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ARTICLE

Economic appraisal of Sirex Wood Wasp (*Sirex noctilio*) control in Australian pine plantations

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ABSTRACT

Sirex noctilio (Sirex) is an exotic wood wasp and a pest of *Pinus* that has been in Australia for 65 years. Our study quantified expenditure on Sirex control between 1952 and 2014 through the National Sirex Control program, and costed the impact of three major outbreaks where large-scale tree mortality occurred. We estimate the combined cost of the program and the outbreaks at $34.5 million (net present value using a 1952 baseline and a 5% discount rate). Expenditure on the program was estimated at $24.8 million, while the combined plantation timber losses from the three studied outbreaks — Pittwater, Delatite and the Green Triangle — were valued at $9.7 million. Much higher expenditure values were generated when discounting was limited to the year that the outbreaks commenced. The outbreak at Pittwater, Tasmania commenced in 1952 and had estimated losses of $5.7 million or $5161 ha^{-1}. This outbreak provided the best insight into the potential of Sirex to impact timber values under a 'no control' scenario. The Sirex outbreak in the Green Triangle, which commenced in 1987, was costed at $21.6 million. It was Australia's largest outbreak and occurred at a time when proven control methods were available. Study of the National Sirex Control program highlights the threats that exotic pests pose to *Pinus* plantations in Australia. Where realised, these threats can translate to major timber loses and costly control programs.

KEYWORDS
biosecurity; *Pinus* plantations; cost-benefit analysis; net present value; NPV; discount rate; tree mortality

Introduction

Sirex (*Sirex noctilio* (Hymenoptera: Symphyta; Siricidae)), and its symbiotic fungus *Amylostereum areolatum*, cause the death of softwood trees through a combination of a phytotoxic mucus (or venom (Bordeaux et al. 2014)) produced by the wasp, and white rot induced by the fungus (Coutts 1969a, 1969b; Neumann et al. 1987). Plantations that are moisture stressed by drought or because of delayed thinning (often due to market failures) are particularly susceptible to Sirex attack (Neumann & Minko 1981). Numerous studies have found that Sirex targets weaker trees (usually suppressed or subdominant trees) within these plantations (Madden 1975; Eldridge & Simpson 1987; Haugen et al. 1990; McKimm and Walls 1980). In the event of a major Sirex outbreak, plantation trees of all ages and silvicultural status can be prone to attack. In general, however, plantations less than 10 years of age have much lower susceptibility.

The first official record of Sirex in Australia was in 1951 in a *Pinus radiata* D.Don plantation (1092 ha) at Pittwater Tasmania, 20 km east of Hobart (Gilbert & Miller 1952). At the time, there were only about 4000 ha of *P. radiata* plantation in Tasmania, and the entire national softwood estate was less than 150 000 ha (ABARES 2016). About 3000 trees were felled and burnt at Pittwater in an unsuccessful eradication attempt (Madden 1975). By 1961, Sirex had killed 40% of the standing trees within the Pittwater plantation, many of which were mature trees close to harvest (Madden 1975). In 1961, Sirex was detected on mainland Australia within a farm woodlot east of Melbourne, Victoria (Irvine 1962). By 1977, Sirex had reached the Green Triangle in the state's west and by 1979 was present in *P. radiata* plantations throughout Victoria (Neumann et al. 1987; Collett & Elms 2009). In 1980, Sirex was detected in South Australia and near Albury in southern New South Wales (NSW) (Eldridge & 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 the state's major *P. radiata* plantations, but had not established in the Southern Pine (*P. elliottii* Engelm., *P. caribaea* Morelet and their F1 and F2 hybrids) plantations in north-east NSW (Carnegie et al. 2005). Sirex was detected in *P. radiata* plantations near Stanthorpe in south-eastern Queensland in 2009 (Carnegie & Bashford 2012) where it appears restricted to these tableland plantations at this time (Nahrung et al. 2016).

