantation within Australia that is susceptible and exposed to the threat of sirex (for definition see Key Terms on p150). Sirex is not present in Western Australia and is yet to pose a direct threat to the majority of the *Pinus* plantations in Queensland, however, 50% of the *Pinus* trees within both of these softwood estates (144,000 hectares) remain susceptible to attack if sirex spreads to them (**Figure 1**).

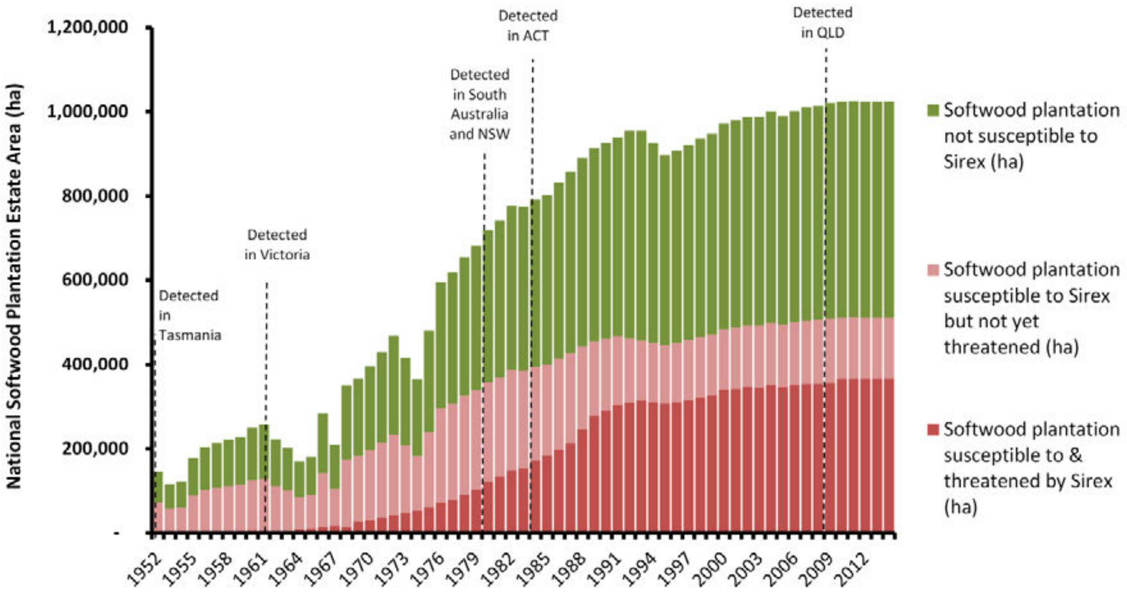

Figure 1: National softwood plantation estate showing the year sirex was detected in each state and the proportion of the estate that is 'non-susceptible' to an outbreak 'susceptible but not yet threatened' and 'susceptible and threatened' (Source: Plantation areas - historic ABARES and BAE publications and National Forest Inventory data)

All known expenditure on sirex control between 1952 and 2014 was captured (**Figure 2**). Using 1952 as the baseline for discounting, total expenditure on sirex control in Australia had a net present value (NPV) of $11.8M or $44.78 per hectare[6].

Ten percent (10%) of the investment (NPV $1.2M) in the national sirex control program has been spent on research. Useable products arising from this research have included an effective biological control and an efficient trap tree technique. Investment in sirex research has been cost effective (i.e. there have been no major outbreaks since the Green Triangle outbreak, due

[6] NPV of annual costs per hectare in $2015s using a 7.5% discount rate and a 1952 baseline for discounting (based on the area of national softwood plantation that existed at the time the expenditure was incurred).

to implementation of the national sirex strategy), but not particularly timely with 30 years elapsing before the major benefits were realised.

Ninety percent (90%) of the investment in the national sirex control program has been directed to operational management. Much of this expenditure occurred in two distinct investment spikes. We concluded that these ‘spikes’ may have been avoided had more investment been directed to finding a biological control in the 1950s and 1960s. The first investment spike, in the 1960’s and early 1970s, was generated by a state-wide surveillance and (physical) eradication program in Victoria. This program most likely slowed the progress of sirex but was very high cost and ultimately did not halt the spread of the pest. The second investment spike in the late 1980s occurred in the Green Triangle in response to a major sirex outbreak. Being a ‘reactionary’ rather than a ‘preventative’ program greatly inflated its cost.

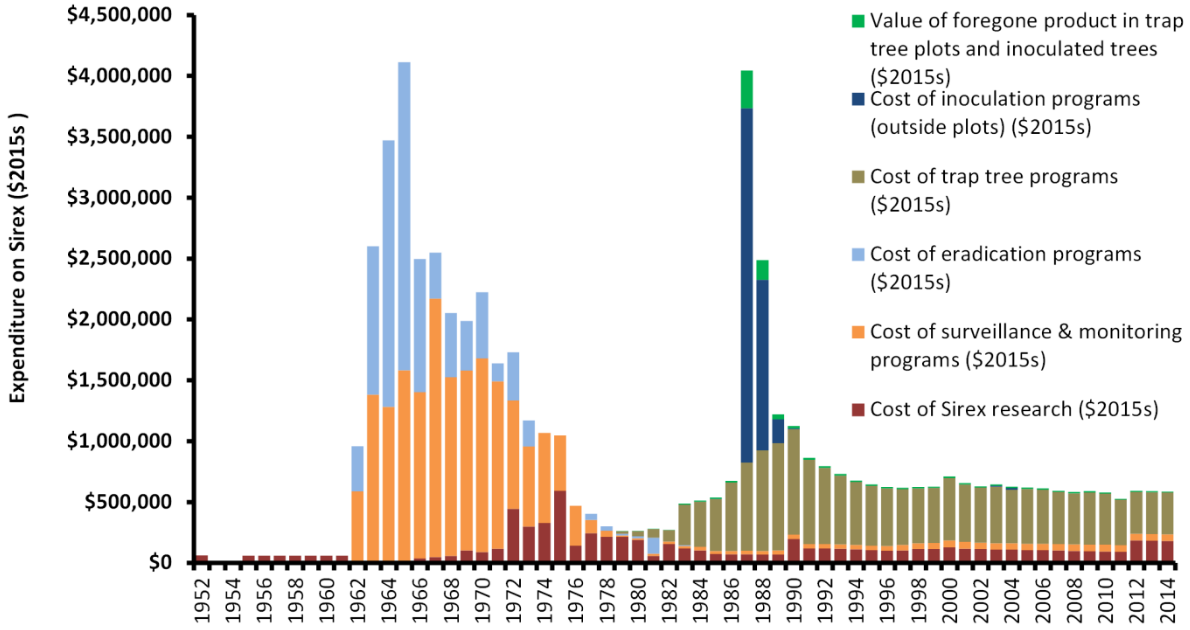

Figure 2: Expenditure on sirex control in Australia (1952-2014) by expenditure type

To evaluate the benefits of the national sirex control program we initially sought to quantify the avoidable loses that would have arisen under a national ‘no control’ scenario. Investigations into the nature of sirex outbreaks revealed that the complex interaction of plantation age, market and environmental factors (e.g. drought) made this task problematic. We therefore followed an alternative method which involved examination and summary of sirex impacts arising from individual outbreaks. For each case study we sought to cost the impact of sirex on the *P. radiata* plantation in terms of the loss of merchantable log value.

Outbreaks of significance that we examined included: Pittwater, Tasmania (1952-1959), Delatite, east-central Victoria (1972-79) and the Green Triangle, Victoria and South Australia (1987-1990). Common attributes of these sirex outbreaks included below average rainfall, overstocked plantations and control measures that were largely ineffective. The sirex outbreak in the Green Triangle which peaked in 1987 was the largest on record and provided the best example of sirex’s potential to cause financial impact.

Before quantifying the financial impact of sirex we sought to understand the nature of sirex attacks. To do this we explored the significance of age and thinning status under a suite of different incidence levels. Our analysis of the nature of sirex attacks on *Pinus* plantations revealed that at low incidence levels (< 10% tree mortality) the pest has a negligible impact on the financial value of a plantation's timber products. This was due to the least valuable trees within the plantation being targeted by sirex first.

Financial analysis of the three sirex outbreaks highlighted that the loss of merchantable log value can be highly variable and very much dependent on the age at which a plantation is attacked. For example, the outbreak at Delatite had a relatively small impact as the attacked plantation was young (10-18 yrs) with only a very small proportion of trees subject to moderate to severe infestation (more than 40% mortality). In contrast, the 1987 outbreak in the Green Triangle impacted over 56,000 hectares of middle and older aged plantation. The outbreak at Pittwater, Tasmania, was a good example of a worst-case scenario where in one compartment over 50% of mature trees (32 years old) were killed.

The results of our financial impact analysis as well as the value of the national sirex control program is provided in Table 1.

Table 1: Cost of national sirex control (NPV @7.5%DR) and estimated value (at time incident occurred and as an NPV) of merchantable timber loses arising from sirex attack for three case studies

Costed Item	Time Period	Net Present Value at the time the incident occurred *		Net Present Value using 1952 as the baseline for discounting *	
		$2015s	$2015s per hectare	$2015s	$2015s per hectare
National sirex control program	1952-2014	n/a	n/a	$11,808,294	~$90
The sirex outbreak at Pittwater, Tasmania	1952-1959	$4,859,000	$4,429	$4,859,000	$4,429
The sirex outbreak at Delatite, Gippsland Vic	1972-1979	$354,660	$300	$54,099	$46
The sirex outbreak in the Green Triangle, Vic & SA	1985-1990	$23,842,776	$422	$1,641,510	$29
			Total Cost of sirex management	$18,362,903	

~ calculated by dividing the annual program cost (in $2015s) by the area of susceptible plantation that existed in that year then discounting back to 1952 to generate a NPV
* NPV based on 7.5% discount rate

For the three sirex outbreaks that we studied the combined cost of the damage had an NPV of $6.5M ($2015s@7.5%DR). Other uncosted sirex outbreaks that occurred within Victoria in the 1960s and early 1970s would add to this cost. When the direct costs of the national sirex control program ($11.8M) are combined with the impact of sirex outbreaks ($6.5M) the total cost of sirex management is greater than $18.3M (NPV $2015s@7.5%D).

Since the 1990s, monitoring and biological control of sirex has proven effective, with small outbreaks periodically occurring in Tasmania, Victoria, South Australia and New South Wales having been effectively contained. Had these outbreaks not benefited from sirex control intervention it may be assumed that greater merchantable timber loses would have ensued.

In summary, our study was unable to estimate the effect of sirex in the absence of a control program or draw any definitive conclusions about the control program's effectiveness. Our study was however able to:

- Show how sirex has been able to progressively invade *Pinus* plantations across the east coast of Australia, and in places cause major damage, despite concerted efforts at its eradication and then management;
- Quantify the extent of *Pinus* plantations which are susceptible to the threat of sirex attack;

- Model the financial impacts of sirex attack and show how these vary with incidence, age and thinning status as well as identify the thresholds beyond which sirex has a serious financial impact;
- Show how individual investment decisions have influenced the overall cost of the national sirex control program;
- Confirm that plantation growers are now well positioned to manage sirex in a cost-effective manner.

Key Findings

- The incursion and establishment of a significant exotic pest (viz. sirex) adds cost to plantation management, both in terms of control and ongoing management. In sirex's case it cost $11.8M, $44.78 per hectare[7] or $0.72 per hectare per year[8] This cost increased to more than $18.3M when the impact of sirex outbreaks were included. This finding emphasises the need to implement effective (biosecurity) measures that can reduce the likelihood of new exotic pests (like sirex) establishing within Australian plantations.
- The performance of forest health programs such as the national sirex control program have to be measured over many decades. Using discounted cashflow analysis to measure performance over periods greater than 30 years does however have its limitations;
- High level investment decisions made early in the life of the program have a major bearing on future performance. Possibly the most important decision is the one that apportions expenditure between research and operations;
- Decision making and management at a regional, state and national level all contributed to the overall performance of the national sirex control program;
- We found that preventing sirex outbreaks is more cost effective than post outbreak treatment. Investing a very high proportion of expenditure on physical eradication over many years rather than investing in research was found to be neither cost effective nor cost efficient;
- The national sirex control program has been successful in delivering a suite of tools and knowledge that (if applied correctly) are highly effective in preventing sirex outbreaks. In particular, investment in the research of sirex biological controls and trap tree techniques has proven to be a justified and cost-effective investment;
- Limited investment in research in the 1950s and 1960s extended the time required to develop and deliver an effective biological control and a reliable trap tree technique;
- Plantation growers are now benefitting from the historic investment that was made in developing biological controls and effective monitoring and surveillance techniques.

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[7] NPV of annual costs per hectare in $2015s using a7.5% discount rate (based on the area of national softwood plantation that existed at the time the expenditure was incurred). Note, does not include costs of sirex outbreaks.

[8] NPV of annual costs per hectare in $2015s using a7.5% discount rate (based on the area of national softwood plantation that existed at the time the expenditure was incurred), divided by 62 (being the duration of the national sirex program in years). Note, does not include costs of sirex outbreaks.

Key Terms

Plantation susceptible to sirex –*Pinus* plantation over 10 years of age that is either unthinned and or periodically subject to drought stress. Includes *Pinus* plantations in Western Australia and Queensland that are not currently threatened by sirex.

Plantation susceptible to and threatened by sirex - *Pinus* plantation over 10 years of age that is either unthinned and or periodically subject to drought stress and located within sirex's known distribution. Excludes *Pinus* plantations in Western Australia and Queensland (with one small exception).