The discovery of Sirex in Victoria led to the establishment of the National Sirex Trust Fund, co-funded by government and growers (Eldridge & Simpson 1987). The Trust funded surveillance and tree destruction (in the belief that eradication was attainable); research into the biology of the pest and the pest-pathogen-host interaction; a biological control program that identified parasitoids (e.g. *Ibalia leucospoides* and *Megarhyssa nortoni* and the nematode *Beddingia* (=*Deladenus*) *siricidicola*(Bedding); and the trap tree technique for attracting Sirex and infecting the wasps with nematodes (Bashford 2008). By 1969, insect parasites were significantly influencing Sirex populations, and subsequently the nematodes had an even greater effect (Marsden et al. 1980).

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Following significant outbreaks in Tasmania (Madden 1975), Victoria (Neumann & Minko 1981) and the Green Triangle (Haugen 1990), there have been only sporadic and short-lived outbreaks of Sirex in Australia (Carnegie et al. 2005; Collett & Elms 2009; Carnegie & Bashford 2012). Sirex is currently effectively managed with a combination of biological control, silviculture, and surveillance and monitoring (Haugen et al. 1990; Carnegie & Bashford 2012). Although the research and control program in Australia has attracted international interest (Slippers et al. 2012), it is unclear how cost-effective it has been (Talbot 1977; Eldridge & Simpson 1987). Here, we collate expenditure on Sirex control since 1952 and re-examine the financial impact of the three main outbreaks. Our aim was to determine whether the Sirex control program has been cost-effective; however, in the absence of a scientific control (in which Sirex could run unchecked) this analysis was not possible.

Method

Investment in Sirex control — the national sirex control program

This study sought to capture the costs in Australian dollars of all investment made in Sirex control in Australia over a 63-year period (1952–2014). Sirex costs were captured and collated from a variety of sources including National Sirex Fund records, peer-reviewed scientific publications, government forest management agency reports, CSIRO reports, unpublished plantation company records, and data supplied by softwood industry personnel with Sirex management expertise. Detailed company records were sourced from Woods & Forests Department SA, Softwood Holdings Limited, SE Afforestation Service and Southern Australia Perpetual Forests, and Conservation Forests & Lands Victoria.

Collated data was classified by expenditure type and then sorted by calendar year (n = 63). Costs incurred on Sirex control were broadly classified as either operational management or research and development. Operational management costs were further divided into five subcategories (Fig. 1):

(1) Surveillance and monitoring, including aerial and ground surveillance.
(2) Eradication programs, mainly mechanical tree destruction and quarantine measures in Victoria during the 1960s and early 1970s.
(3) Inoculation programs, inoculating naturally attacked trees with nematodes outside the trap tree program, such as was operationalised in the Green Triangle outbreak.
(4) Trap tree programs, including establishment, inoculation and monitoring of parasitism.
(5) Foregone product value in trap tree plots and inoculated trees: the value of sacrificed trees.

Research and development costs included the establishment of CSIRO laboratories at Silwood, UK and Hobart, Tasmania, and the associated employment of specialist researchers to develop and refine biological control agents and develop trap tree techniques. Costs for production and deployment of biological control agents were combined with research costs as we were unable to readily separate them. Production included the operational rearing and deployment of parasitoids (e.g. *I. leucospoides* and *M. nortoni*) and nematodes (e.g. *B. siricidicola*).

The cost of Sirex control was also calculated on a per hectare basis. For this calculation, we obtained softwood plantation[1] area statistics dating back to 1952 from the Australian Bureau of Agricultural and Resource Economics and Sciences (Fig. 2). Over the period of our study, the area of softwood plantation increased sevenfold (from 145 486 ha to 1 024 181 ha).

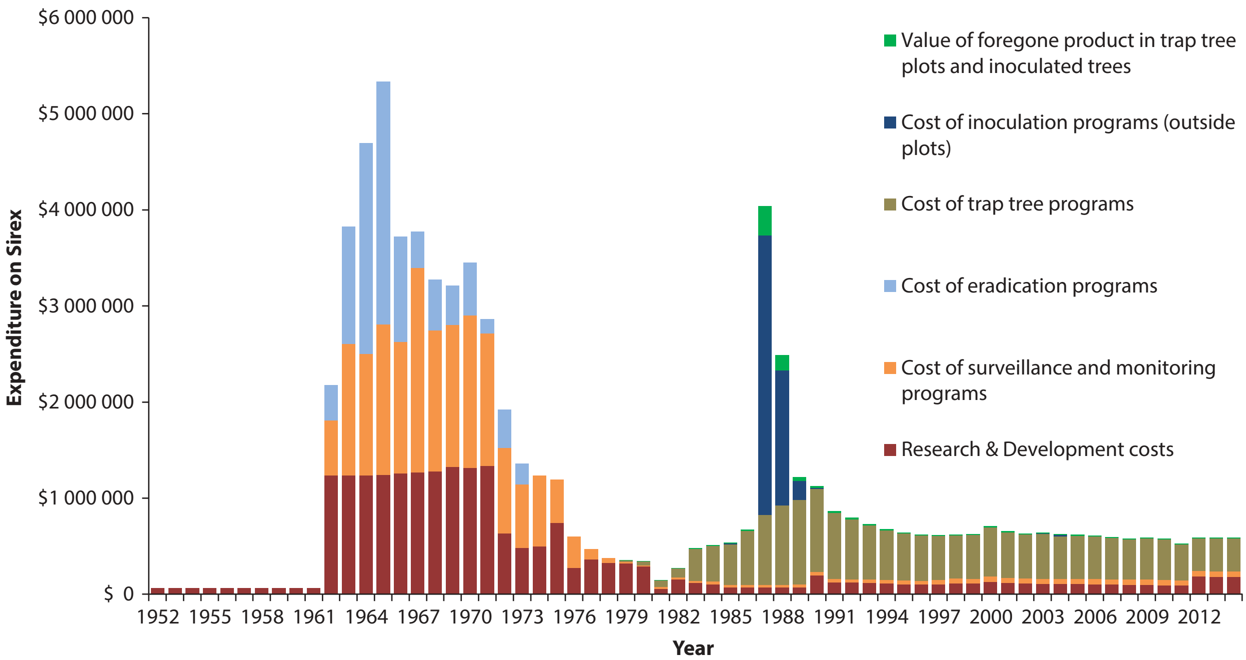

Figure 1. Expenditure on Sirex control in Australia (1952–2014) by expenditure type. All expenses adjusted to 2015$

[1]Plantation area statistics just for *Pinus* species were unavailable. Softwood plantation statistics include a small percentage of native pines species that are not susceptible to Sirex.