About Sirex

The sirex wood wasp (*Sirex noctilio* Fabricius (Hymenoptera: Siricidae)) and its symbiotic fungus *Amylostereum areolatum* (Fr.) Boiden, cause the death of softwood trees through a combination of a phytotoxic mucus produced by the wasp and white rot induced by the fungus (Neumann et al, 1987).

Plantations that are moisture stressed by drought or because thinning has been delayed (often due to market failures) are particularly susceptible to sirex attack. Numerous studies (Eldridge, 1987; Haugen et al., 1990; Madden, 1975; McKinn et al., 1990) have found that sirex targets weaker trees (usually suppressed trees with smaller diameters) within these plantations.

Neumann et al. (1987) describe sirex as a secondary wood-boring pest of which prevention of economically important outbreaks is largely a management problem that can be alleviated by routine surveillance and the application of timely silvicultural measures. The evidence that was compiled for this study directly supports this view.

Since 1990 applied control measures in combination with improved forest management have proven effective in keeping sirex under control within Australian *Pinus* plantations. The use of a nematode (*Beddingia siricidicola*) is the primary biocontrol agent that is used to manage sirex populations along with parasitoid wasps (e.g. *Ibalia leucospoides*) which attack sirex larvae. Sirex, however, remains an opportunistic pest that under the right settings – low or no surveillance, prolonged drought and or a limited market for plantation thinnings – still has the potential to have a major impact on plantation wood values.

Aim & Method

This study sought to detail the spread of sirex within Australian softwood plantations and quantify and evaluate the investment made in its control over a 62-year period, 1952-2014. It did this by collating existing records of expenditure from a variety of sources including peer-reviewed scientific publications, government forest management agency reports, unpublished plantation company records and data supplied by personnel with sirex management expertise.

To allow fair comparison over time all historic expenditure data was converted to $2015s using All Groups CPI Australia (Series ID A2325846C). In the interest of costing consistency, current industry rates were used for common recurrent expenditure items (e.g. trap tree plots were costed at $850 per plot). Costs incurred on sirex control were able to be grouped and classified and profiled over time as well as converted to a single net present value (NPV in $2015s).

To evaluate the benefits of the national sirex control program our goal was to quantify the avoidable losses that would have arisen under a national 'no control' scenario. Investigations into the nature of sirex outbreaks revealed that the complex interaction of plantation age, market and environmental factors (e.g. drought) made this task problematic. In particular, to reliably predict a major outbreak it would have been necessary to have detailed knowledge of plantation age class, stocking density, thinning status and seasonal moisture stress levels. This information was needed for all of the affected major *Pinus* plantation estates over the 62-year period that sirex has been in Australia. These modelling input requirements were well beyond the resourcing capabilities of this study; as such it was necessary to find an alternative approach.

Our alternative method involved examination and quantification of sirex impacts arising from individual outbreaks. To do this we developed a model that took into account the relationship between plantation age, thinning status and incident mortality level. Sirex outbreaks that we costed included Pittwater, Tasmania (1952-1959), Delatite, east-central Victoria (1972-79) and the Green Triangle, Victoria and South Australia (1987-1990) (**Figure 19**). The costing of these outbreaks did not assist us to generate a benefit-cost ratio (BCR) but did allow us to estimate the total cost of sirex management in Australia.

Sirex spread and management

The native habitat of the sirex wood wasp includes Europe, southern Russia, Siberia, and Mongolia (in green in Figure 3). Sirex has been introduced and is now established within southern South America, South Africa, north east USA, New Zealand and south east Australia (in dark blue in Figure 4). Since the map was last updated in 2014 sirex has also become established in Canada and China.

Initial concern about the potential impact of sirex in Australia was triggered by the damage the pest had caused in New Zealand. In New Zealand between 1946 and 1951, 20 to 33% of intermediate-age *P. radiata* trees were killed by *S. noctilio* in 120,000 hectares of overstocked plantations, following a severe drought in 1946 (Rawlings 1948, 1955, NZ Forest Service 1974 as cited in Neumann & Minko, 1981).

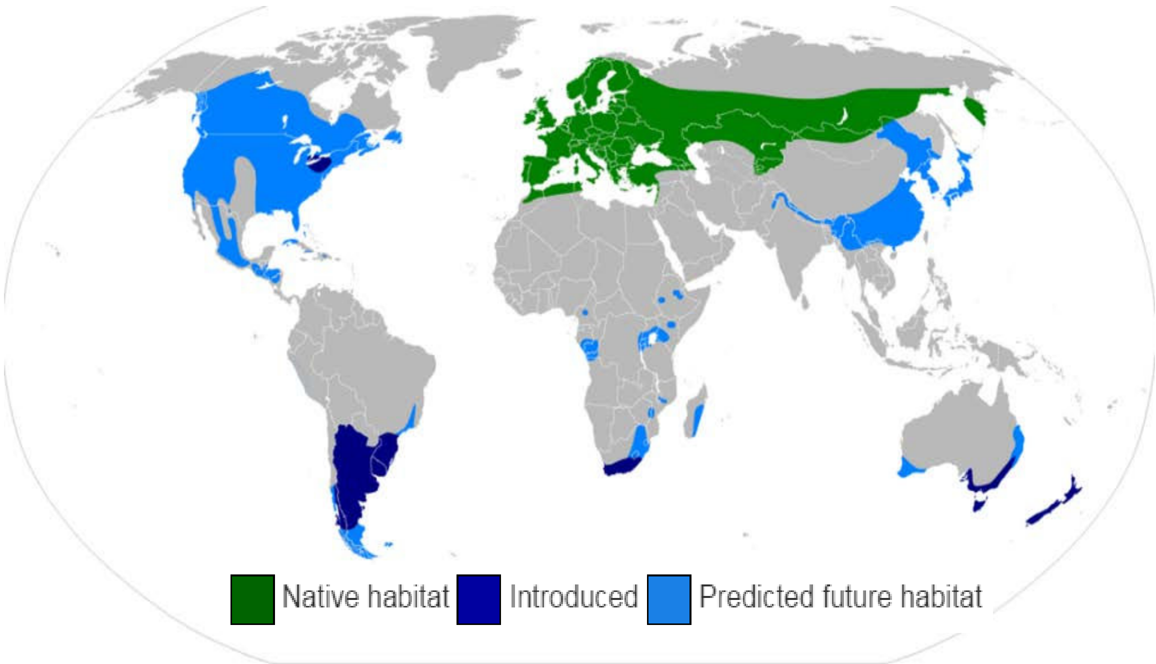

Figure 3: Global distribution of Sirex wood wasp (Source: https://commons.wikimedia.org/wiki/File:Sirex_noctilio_distribution.PNG)

The first official record of sirex in Australia was in 1951 in a *P. radiata* plantation (1,092 hectares) at Pittwater Tasmania (Gilbert and Miller 1952), 20 kilometres east of Hobart. At the time, there was only about 4,000 hectares of *Pinus radiata* plantation in Tasmania and the entire national softwood estate was less than 150,000 hectares (ABARES, 2016 unpublished). Between 1952 and 1959 sirex spread throughout Tasmania, however many *P. radiata* plantations were not impacted due to their young age (< 10 years). By 1961 sirex had killed 40% of the standing trees within the Pittwater plantation and this led to the establishment of the National Sirex Fund.

In 1961 sirex was first detected on mainland Australia within a farm woodlot east of Melbourne, Victoria (Irvine 1962). By 1963 the Forests Commission Victoria reported that sirex infestations had been found on 534 properties and that they had been involved in the destruction of 9,911 trees, together with logs and other debris infested with sirex.

By 1977 sirex had reached the Green Triangle and by 1979 it was present in all plantations in Victoria (Neumann et al. 1987; Collett and Elms 2009). In 1980 sirex was detected in South Australia and near Albury in southern New South Wales (NSW) (Eldridge and Taylor 1989). Following its arrival in southern NSW the pest spread north and east. By 2002 sirex had reached Tenterfield in the state's far north and was present in all of the state's major *P. radiata* plantations (Carnegie et al., 2005). Sirex was detected in *P. radiata* plantations near Stanthorpe in south eastern Queensland in 2009 and remains only within these tableland plantations to this date.

Figure 4 highlights the growth of the national softwood plantation estate between 1952 and 2014 and identifies the years when sirex was first detected within each state. The graph also shows the area of the national softwood estate that is susceptible to and threatened by a sirex outbreak (red) as well as the proportion of plantation that remains susceptible to sirex but is not yet directly threatened by an outbreak (pink) [refer definitions under Key Terms page 150.

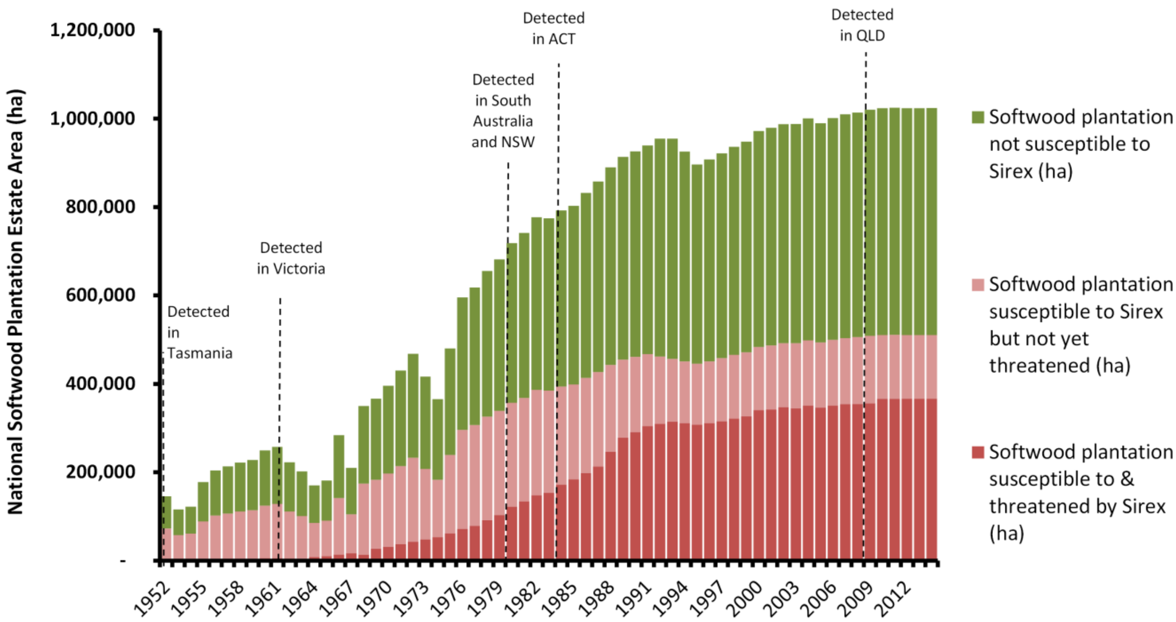

Figure 4: National softwood plantation estate showing the year sirex was detected in each state and the proportion of the estate that is 'non-susceptible' to an outbreak 'susceptible but not yet threatened' and 'susceptible and threatened' (Source: Plantation areas - historic ABARES and BAE publications and National Forest Inventory data)

We estimate that there is around 366,000 hectares of *Pinus* plantation within Australia that is currently susceptible and exposed to the threat of sirex. Sirex is not present in Western Australia and is yet to pose a direct threat to the majority of the *Pinus* plantations in Queensland, however, 50% of the *Pinus* trees within both of these softwood estates (144,000 hectares) remain susceptible to attack if sirex spreads to them (**Figure 5**). Here we assume that the *P. caribaea x elliottii* hybrids planted in subtropical eastern Australia are equally susceptible to sirex as *P. radiata*; *P. pinaster* is already known to be susceptible to sirex under Australian conditions.

In the event of a major sirex outbreak plantations of all ages and silvicultural status can be prone to attack. In general, however, thinned plantations and plantations that are less than ten years of age have much lower susceptibility. Based on the actual extent of Australia's largest sirex outbreak in the Green Triangle (1987-1990) we used 50% as being a reasonable estimate of the proportion of pine that is generally 'non-susceptible' to sirex attack in the event of an outbreak (Figure 5). This encompasses much of the younger estate (<10 years old) and the older, thinned estate.

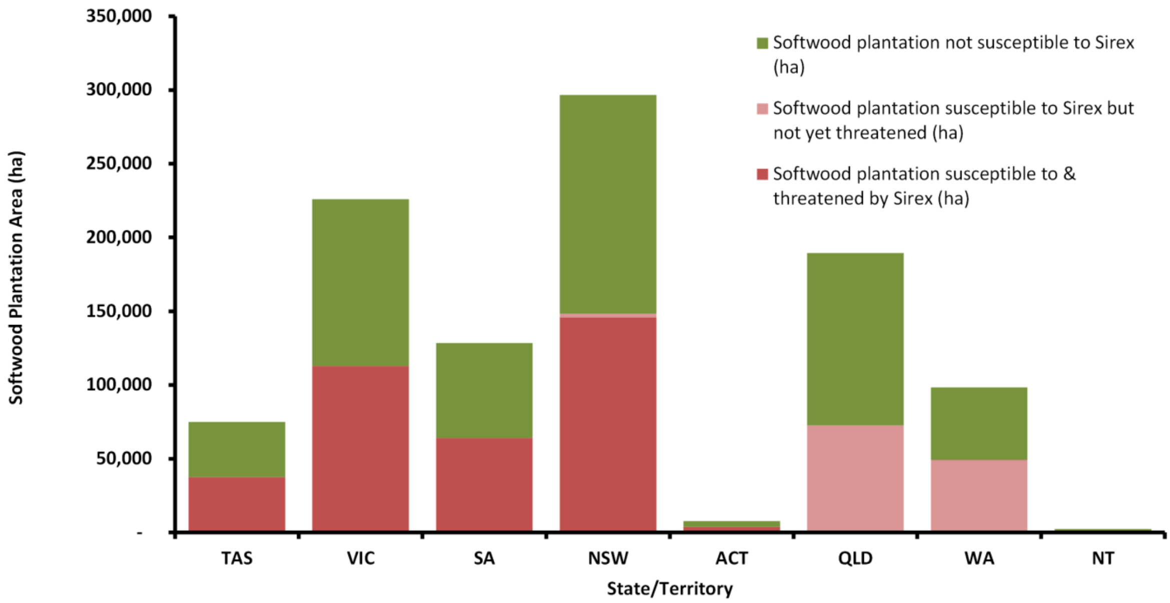

Figure 5: Current area of softwood plantation by State showing extent to which plantations are susceptible to and threatened by a sirex outbreak (red) and susceptible to but not yet threatened by a sirex outbreak (pink)

Investment in Sirex Control

Expenditure on sirex control in Australia has been ongoing for 65 years (1952-present). Major investment spikes occurred in the 1960s in Victoria and in the late 1980s in the Green Triangle (South Australia and Victoria).