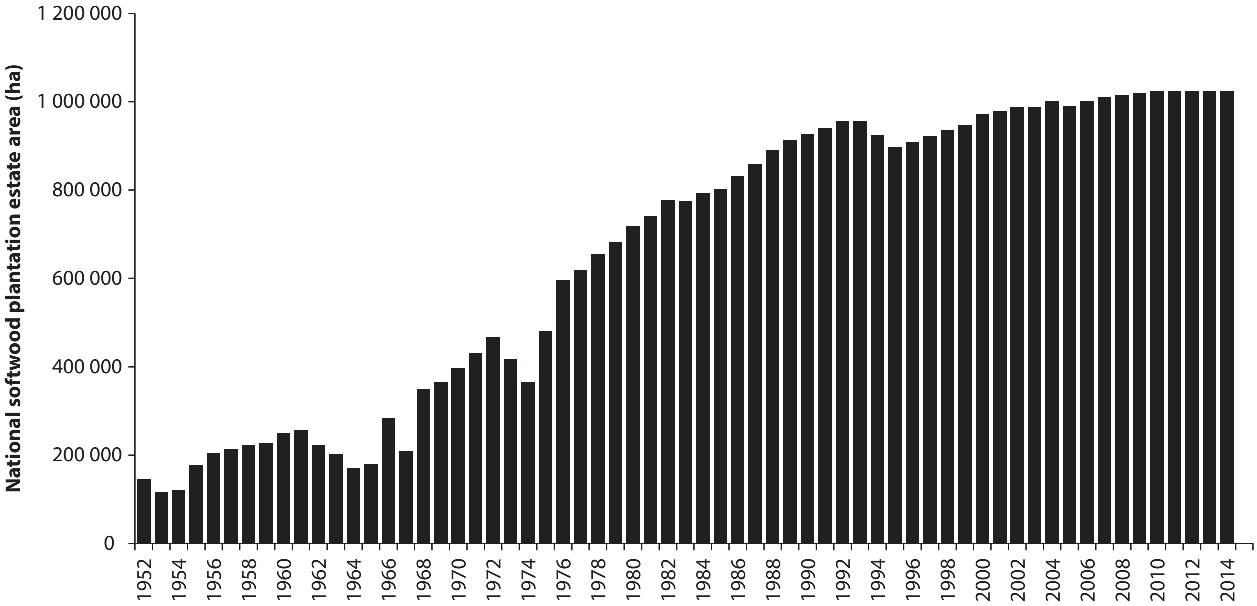

Figure 2. National softwood plantation estate area, by year (unpublished ABARES 2016)

There are many different ways in which costs per hectare can be applied and reported. These ways include using the total area of the national softwood plantation estate, the area of plantation that is susceptible to attack, and the actual area of plantations that is attacked. In this paper, we calculate cost per hectare per year by dividing annual costs by the area of the national softwood plantation estate for that year (Fig. 3). For the Green Triangle outbreak, we also calculated cost per hectare based on the area of plantation that was attacked by Sirex.

To allow fair comparison of annual expenditures over time, the expenditure amount by type for each year was converted to 2015$ using an inflation index published by the Australian Bureau of Statistics:

$$\textbf{Value in 2015\$} = \$X_t\textbf{x}CPI_{2015} \div CPI_t$$

$X **= Expenditure amount**
T **= Year of expenditure**
CPI = Australian Consumer Price Index [All Groups All Capital Cities (Series ID A2325846C)].

For consistency, current industry rates (in 2015$) were used for some common recurrent expenditure items (e.g. trap tree plots were costed at $850 per plot, an average of current rates for several growers).

A net present value (NPV) formula was used to account for the time value of money and determine the present value of each expenditure type.