Initial investment in sirex control in Australia was limited to a small Hobart-based CSIRO entomology team who worked part time on sirex between 1952 and 1961. The role of this team, to receive and test parasitoids, continued until 1980.

Major investment in sirex control was initiated in 1961 when sirex was discovered in Victoria. The formation of a National Sirex Trust and Committee enabled funding for survey and eradication (aka the National Sirex Fund) and later for research and control and management strategies. Locations of dying trees were mapped from fixed-winged aircraft during October of each year; then ground checks were used to determine the presence of sirex in a sample of these trees (Neumann et al., 1987). These trees were subsequently destroyed. In 1963 a sirex biological control unit was established by CSIRO (8 staff) at Silwood Park in the United Kingdom. Between 1962 and 1972 a world-wide search for natural enemies of sirex was conducted. Twenty-one species of parasitoids were imported, ten were released in Australia and five became established (Taylor 1976). A search for effective nematodes was also conducted and several imported and released in Australia (Bedding 2009). In the late 1970s a trap tree technique was developed (Neumann et al 1982) that greatly improved the efficiency of introducing the parasitic nematodes into sirex populations over large areas of susceptible plantation (Haugen, 1988). For the Green Triangle, however, use of this technique was infrequent up until 1985 (Haugen, 1988).

When a major sirex outbreak occurred in the Green Triangle in 1987 the forest owners embarked on a massive nematode inoculation project known as SWAT (Sirex Wasp Assault Team). During the 1987 SWAT program 147,000 tree equivalents were inoculated (Haugen, 1988).

In 1990 a voluntary levy on major *Pinus* growers was introduced to ensure ongoing availability of funds for sirex research. The fund was initially set at $0.16 per hectare then reduced to $0.10 per hectare before being increased to $0.11 per hectare in 1998. The levy continues to operate and currently generates about $85,000 per year. This voluntary levy picks up most of the major pine growers in each state, including WA and Qld, as well as many much smaller growers (<2000 ha). A few moderately sized plantation growers do not contribute. Details of the operational management of the national sirex fund have been documented by Carnegie and Bashford (2012).

Today, management of sirex by individual growers is focused on preventing outbreaks through silviculture, surveillance and monitoring and the use of trap tree plots.

Valuing the Impacts of Sirex

Within Australia, attempts to quantify the financial impact of sirex beyond the local scale have been limited.

To assist in valuing the impacts of sirex, we divided the trees within a plantation into three broad classes based on their life span and end use:

- T1 - First thinning trees that produce pulpwood only when harvested at around age 14 and represent 53% of initial stocking;
- T2 – Second thinning trees that produce 50% pulpwood and 50% sawlog when harvested at age 23 and represent 26% of initial stocking, and;
- CF – Clearfall final crop trees that produce 20% pulpwood and 80% sawlog when harvested at age 32 and represent 21% of initial stocking

It is acknowledged that not all *Pinus* plantations are subject to the above regime, however all plantations will have trees that may be classified into one of the above three product mix categories (i.e. trees that produce just pulpwood, trees that produce a mix of pulpwood and sawlog and trees that produce predominantly sawlog).

Although sirex is distributed over large plantation areas, and usually kills the trees that it attacks, the percentage of trees that succumb to this pest is typically very small. Trees that are attacked are often the smaller and weaker ones which are under moisture stress. Graphical interpretation of an analysis undertaken by Carnegie et al. (2005) on the extent and severity of sirex outbreaks in NSW between 1981 and 1996 illustrates the frequency/extent of different incidence levels (Figure 6). It reveals that over 80% of the area affected by sirex had mortality incidence of less than 10%. Mortality incidence of less than 10% within unthinned plantation may be assumed to have limited financial impact (Figure 11). Interestingly, incidence where mortality reached 20% or more all occurred between 1994 and 1998 which was during the millennium drought.

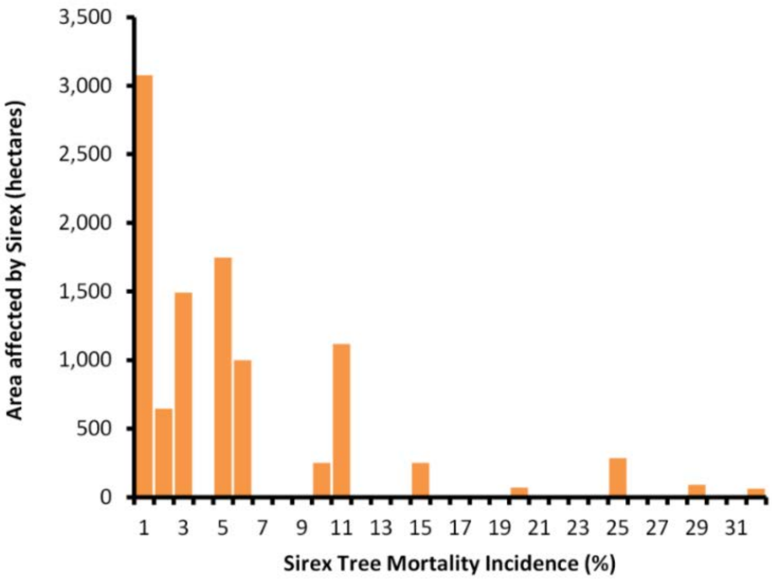

Figure 6: Area and incidence of sirex mortality in *Pinus radiata* plantations in New South Wales. Data collection from 1981 to 1995 by Forestry Corporation regional and research staff, 1996–2005 by the Forest Health Survey Unit. Damage of less than 1% not reported here.

Understanding the significance of 'incidence' is critical to financial impact valuation. Figure **7** shows the spatial effect of six randomly generated incidence levels using GIS. Of particular note are the 20% and 30% mortality images which show that the tree deaths include some random 'clusters'. Several South American studies of sirex outbreak dynamics (Lantschner & Corley, 2015; Aparicio et al., 2013; and Corley et al., 2007) have found that the amount of 'clustering' in sirex attacks is greater than that which occurs purely by chance. The findings of these studies raise an important question concerning the extent to which 'clustering' of sirex attack may impact on the value of plantation log products (and the associated trigger points for silvicultural intervention). One of the authors, Dr Angus Carnegie, advised that clustering of dead trees attacked by sirex is not a characteristic that he has observed for sirex incidence mortality levels under 10% However, some clustering can occur when a stand has a high proportion of wildlings and these are being attacked by sirex.

When tree deaths occur in clusters the opportunity to manage the effects of mortality through silvicultural intervention are reduced. For example, if a single tree dies (within an unthinned plantation) it provides additional space and light for neighbouring trees to grow into. When this occurs, the loss of value of an isolated dead tree can (over time) be fully offset by the value that is added by surrounding live trees. In contrast when a cluster of trees dies the capacity of the surrounding live trees to exploit the resources within the newly created gap may be limited as may the ability to offset the lost value of the dead trees.

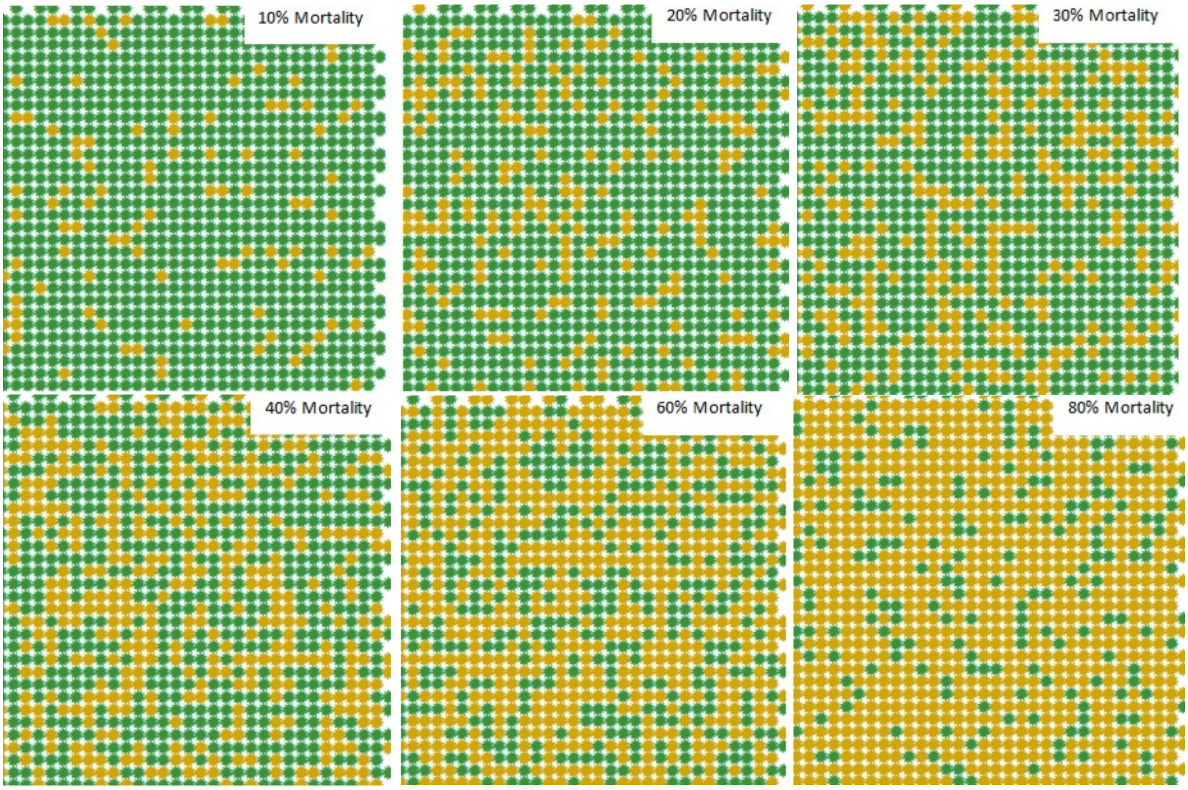

Figure 7: Visual effect of six different mortality levels on a 1 hectare (1,000 stems) block of pine (mortality randomly generated by GIS)

The ability to shift value from one tree to another (within spatial constraints) is an underlying principle of plantation silviculture. For example, a first thinning event will typically remove around half of a plantation's stems however the net return from the sale of these stems (after costs) is usually low (close to break-even). The financial benefit however is realised over the longer term as the retained stems, which are afforded more room to grow, better access to nutrients and water etc., can produce larger log products that have higher value.

The ability to offset the impacts of sirex by shifting value from one tree to another is also dependent on a plantation's age and whether or not it has been thinned. The greatest ability to offset the impacts of sirex occur when a plantation is unthinned and between 10 and 15 years of age. Fortuitously perhaps, this is also the type of stand which is most susceptible to sirex attack. At this time not all trees have developed saleable log products and where they have the value of those produced is typically low (e.g. pulpwood only). During this period there is also capacity within the plantation to shift value from one tree to another. If the plantation remains unthinned around half of the trees within the stand will maintain a higher level of susceptibility to sirex attack (Figure 8).

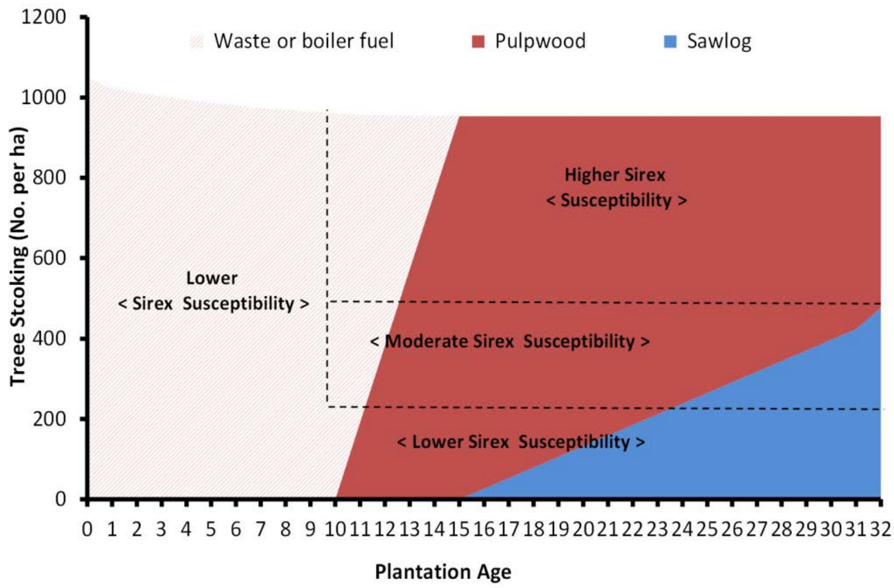

Figure 8: Relationship between product type, tree stocking, plantation age and sirex susceptibility for an unthinned *Pinus radiata* plantation

If a plantation is thinned its susceptibility to sirex is much reduced. Only in severe outbreak events (such as occurred in Pittwater in the 1950s and the Green Triangle in 1987) does sirex become less selective and a direct threat to thinned stands.

> *The class of tree initially preferred and killed by Sirex was of the smaller diameter and suppressed type, although in later years dominant trees were also attacked and killed. The data infer that, as the outbreak advanced to epidemic status, the over-abundance of insects obscured inter-tree discrimination with subsequent attack on normally healthy trees (Madden, 1975)*

In the event that a thinned plantation is attacked the potential for financial impact is high as all trees will have saleable log products and depending on their age they may contain valuable sawlogs (Figure 9).

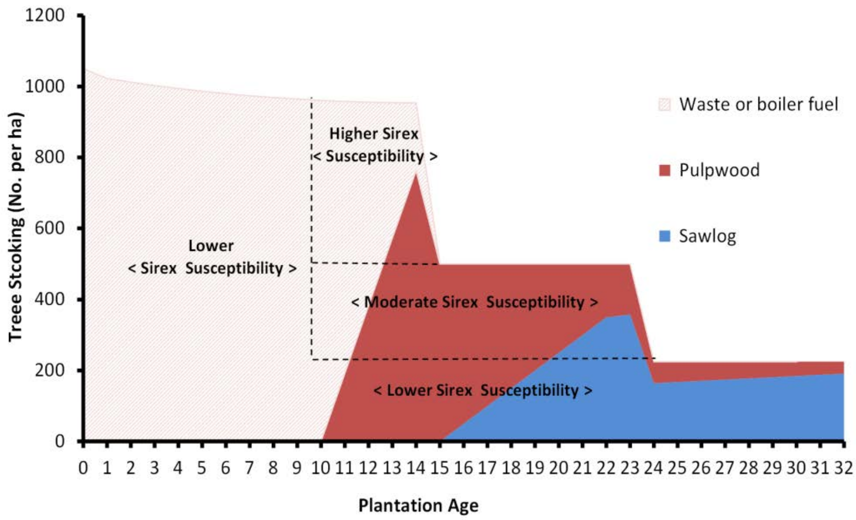

Figure 9: Relationship between product type, tree stocking, plantation age and sirex susceptibility for a Pinus radiata plantation subject to two thinnings

The ability to offset the impact of a sirex attack in a thinned stand through silvicultural intervention is limited. An exception to this includes plantations that have been subject to an early first thin which are less than three quarters grown (i.e. age 24). In this case, it may be possible to transfer value to a neighbouring tree provided that the attacks have been isolated. Using yield and royalty information for an average quality *Pinus radiata* plantation grown in central western NSW we were able to illustrate the relative value of T1, T2 and CF trees using discounted cashflow analysis (Figure 10).

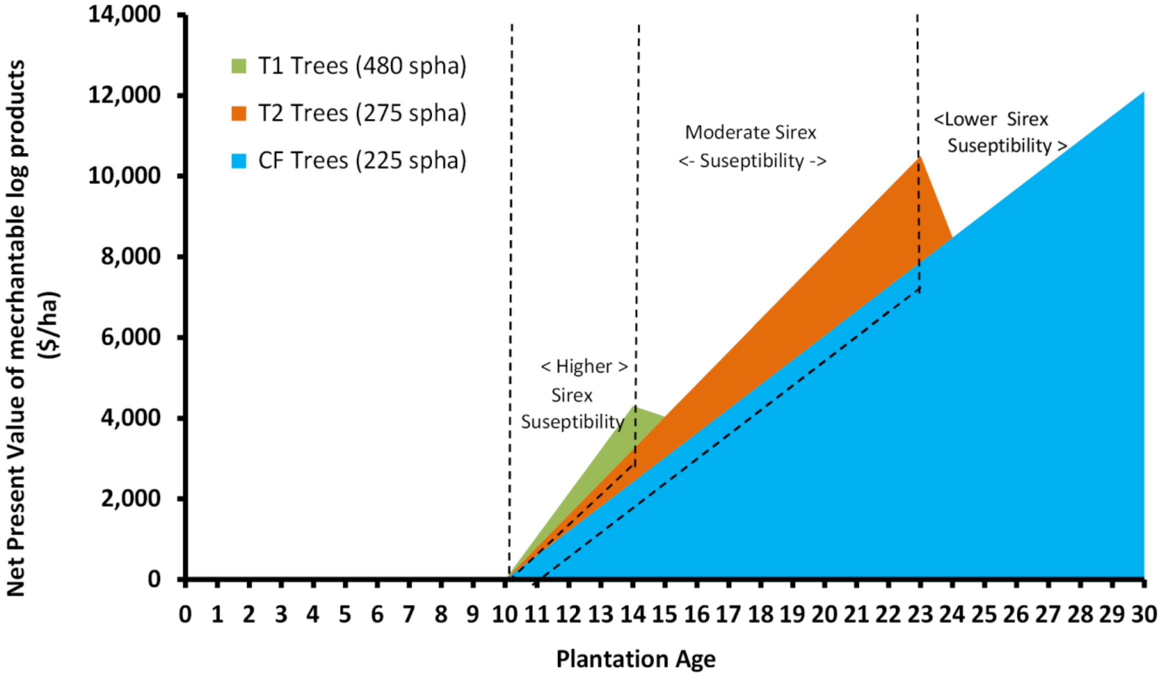

Figure 10: Relationship between tree type, tree value and sirex susceptibility for a *Pinus radiata* plantation subject to two thinnings. Note, merchantable log product NPV does not include plantation management costs

A first thinning (T1) event at age 14 will commonly remove 50% of the plantation trees with all of the merchantable timber sold as pulpwood. Using our model and a pulpwood stumpage rate of $10 per tonne we valued an individual T1 tree (at harvest time) at $2.40.
Trees removed at second thinning (T2) at age 24 will produce 50% pulpwood and a mix of small and intermediate sized sawlogs. For our analysis an individual T2 tree (at harvest time) was valued at $9.60.

Of the three tree classes, Final Crop (FC) trees are by far the most valuable. A tree aged 14 that will grow on to become a final crop tree is four and a half times more valuable ($10.80 per tree) than a tree that is harvested for pulpwood as a T1 tree ($2.40 per tree). Similarly, the value of a final crop tree aged 24 is three and a half times greater ($35.00 per tree) than a tree aged 24 that is harvested as a T2 tree ($9.60 per tree). By the time a final crop tree reaches harvest age the value of its products increased to $59.00 per tree using our analysis.

Using our understanding of tree value we were able to model the relationship between sirex tree mortality level and loss in log product value. Loss in log product value was calculated as percentage of total log product value (Figure 11) and as an actual monetary value (Figure 12) for an average quality *P. radiata* plantation grown in central west NSW[9]. The financial impact of tree mortality scenarios greater than 60% was not modelled due to uncertainties around commercial viability and the additional complexities associated with salvage

[9] Based on 2014 data supplied by Forestry Corporation of NSW

harvesting.

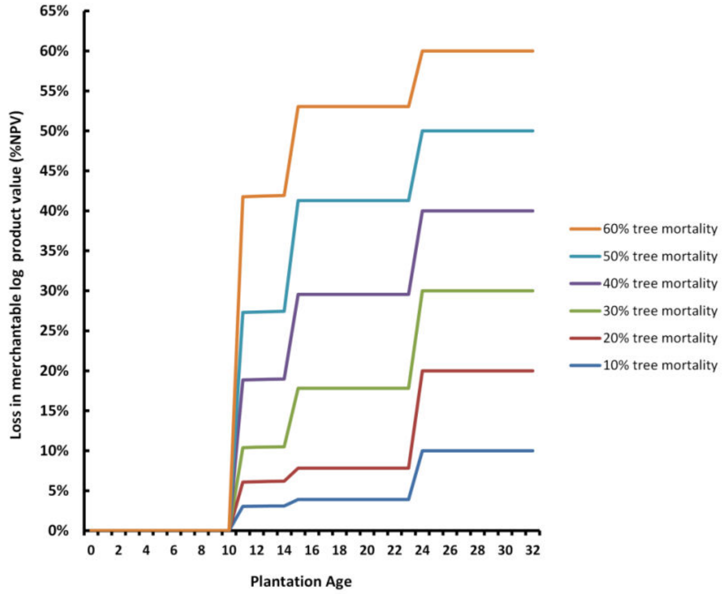

Figure 11: Percentage loss in log product value for six sirex tree mortality scenarios applied to a *Pinus radiata* plantation subject to two thinnings (with sirex risk commencing in year ten)

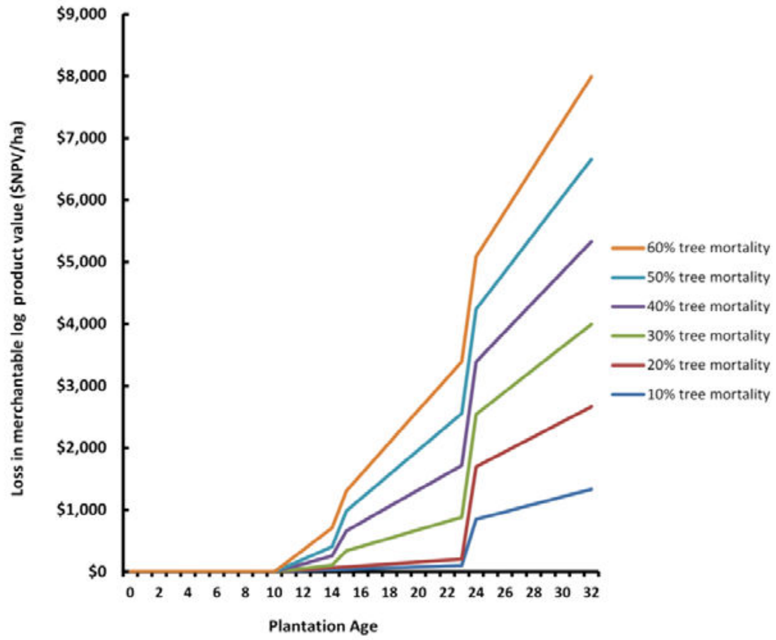

Figure 12: Log product value loss for six sirex tree mortality scenarios applied to a *Pinus radiata* plantation subject to two thinnings (with sirex risk commencing in year ten)

Applying the results shown in Figure 11 and in Figure 12 we concluded that sirex has a relatively minor impact on the product value of an unthinned plantation at mortality levels of 20% or less (e.g. 3.1% loss for 10% tree mortality at age 14 and 6.2% loss for 20% tree mortality at age 14). At 30% tree mortality levels the percentage loss of product value becomes more substantial (e.g. 10.5% loss for an unthinned stand at age 14 and 17.8% loss for a thinned stand aged 20). Sirex attack at low levels (<10%) has been referred to as a "natural thinning" by some foresters in Australia, and as such of no consequence. Our analysis would seem to corroborate this statement. But this assumes that any outbreak stops at these low levels, and does not continue to increase or spread to attack T2 and FC trees (which was the case in the Green Triangle and Pittwater). Note than any increase in sirex levels would also result in an increase in costs to control such an outbreak (e.g. increased trap tree plots and inoculation of naturally struck trees).

Results

Costing national sirex control

For this study we sought to capture and present all expenditure on sirex control between 1952 and 2014. Historical data was gathered from major growers, with some extrapolated where information was not available. The results are captured within a single graph (Figure 13) including a breakup by expenditure category (5 in total).

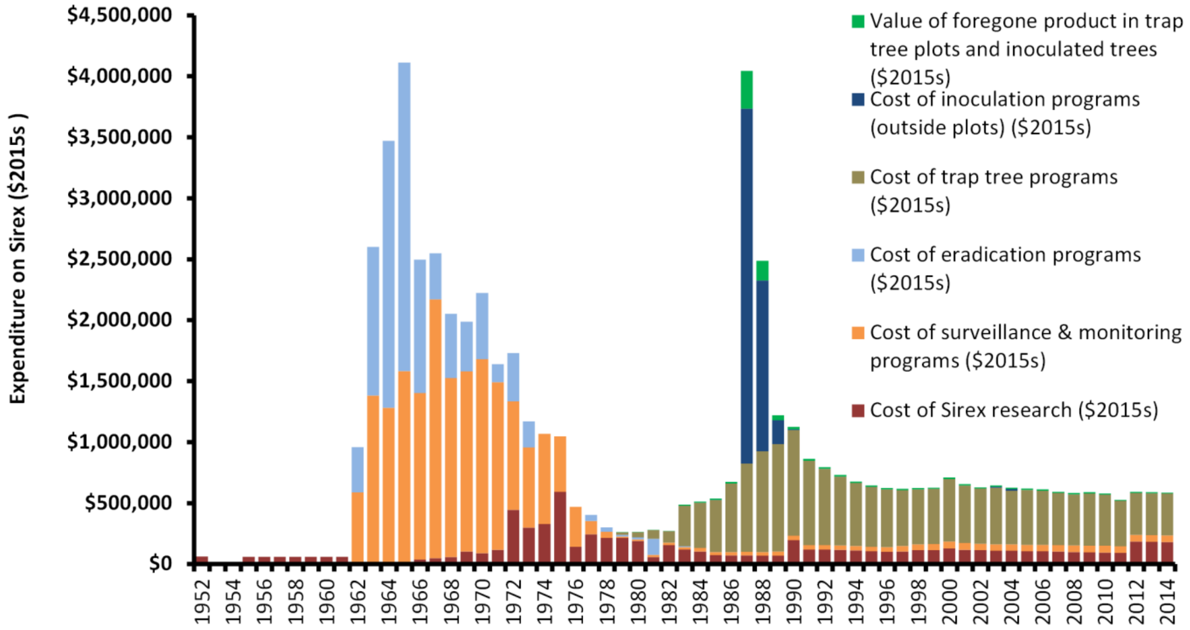

Figure 13: Expenditure on sirex control in Australia (1952-2014) by expenditure type ($2015s)

Using 1952 as the baseline for discounting, total expenditure on sirex control in Australia had a net present value (NPV) of $11.8M ($2015s@7.5%DR). 90% was spent on operational control and 10% on research (Figure 14).

Research costs (relative to operational costs) remained relatively stable over the program's 63-year duration with investment primarily directed toward the development and supply of biological controls and the development and refinement of trap tree techniques. The major benefits of this investment were not effectively realised in an operational sense until the early 1980s, when trap tree plots were established on a broad scale.

Operational control costs were incurred in five distinct areas: (1) surveillance and monitoring, (2) eradication (tree destruction), (3) inoculation programs, (4) trap tree programs and (5) product foregone in trap tree plots and inoculated trees. In the 1960s investment was limited to surveillance and monitoring and attempted eradication (falling and burning of infested trees). From the early 1980s operational controls became far more sophisticated with much greater focus on the application of biological controls in trap tree programs. When a major outbreak of sirex occurred in the Green Triangle in the mid-late 1980s much money was also spent on the direct inoculation of individual trees.

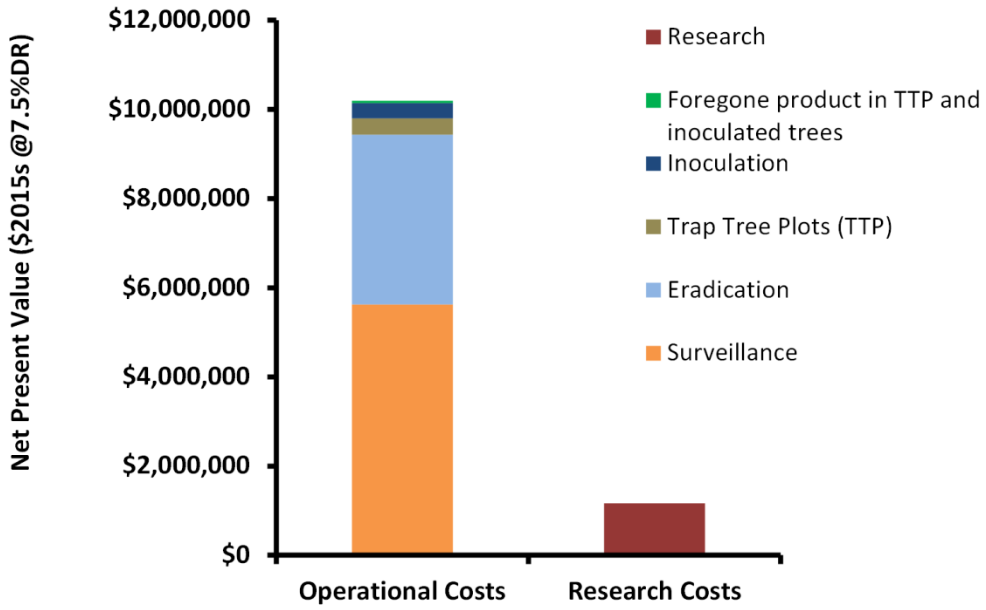

Figure 14: Net present value (NPV) of national sirex expenditure (1952-2014) using 1952 as base year for discounting and a discount rate of 7.5%

By 1990, techniques for monitoring and controlling sirex had become well refined and highly effective. National expenditure on sirex since 1990 (using 1990 as the baseline for discounting) had an NPV of $8.5M ($2015s@7.5%DR) (Figure 15). Of this 17% was spent on research and 83% on operational control.

Today, the greatest expense for sirex control is trap tree plots (TTP) [$850 average cost per plot] or their equivalent (e.g. panel traps). The cost of this activity nationally has reduced from $885,000 per year in 1990 to $350,000 per year in 2014 (note these values include the loss of product in inoculated trees). This reduction is due to better targeting and installing TTPs at lower densities. For example, in Bathurst Region (NSW) 160 TTP were established in the early 2000s, but this has now been reduced to 28 using risk analysis (Carnegie and Bashford, 2012), and with continued surveillance the risk of an outbreak is not believed to have changed. UPDATE: Recent examination of trap trees in NSW (and elsewhere) indicate that the assumptions made by Carnegie and Bashford (2012) to reduce the number of trap tree plots (i.e. that 8 or more trees per plot were attacked by sirex, and were getting infected by nematodes) may have been incorrect; in many instances current trap tree plots have only two trees attacked by sirex, resulting in significantly fewer infected females emerging from a trap tree plot. It is likely that the intensity of trap tree plots will be increased in future to accommodate this (Carnegie, pers. comm.).

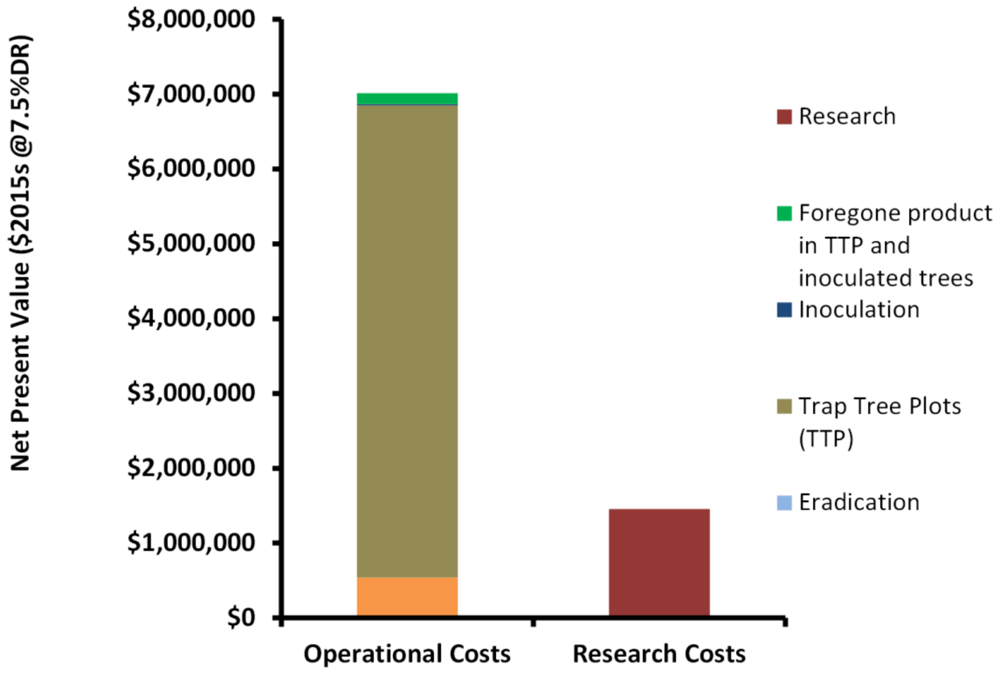

Figure 15: Net present value (NPV) of national sirex expenditure (1990-2014) using 1990 as base year for discounting and a discount rate of 7.5%

Expenditure on sirex control within Australia has been a shared responsibility although the contributions of affected parties have not always been equal. Between 1952 and 1978 the Commonwealth played a major funding role. From 1979 the State forestry agencies took control of the national program and there was a much-reduced level of investment. A spike in expenditure in the mid to late 1980s was driven by direct need (in response to the major outbreak in the Green Triangle) and shared by the private companies and public forest agencies that were directly affected. Since 1990 expenditure on sirex control has stabilised and is spread across individual major growers who contribute to the national sirex levy. These entities typically also invest in forest health surveillance and trap tree plots.

There are three ways that sirex costs were analysed on a per hectare basis. The first method involved calculating the cost using the area of national softwood plantation estate area which existed at time the expense was incurred (Figure 17). As the national area of plantation has grown ten-fold over the 62-year life of the sirex program this method results in a progressive dilution of the costs per hectare over time, regardless of whether there have been any efficiency gains. The total cost (NPV@7.5%DR) using this method was $44.78 per hectare or $0.72 per hectare per year.

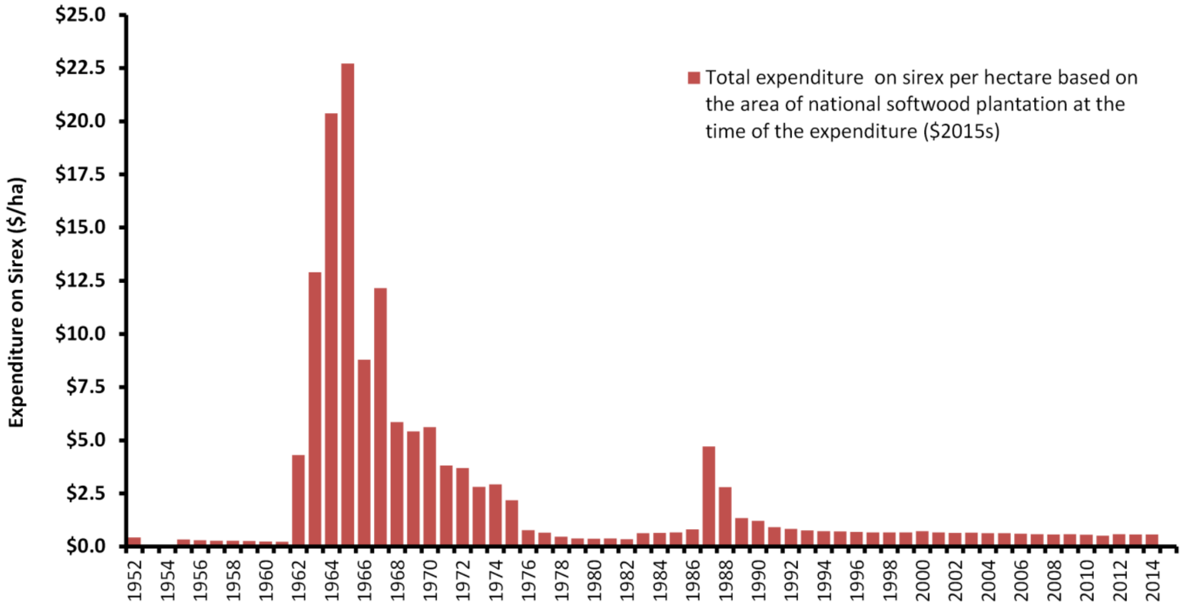

Figure 16: Profile (1952-2014) of national sirex control costs ($2015s per hectare). Calculated using total annual expenditure (converted to $2015s) divided by the area of national softwood plantation that was susceptible to sirex at the time that the expenditure was incurred

The second method involved calculating the cost using the hectares of plantation that were susceptible to sirex at the time the expense was incurred (Figure 17). The susceptible areas being roughly half the size of the national softwood plantation estate areas. The total cost (NPV@7.5%DR) using this second method was $89.67 per hectare or $1.45 per hectare per year.

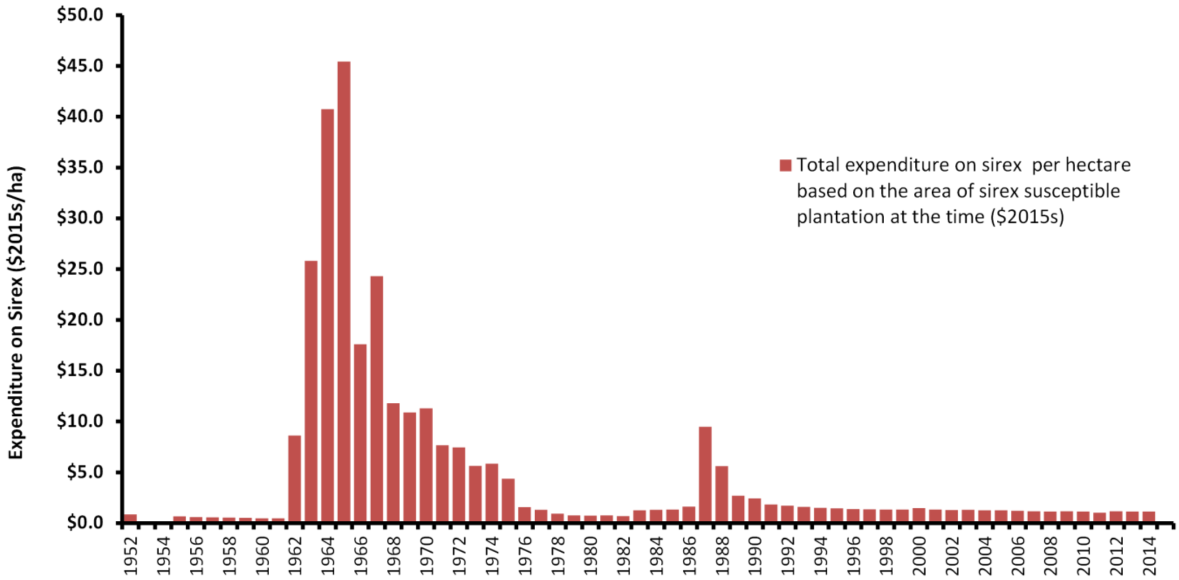

Figure 17: Profile (1952-2014) of national sirex control costs ($2015s per hectare). Calculated using total annual expenditure (converted to $2015s) divided by the area of national softwood plantation that was susceptible to sirex at the time that the expenditure was incurred

The third method involved calculating the cost per hectare based on a fixed plantation area. We used the total area of the national softwood plantation estate as at 2014. This approach allowed a more direct comparison of unit costs from one year to the next (Figure 18) and shows how costs can be lowered when distributed (shared) over the entire national estate. The total cost (NPV@7.5%DR) using the third method was $11.53 per hectare or $0.19 per hectare per year.

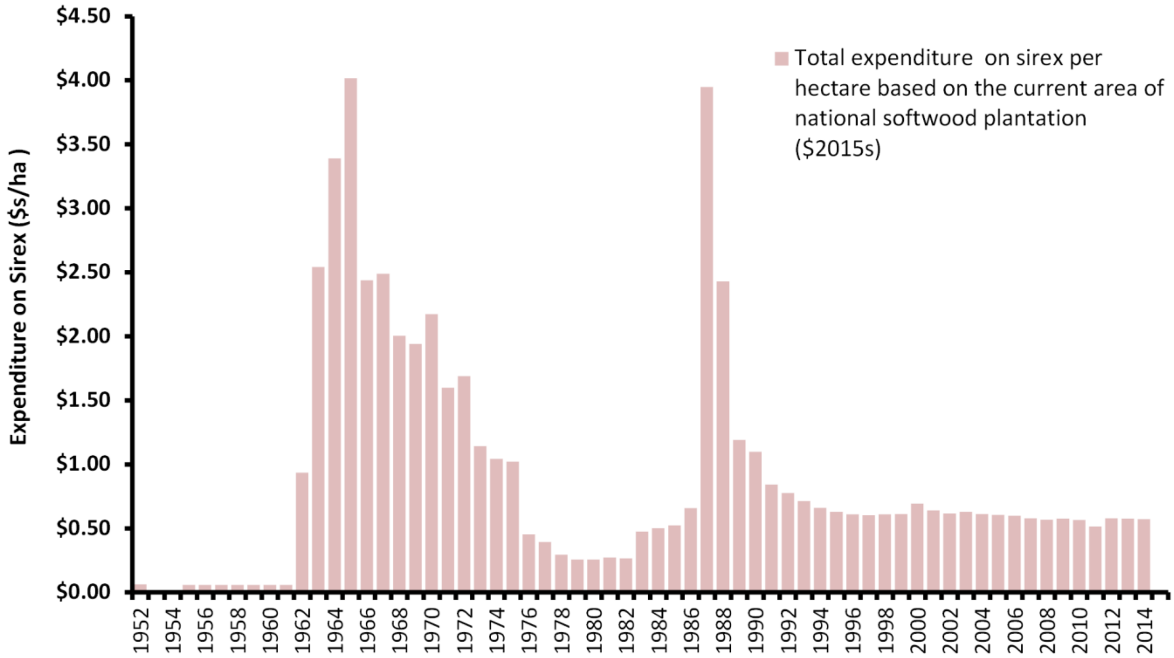

Figure 18: Profile (1952-2014) of national sirex control costs ($2015s per hectare). Calculated using total annual expenditure (converted to $2015s) divided by the area of national softwood plantation in 2014

Costing Sirex Impacts

The extent and number of documented sirex outbreaks that have caused financial impact has been relatively low. Figure 19 is a subjective portrayal of the relative severity and extent of more major (well documented) outbreaks.

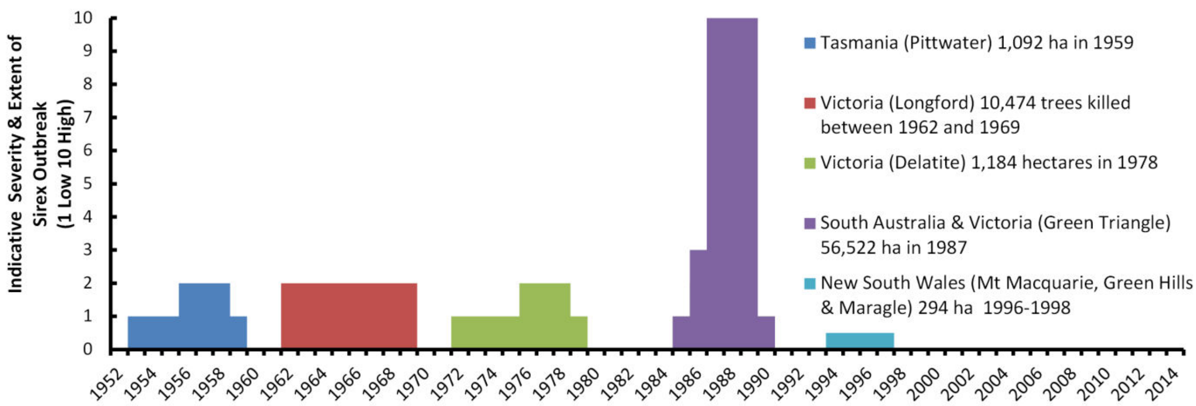

Figure 19: Sirex outbreaks that have caused financial impact that have been the subject of detailed scientific documentation (note scale is subjective and indicative only)

We selected three of these outbreaks for case study analysis. For each case study, we sought to cost the impact of sirex on the *P. radiata* plantation in terms of the loss of merchantable log value using the valuation methodology detailed above.

1. The Pittwater Tasmania Outbreak (1952-1959)

The Pittwater plantation was established between 1929 and 1935 at 1700 stems per hectare and thinned to 1000 stems per hectare. In 1950 and 1951 three small fires occurred in the plantation which killed trees of merchantable size. Sirex was subsequently found in mill flitches that had been sawn from the salvaged trees (Elliott et al 2008).

In 1954 the plantation was subject to a major outbreak. At this time the age of the plantation ranged from 19 to 25 years of age. Attempts to eradicate the pest failed, and by 1959 it had killed about 40% of slow-growing intermediate-aged trees in 1,092 hectares of plantation (Mucha 1967, Madden 1975 cited in Neumann et al, 1987). Surveys of the Pittwater plantation in 1964 indicated that mortality of trees due to sirex attack ranged from 80% in some western compartments to 30% in the east (Madden, 1975).

The role of biological control agents in the decline in tree mortality was insignificant as parasites were not introduced into Pittwater until 1957 and 1959 (Taylor, 1967 cited by Madden, 1975). This fact made the plantation an ideal case study for a 'no control' scenario.

In 1964 CSIRO's Division of Entomology at Hobart chose a compartment (121.5ha) within the Pittwater plantation (presumably that was broadly representative of the effects of the outbreak) to measure sirex impacts within randomly selected plots. The findings of this study were presented in a paper by Madden (1975). Data contained within Table 1 of Madden's paper was used to value the impact of sirex on the loss of merchantable log value. The results of this valuation are presented in Figure 20.

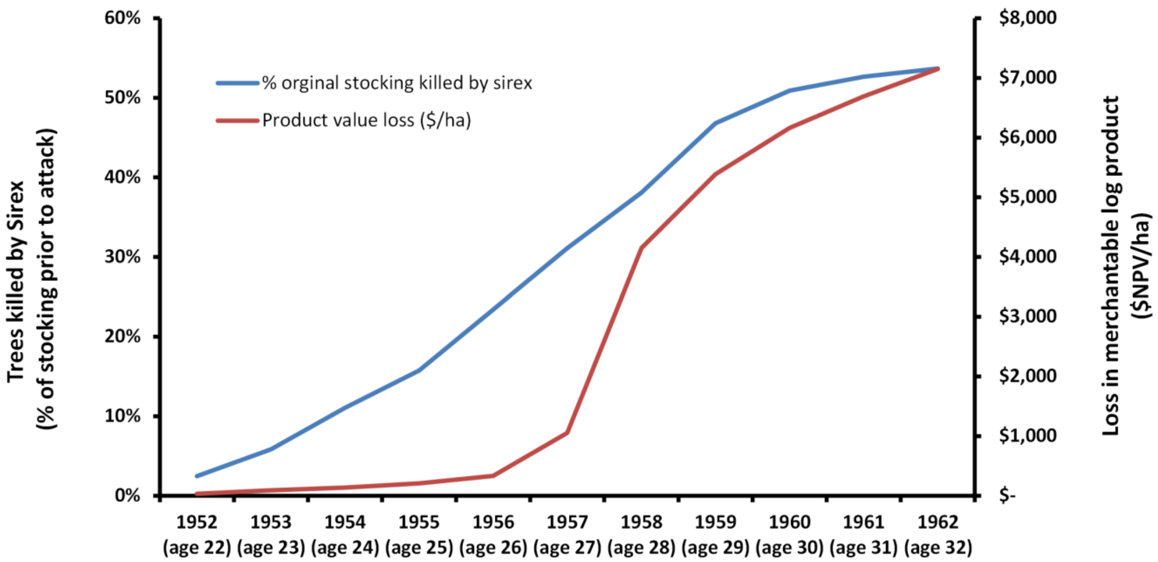

Figure 20: Annual % of trees killed by sirex and corresponding loss in value per hectare ($2015s) in a compartment planted in 1929-30 at Pittwater, Tasmania (based on data published by Madden, 1975)

In this case study the peak of the outbreak occurred (coincidentally) at the time the plantation reached commercial maturity. This resulted in the maximum possible impact on the plantation's merchantable log products. Using our valuation model we estimated that the losses peaked at $7,150 per hectare[10]. Using 1952 as the baseline for discounting generated an NPV of $4.86M or $4,429 per hectare (NPV in $2015s @7.5%DR). This outbreak highlighted that without effective control sirex can cause significant damage to mature plantations. Having occurred 60 years ago many current forest managers may not be aware that sirex has the capacity to do this much damage.

2. The Delatite, Victoria Outbreak (1972-79)

The Delatite plantation in central north-east Victoria comprised 1,906 hectares of *Pinus radiata* with age classes ranging from trees planted in 1959 to 1968. In 1972 the Forest Commission of Victoria plantation became subject to a sirex outbreak that peaked five years later in 1977 and culminated in 1979. At the peak of the outbreak the plantations ranged in age from 8 to 18 years. Trees less than 10 years of age remained uninfested.

A survey of the damage by McKimm and Walls (1980) reported standing merchantable volume loses of 38,000m^3 or 12% of the plantation's total merchantable volume. 1,184 hectares were affected at varying incidence levels (Figure 21).

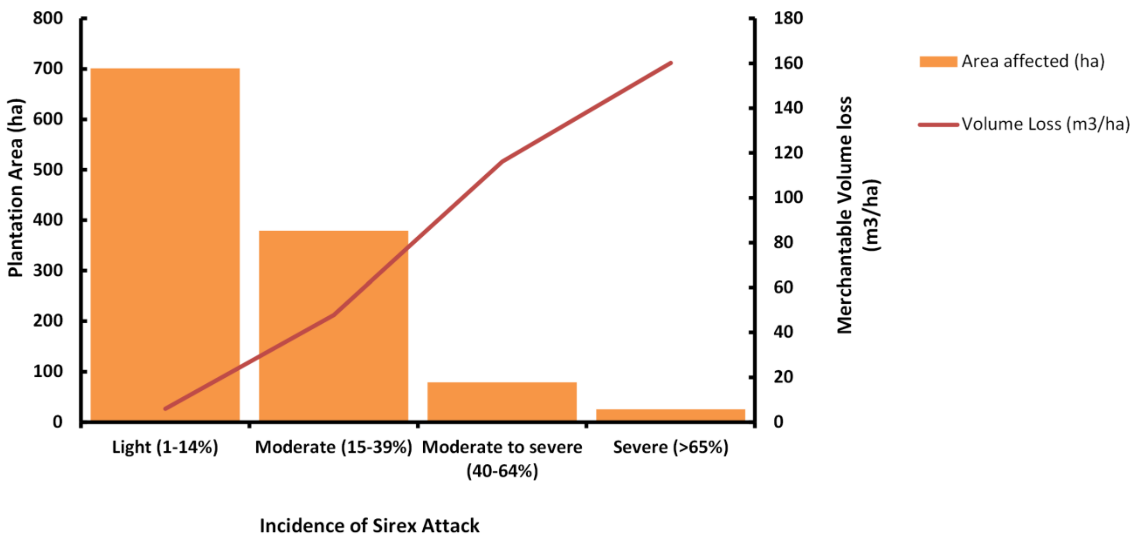

Figure 21: Extent and severity of damage caused by sirex in a 1906 hectare *Pinus radiata* plantation at Delatite Victoria (source data: McKimm and Walls, 1980)

Assuming all lost product was pulpwood (based on age of trees) valued at $10/m^3 we calculated the value of the Delatite loss at $355,000 or $300 per hectare (average). The NPV of these values using 1952 as the baseline for discounting were $54,000 or $46 per hectare (NPV in $2015s@7.5%DR).

3. The Green Triangle Outbreak (1985-1990)

The sirex outbreak in the Green Triangle which peaked in 1987/88 is the largest on record in Australia and provides perhaps the most salient lesson of what can occur when sirex controls are not working to their potential.

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[10] Modelling based on Forestry Corporation of NSW yield models and stumpage data.

Up until 1988 attempts to control the outbreak were not effective due to problems with efficacy of the biological controls. An under estimation of the seriousness of the issue in the early and mid-1980s also meant that a large scale coordinated response was not organised until the sirex populations had reached their tipping point (i.e. where they transition from background to epidemic levels).

In 1987 there were four main plantation landholders:

i) Woods & Forests Department South Australia
ii) Softwood Holdings Limited (which became CSR Softwoods in 1988)
iii) SE Afforestation Service (SEAS) and Southern Australia Perpetual Forests (SAPFOR)
iv) Conservation Forests & Lands, Victoria

Between them these entities managed 104,441 hectares of *P. radiata* plantation. Of this estate 56,522 hectares (54%) was attacked by sirex (Figure 22), 30,233 hectares in the 10-20 year age cohort and 26,289 hectares in the 21-30 year age cohort.

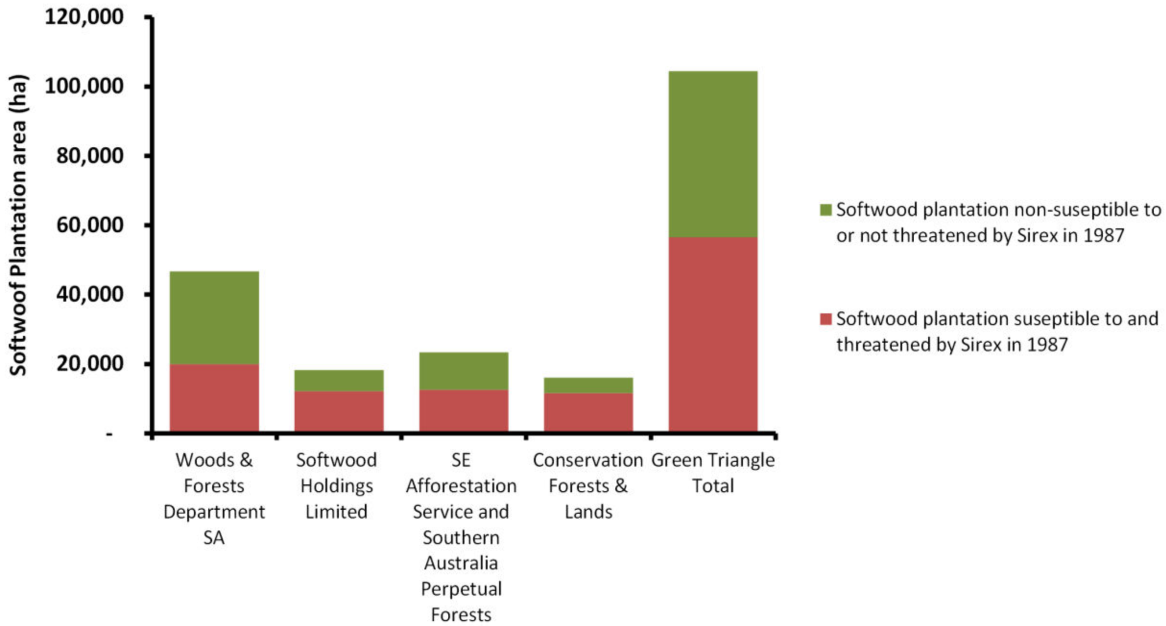

Figure 22: Area of *Pinus radiata* plantation in Green Triangle showing area of plantation impacted by sirex during a major outbreak in 1987 by plantation grower

In 1988 Softwood Holdings undertook an inventory of the trees that had been attacked by sirex within their estate. They estimated that 289,000m^3 or 12.6% of their standing volume had been lost to sirex. The product classification of the affected volume was 6% culls, 77% pulpwood and 17% sawlog. Assuming stumpages of \$10/m^3 for pulpwood and \$30/m^3 for small sawlog the value of Softwood Holdings' loss was \$3.73M (\$2015s). Extrapolating the losses incurred by Softwood Holdings to the whole of the Green Triangle we estimate the region's losses at the time at \$24.9M or \$440 per hectare (average). The NPV of these values using 1952 as the baseline for discounting were \$1.71M and \$30.30 per hectare (NPV in \$2015s@7.5%DR).

In the Woods & Forests Department's 1989/90 annual report, it estimated the royalty component of sirex loses (up to 1989) at $5M. In $2015s this equates to $10.2M. If the losses incurred by Woods & Forests are extrapolated to the whole of the Green Triangle they equate to $22.8M or $403 per hectare (average). The NPV of these values using 1952 as the baseline for discounting were $1.57M and $27.78 per hectare (NPV in $2015s@7.5%DR). The similarity of the valuations sourced independently from Softwood Holdings and the Woods and Forests Department give credibility to their reliability.

Post 1988 reports by Woods & Forests (1989) indicated that biological control measures, particularly the parasitic nematode *Deladenus siricidicola,* were markedly reducing sirex populations. There was also evidence of the presence of "background" parasitoid and nematode populations representing an important part of the total parasitoid and nematode populations in controlling the outbreak. Thinning of plantations also reduced the amount of plantation that was highly susceptible to attack. In total, these reports suggest that the financial impacts may have been much greater had there not been any biological control measures.

In summary, we estimate the impact of sirex in the Green Triangle at $23.8M or $422 per hectare (average). Using 1952 as the baseline for discounting reduced the NPV to **$**1.64M or $29.04 per hectare (NPV in $2015s@7.5%DR).

Case Study and Control Program Costing Summary

Table 2 summarises the costs of national sirex control over 62 years and three costed examples of a 'no control' scenario.

Table 2: Cost of national sirex control (NPV @7.5%DR) and estimated value (at time incident occurred and as an NPV) of merchantable timber loses arising from sirex attack for three separate 'no control' scenarios

		Net Present Value at the time the incident occurred *		Net Present Value using 1952 as the baseline for discounting *	
Costed Item	**Time Period**	$2015s	$2015s per hectare	$2015s	$2015s per hectare
National sirex control program	1952-2014	n/a	n/a	$11,808,294	$90
The sirex outbreak at Pittwater, Tasmania	1952-1959	$4,859,000	$4,429	$4,859,000	$4,429
The sirex outbreak at Delatite, Gippsland Vic	1972-1979	$354,660	$300	$54,099	$46
The sirex outbreak in the Green Triangle, Vic & SA	1985-1990	$23,842,776	$422	$1,641,510	$29

* NPV based on 7.5% discount rate

Evaluating the Effectiveness of the Sirex Control Program

It was not possible to prove that the techniques that have been developed for controlling sirex (i.e. biological control, surveillance and monitoring, trap trees and thinning) have been effective, as we did not have a 'no control' plantation to use as a reference point. That said, over the last 25 years (1990-2014) there has been an ongoing control program and no major outbreaks. A test of the program's effectiveness arguably occurred in 2007-2008 when much of south-eastern Australia was in drought; drought being a key factor in increasing tree susceptibility to sirex. In the Green Triangle and in parts of NSW and Tasmania, this drought coincided with a build-up of unthinned stands (due to weak pulpwood markets) and this in turn supported the build-up of sirex populations. Sirex control measures that were applied during this period prevented sirex populations from growing to incidence levels that have an impact on plantation value (Carnegie pers. obs.).

Prior to 1990 our investigations revealed that sirex populations were managed but not effectively controlled. Much conjecture remains about the extent to which the national program was effective during this period. If the national sirex control program had been 100% effective then we may assume that the value of the impacts on plantation value would have been zero (NPV[11] = $0). From our analysis we found that the NPV of the three major outbreaks totalled $6.5M. This estimate does not however account for the many smaller uncosted outbreaks which occurred within Victoria during the 1960s and 1970s.

With the NPV of the national sirex control program costed at $11.8M we were able to conclude that the total cost of sirex in Australia has an NPV of at least $18.3M.

Discussion

The cost of the sirex control program in Australia over a 62-year period has been significant, with a NPV of $11.8M or $44.78 per hectare[12], and more than $18.3M when the damage cost of the three largest sirex outbreaks are taken into account.

The spread of sirex to six Australian states has clearly proved the worth of having a National Sirex Control Committee (NSCC) which has coordinated research, education and control activities over many decades. The participation of unaffected growers prior to sirex arriving has been important, as has the maintenance of standards and effectiveness for what is a small but important control maintenance program.

We found that Sirex research (NPV $1.2M) constituted ten percent (10%) of the value of the national sirex control program and represented only 6.6 percent (6.6%) of the total cost of sirex management ($18.3M). Useable products arising from this research have included an effective biological control and an efficient trap tree technique. We conclude that investment in sirex research has been cost effective but not particularly timely. We found that 30 years elapsed before biological controls became readily available and almost 40 years elapsed before control measures were refined and made fully effective. We conclude that if a greater proportion of the investment in sirex control had been directed to research, particularly in the 1950s and 1960s this would have likely resulted in an effective biological control being available much sooner.

Ninety percent (90%) of the investment in the national sirex control program has been directed to operational investment. Most of this expenditure occurred in two distinct investment spikes. In accord with the comments above we concluded that these 'spikes' may have been avoided had more investment been directed sooner to the development of a biological control and the development and implementation of the trap tree technique.

The first investment spike in the 1960's was generated by a state-wide surveillance and eradication program in Victoria. This program was in essence a sirex 'search and destroy' operation (Neumann et al., 1987) where the goal was to have infested trees identified then

[11] All NPVs in this section use 1952 as the baseline for discounting.

[12] NPV of annual costs per hectare in $2015s using 7.5% discount rate (based on the area of national softwood plantation that existed at the time the expenditure was incurred). Note, does not include costs of sirex outbreaks.

burnt (to stop sirex from spreading). At the time, biological control measures were still being refined and so did not play a part in controlling sirex. We found that the surveillance and eradication program did not halt the spread of the sirex to other states, but most likely slowed the pest's progress and prevented some major outbreaks. This finding was made on the understanding that the program operated successfully for over a decade and that it targeted sirex populations before they were able to rapidly expand. We also found, however, that the surveillance and eradication program came at a very high cost, particularly when compared to the subsequent biological control programs that were introduced in the 1980s.

The second investment spike related to the inoculation of over 200,000 trees in the Green Triangle in response to a major sirex outbreak. Prior to the Green Triangle outbreak, there were a wide range of biological controls in play and plenty of technical information available about how to effectively monitor and control the pest. The increased risk of outbreaks occurring during periods of drought and within unthinned stands had also been well documented (Madden 1975, McKimm and Walls 1980). In the case of the Green Triangle, we found that preventative biological and silvicultural control measures were not up to standard and not applied in a timely manner. Why more timely action was not taken remains the subject of some debate. One explanation is that there were four competing plantation growers that may not have been naturally inclined toward working together, at least until evidence of the need to cooperate became overwhelming. Another explanation is that the plantation growers did not fully appreciate the level of the threat that their plantations faced; grossly under-estimating the capacity of the sirex populations (when all environmental settings are favourable) to rapidly expand from background to epidemic levels. Regardless of the reasons, the timing of the second investment spike reveals that the response was reactionary and belated. Had preventative action been taken in the early 1980s, when expenditure on sirex was very low (Figure 13), we believe that it would have been much more cost effective.

The high proportion of investment directed to the operational control of sirex is in stark contrast to our findings for the Leaf Beetle IPM Program in Tasmania. In the Tasmanian case study, operational costs only represented 33% of total costs with research costs making up the balance (67%). The sirex program's two operational investment spikes go a good way to explaining why the difference between the two programs was so great.

Being such a long running program created some limitations for the application of discounted cashflow analysis. The issue being that discounting of values beyond a 30 year time horizon reduces values to such an extent that the NPVs become relatively meaningless.

In summary, although we were unable to clearly determine whether the investment in a national sirex program has delivered a positive benefit-cost ratio, the learnings from this study were still considerable. Our key findings were:

- The incursion and establishment of a significant exotic pest (viz. sirex) adds cost to plantation management, both in terms of control and ongoing management. In sirex's case it cost \$11.8M, \$44.78 per hectare[13] or \$0.72 per hectare per year[14] This cost increased to

[13] NPV of annual costs per hectare in \$2015s using a7.5% discount rate (based on the area of national softwood plantation that existed at the time the expenditure was incurred). Note, does not include costs of sirex outbreaks.
[14] NPV of annual costs per hectare in \$2015s using a7.5% discount rate (based on the area of national softwood plantation that existed at the time the expenditure was incurred), divided by 62 (being the duration of the national sirex program in years). Note, does not include costs of sirex outbreaks.

more than $18.3M when the impact of sirex outbreaks were included. This finding lends support to (biosecurity) measures that can reduce the likelihood of new exotic pests (like sirex) establishing themselves within Australian plantations.

- The performance of forest health programs such as the national sirex control program have to be measured over many decades. Using discounted cashflow analysis to measure performance over periods greater than 30 years does however have its limitations;
- High level investment decisions made early in the life of the program have a major bearing on future performance. Possibly the most important decision is the one that apportions expenditure between research and operations;
- Decision making and management at a regional, state and national level all contributed to the overall performance of the national sirex control program;
- We found that preventing sirex outbreaks is more cost effective than post outbreak treatment. Investing a very high proportion of expenditure on physical eradication over many years rather than investing in research was found to be neither cost effective nor cost efficient;
- The national sirex control program has been successful in delivering a suite of tools and knowledge that (if applied correctly) are highly effective in preventing sirex outbreaks. In particular, investment in the research of sirex biological controls and trap tree techniques has proven to be a wise and cost-effective investment;
- Limited investment in research in the 1950s and 1960s extended the time required to develop and deliver an effective biological control and a reliable trap tree technique;
- Plantation growers are now benefitting from the historic investment that was made in developing biological controls and effective monitoring and surveillance techniques.

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Sirex control has been the subject of ongoing investment within Australia for 65 years. Much of this investment was concentrated in the 1960s and 1980s. Since then most of Australia's foremost experts on sirex have retired. Fortunately their legacy remains and much of their work has proven highly valuable for this study. The work by Dennis Haugen and Frederick Neumann deserves special mention. Special thanks also go to Mike Powell (Forestry SA) Andrew Moore and Abbie Sorrell (Green Triangle Forest Products), Tim Wardlaw (Forestry Tasmania) Humphrey Elliott (former Forestry Tasmania research officer), Angus Carnegie (NSW DPI) and Mijo Gavran (ABARES) for sourcing and supplying unpublished material.

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Discussion and Conclusions

Risk of Exotic Pests

Chapter 1 of this report illustrated that there is a clear – and ongoing and increasing – risk of exotic forest pests arriving into Australia as well as moving worldwide (see Wingfield et al. (2015) for a comprehensive review of the global situation), but that there are control activities that aim to reduce the chance of these pests entering and spreading into Australia. However, despite these control activities exotic pests have and will continue to establish in Australia, resulting in ongoing and possibly also growing pest management costs to industry. This is due in large part to the huge increases in the volume of world trade swamping our ability to intervene, particularly at the border, where only a small percentage of total volume can be inspected.

Given that there is a very large suite of exotic pests of forests trees that are not yet established in Australia, we recommend that more effort should be put into refining the pest lists we have and to carry out risk analyses for the key pests identified on our lists and through our analysis of the intercept data. While pest lists are still of value, they fail to capture pests that are not pests in their native range but that only emerge as pests once they have invaded a new environment. To lessen the risks posed by these pests, much recent effort in global biosecurity has focussed on shutting down the pathways along which these pests move. There are data that suggest that this approach is succeeding (Haack et al. 2014), but to a large extent we are faced with what is a sheer 'numbers game'. Our analysis of Australian trade data confirms what is reported globally in that movement of goods and people continues to increase hugely. Therefore, even if management of pathways reduces the incidence of pests moving on the pathway the sheer volume of trade ensures that significant numbers of pests will still be arriving at our borders.

Our analysis of recently obtained interception data demonstrate that only a small proportion of the total number of insect pests identified in pest lists appear to moving on various pathways (primarily wooden packaging and containers) into Australia (note that diseases were not covered in these intercepts, and mostly require a different approach pre- and post-border). A high proportion of our insect pest intercepts do occur on the Plantation Forest Industry Biosecurity Plan high priority pest list (9 of 13 pests intercepted between 2000 and 2015). Our analysis of interception data showed a general trend in increased numbers of intercepts over time of total pests, including high priority pests, and with an especially rapid increase in numbers since 2010. Of particular concern for the pine plantation sector is that a high proportion of all forest pest intercepts have *Pinus* spp. as recorded hosts. This reinforces the fact that at the same time as the Australian forest industry relies heavily on exotic *Pinus* species this industry is most at risk from introduced exotic pests.

Established exotics such as the bark beetles *Ips grandicollis*, *Hylastes ater* and *Hylurgus ligniperda* continue to be intercepted. Multiple interceptions of species already established increases the risk of new strains of associated fungi being introduced, with unpredictable consequences, or broadening the genetic diversity of the established pest that could increase its pest status. Genetic analysis of introduced exotic species is showing that multiple introductions are common (e.g. Sirex woodwasp – Boissin et al. (2012)).

Numbers of intercepts of one of the main pest groups (beetles in the family Cerambycidae) formed both the major proportion of intercepts and the group showing the sharpest increase in intercepts since 2010 This raises questions as to the effectiveness of ISPM 15, which was especially designed to try and shutdown the wood packaging material pathway, which is the major route of entry for this group of pests. However, a recent analysis of ISPM 15 in the USA demonstrated that the net benefits of this measure could exceed US$11 billion by 2050 (Leung et al. 2014).

We know that only a relatively small proportion of pests that move on pathways are likely to enter, establish and then to have serious impacts on the forest industry. The probability of establishment largely depends on propagule pressure, which is a measure of propagule sizes (populations in source countries), propagule numbers (numbers travelling on pathways), and temporal and spatial patterns of propagule arrival (Simberloff 2009). We can use interception data as proxy for more detailed data on propagule pressure and it has been shown that the more times a pest is intercepted the higher the probability that pest may become established. i.e. there is highly significant association between interceptions and establishment (Brockerhoff et al. 2006). On the other hand, there are biological factors that mitigate against establishment of exotic pests in a new environment. A newly arrived pest must find suitable hosts within its dispersal range upon arrival and also be able to mate before it can reproduce (for most species – there are some insect species which are parthenogenetic, which enable them to invade more easily). 'Allee effects' are important in this context, and predict that per capita growth rates decline with decreasing abundance. Liebhold and Tobin (2010) recommend that strategies to eradicate newly established populations should focus on either enhancing Allee effects or suppressing populations below Allee thresholds such that extinction proceeds without further intervention. Recent responses to post-border intercepts of longicorn beetles have used this concept by ramping up trapping systems around the intercept and within the known dispersal distance of the pest in an attempt to reduce populations of the intercepted pest even further. This is a part of the 'numbers game' that can act in our favour.

We have also highlighted activities through the biosecurity continuum that can reduce the likelihood of exotic pests entering and establishing into Australia. In particular, recent programs run by the Federal Department of Agriculture and Water Resources illustrate the potential cost-effectiveness of pre-border interventions in reducing numbers of pests arriving at the border (i.e. reducing propagule pressure at the source). Given the diminishing returns from biosecurity investment at the border due to the huge increase in volumes of imports and human movement and the limitations imposed by budgets on how much can be inspected, targeted pre-border measures may be more cost-effective in preventing future establishment of pests.

Post-border surveillance is also a key measure that can help prevent establishments of new pests. For example, (Epanchin-Niell et al. 2014) show that even low levels of surveillance are useful in that the economic benefits from surveillance more than offset the rising costs associated with increasing trapping density. They also show that greater surveillance is necessary in areas closer to at-risk, high-value resources and in areas that receive more imported goods that serve as an invasion pathway. The forest industry would benefit from a better targeted, more nationally structured and long-term funded post-border surveillance system that is currently being discussed in relation to specific activities under the Federal Government's 2015 Agricultural Competitiveness White Paper.

Benchmarking forest health surveillance and biosecurity activities for managing Australia's exotic forest pest and pathogen risks

Chapter 2 benchmarked current arrangements around forest health surveillance and biosecurity across Australia. An industry survey and our current understanding of biosecurity programs in place were used carry out a gap analysis. The key findings were that:

Benchmarking

- There is a lack of coordination of forest health surveillance activities and inconsistency in data capture that hinders our ability to report on the status of forest health and biosecurity nationally.
- Post-border forest biosecurity is not adequately covered in Australia, increasing the risk of pest incursions establishing.
- There is an uncertain future for sustainability of access to technical experts in forest health and biosecurity.
- Poor use of the forest workforce due to lack of coordinated and national training results in an over-reliance on pest detection by a small cohort of technical experts (in-house and consultants).
- The forest industry is relying too heavily on motivated technical experts to lead forest biosecurity at a state and national level.

More specifically, the gap analysis we conducted highlighted some significant deficiencies.

Gap Analysis

Forest Health Surveillance

Although there is relatively good coverage of the plantation estate with some sort of forest health surveillance activity, there are inconsistencies in methodology and the area being surveyed. This means that a proportion of the plantation estate is not adequately surveyed, with risks of pest outbreaks (including new biosecurity pests) going undetected in these areas.

- There is no national coordination of surveillance activities, nor a mechanism to ensure consistency in data capture. This restricts the ability to collate data and report at a regional or national level, including on Pest Area Freedom status, which is important for international trade.
- Pest and disease issues identified during routine operational activities that growers conduct, such as inventory plot assessments and establishment surveys, are not adequately captured in overall forest health status reporting. Therefore, data on potential emerging issues, or the lack thereof, are potentially not captured at a national level.
- Forest health surveillance methodologies are designed to detect and map the extent and severity of established or endemic pests, not biosecurity threats. Thus, the data captured, and the time and resources spent conducting such surveys, may not be able to be used for biosecurity purposes, such as declaration of Pest Area Freedom.
- There is little structured surveillance in native forests.

Biosecurity

- Forestry pests are inadequately surveyed for in post-border biosecurity surveillance programs in Australia, with no nationally coordinated program and only one forestry pest surveyed for nationally. This increases the chance that exotic incursions will become established and spread into production forests before being detected.
- General surveillance (i.e. the general public) is not consistently or well harnessed nationally. Utilising general surveillance increases the chance that new incursions are

detected in urban and peri-urban environments, increasing the chance of — and reducing the cost of — eradication.
- There is a lack of transparency in what activities the federal government is conducting in biosecurity at the border. A greater understanding of these activities will allow risk assessments to be made about resource allocation for post-border surveillance.

Technical expertise and training
- There has been a gradual decline in the number of technical experts actively working on forest health and biosecurity in Australia, with no body (industry or government) taking responsibility for succession planning. Within five years, the cohort of experienced technical experts will effectively be halved due to natural attrition.
- Training of industry is *ad hoc* and not consistent nor coordinated, and there is no nationally recognised course. This reduces the ability of this large work force from effectively being able to detect new pests and disease issues, including incursions, during their normal duties.

Industry engagement
- There is a lack of industry leadership in biosecurity issues at a national level, with this generally being left to motivated technical experts. This has the potential for biosecurity issues to not be taken seriously by industry, or government to not take seriously forest industry needs in this arena.

The gap analysis outlined above has been incorporated and expanded upon in "A Framework for National Biosecurity Surveillance of Exotic Forest Pests" published in 2016 (PHA, DAWR) and specific measures to address these gaps have been included in the "National Forest Biosecurity Surveillance Strategy 2017-2022" and its associated Implementation Plan (PHA, DAWR 2017). These publications should be consulted for further detail.

Costs and benefits of managing Chrysomelid leaf beetles by Forestry Tasmania

Chapter 3 investigated the costs and benefits of managing native pests (Chrysomelid leaf beetles) in eucalypt plantations in Tasmania. Key findings were:

- Above-threshold leaf beetle populations (that cause severe defoliation if uncontrolled) could be described by relationships with: (i) plantation age (likelihood of above-threshold populations peak at age 4-5 years and decline to a low value by age 12 years); (ii) site leaf beetle risk class (sites of low leaf beetle risk have fewer above threshold populations between years 3-12 years than sites of medium or high leaf beetle risk).

- Simulations of above-threshold leaf beetle populations in Forestry Tasmania's plantation estate between 2003-2034 found that the leaf beetle IPM, though controlling above-threshold populations, averted losses of 1.7M m^3 of merchantable wood volume (all products), equating to 7.7% of the total merchantable wood volume.

- The IPM program has been a 'break-even' proposition for Forestry Tasmania, generating a net benefit of (+) $476K (NPV @7.5%DR) when the cost of 'soft insecticide' research is excluded and a net cost of (-) $375K (NPV@7.5%DR) when 'soft insecticide' research is included.

- The benefits of the IPM program took many years to be realised operating for 20 years before achieving a positive cash-flow. Now that the program is well established it is generating a high level of ongoing net benefits.

- The time value of money was found to be a key driver of the IPM program's financial performance. This finding highlights the importance of minimising the time between the initiation of research and the operational implementation of management arising from that research.

- Having high fixed research costs made the scale of the program important. Programs with high fixed costs such as this one lend themselves to be undertaken on scale through cooperative arrangements.

- Investment in 'soft insecticide' research did not yield any financial returns. If 'soft insecticide' research can be applied in the future, it will enable certification by the Forest Stewardship Council (FSC). FSC certification is likely to generate 'social licence' and timber marketing benefits.

An analysis of pest risk and potential economic impact of pinewood nematode, *Bursaphelenchus xylophilus*, and its vector, *Monochamus alternatus,* to softwood plantations in Australia

Chapter 4 analysed the risk and potential impact of a high priority forestry pest (pine wilt disease) using an incursion scenario based around the southeast Queensland pine plantation estate. Key findings were:

- The economic analysis revealed substantial expected present value of damage costs due to pine wilt disease, even at low probabilities of establishment, and low rates of spread and mortality. This translates into high expected benefits from biosecurity programs.
- In the event that pine wilt disease did establish at Beerburrum, and it was detected early due to a well-funded biosecurity program, eradication may be possible.
- The expected value the plantation estate examined increased with increased forest pest biosecurity. Consequently, economically sound biosecurity policy would encourage cooperative control programs with the plantation owners. Of course, since the pest is lethal for many northern hemisphere coniferous species that may be grown outside commercial plantations, there are broader social benefits associated with keeping pine wilt disease out of southern Queensland, and a taxpayer-contribution to a biosecurity program would be justified, according to a cost-sharing arrangements decided by a categorisation for this pest.

Case Study - Sirex woodwasp (*Sirex noctilio* Fabricius [Hymenoptera: Siricidae])

Chapter 5 carried out an historical review of the total costs and benefits of Sirex management in Australia since its establishment in 1952. Our key findings were:

- The incursion and establishment of a significant exotic pest (viz. sirex) adds cost to plantation management, both in terms of control and ongoing management. In sirex's case it cost $11.8M, $44.78 per hectare or $0.72 per hectare per year. This cost increased to more than $18.3M when the impact of sirex outbreaks were included. This finding lends

support to (biosecurity) measures that can reduce the likelihood of new exotic pests (like sirex) establishing themselves within Australian plantations.
- The performance of forest health programs such as the national sirex control program have to be measured over many decades. Using discounted cashflow analysis to measure performance over periods greater than 30 years does however have its limitations;
- High level investment decisions made early in the life of the program have a major bearing on future performance. Possibly the most important decision is the one that apportions expenditure between research and operations;
- Decision making and management at a regional, state and national level all contributed to the overall performance of the national sirex control program;
- We found that preventing sirex outbreaks is more cost effective than post outbreak treatment. Investing a very high proportion of expenditure on physical eradication over many years rather than investing in research was found to be neither cost effective nor cost efficient;
- The national sirex control program has been successful in delivering a suite of tools and knowledge that (if applied correctly) are highly effective in preventing sirex outbreaks. In particular, investment in the research of sirex biological controls and trap tree techniques has proven to be a wise and cost-effective investment;
- Limited investment in research in the 1950s and 1960s extended the time required to develop and deliver an effective biological control and a reliable trap tree technique;
- Plantation growers are now benefitting from the historic investment that was made in developing biological controls and effective monitoring and surveillance techniques.

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