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

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

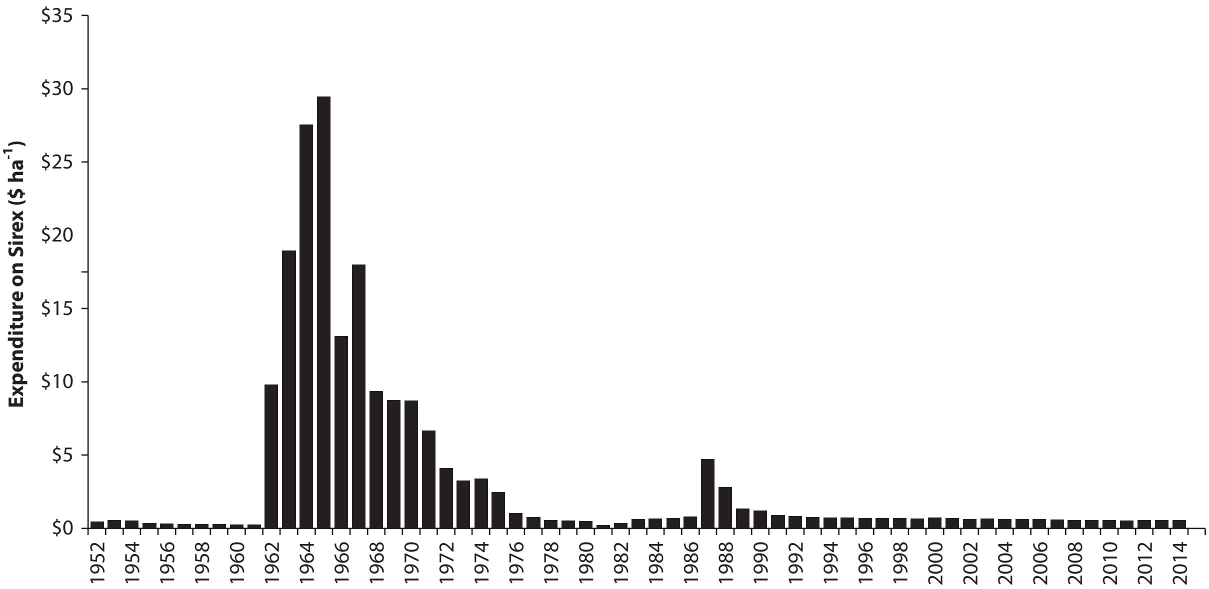

Figure 3. Total expenditure per hectare on Sirex based on the national area of softwood plantation at the time of the expenditure. All expenses adjusted to 2015$

As 1952 was the first year that expenditure was incurred, this was used as the baseline year for our NPV calculations. Expenditure incurred after 1952 was discounted back to 1952 using a 5.0% real rate of interest. Discount rates between 4.0 and 6.0% are commonly applied when evaluating the costs and benefits of primary industry research (Cubbage et al. 2000; Wu et al. 2005; Chudleigh et al. 2006; Chudleigh et al. 2017). Sensitivity analysis was carried out using higher (7%), lower (3%), and zero (0%) discount rates (Table 1).

Costing the impact of Sirex outbreaks under 'control' and 'no control' scenarios

The study sought to quantify the impacts of Sirex outbreaks on plantation timber values under 'control' and 'no control' scenarios. The 'control' scenario comprised the costs of the National Sirex Control program (detailed above) and the costs of the Sirex outbreaks that impacted on plantation timber values while the program was in operation (1952–2014).

The 'no control' scenario posed a conundrum as there was no reliable way to predict the impacts of Sirex outbreaks over time across all of Australia's susceptible pine plantations (Fig. 1). An insight into the 'no control' scenario was, however, achieved by quantifying the impacts on timber value of the Sirex outbreak that occurred at Pittwater, Tasmania (1952–1961). At the time of this incident there were no effective control measures and Sirex was able to spread largely unchecked.

Table 1. Net present values of National Sirex Control program costs at different discount rates using 1952 as baseline year

Discount rate (%)	Period	NPV ($)	NPV ($ ha^{-1})
0% (undiscounted)	1952–2014	$71 641 824	$200
3%	1952–2014	$36 101 132	$121
5% (base case)	1952–2014	$24 833 391	$90
7%	1952–2014	$17 842 497	$69

NPV, net present value
All values adjusted to 2015$

Quantification of the impacts of Sirex on plantation timber values required an understanding of the nature or trajectory of Sirex outbreaks. Levels of Sirex attack can increase significantly from year to year, and controlling a Sirex outbreak has a lag phase after initiation (i.e. even if all the infected trees are inoculated, the emerging Sirex will still kill trees the following year). To build on this knowledge, we explored the significance of age and thinning status under a suite of different simulated incidence levels (10, 20, 30, 40, 50 and 60%) (Fig. 4).

Data for costing the impact of Sirex was sourced from company and government forest agency reports for the country's three largest documented outbreaks, namely, Pittwater, Tasmania (1952–1959) (Madden 1975), Delatite, east-central Victoria (1972–1979) (McKimm & Walls 1980) and the Green Triangle, Victoria and South Australia (1987–1990). A plantation valuation model was developed to cost the impacts of the Sirex outbreaks at Pittwater and Delatite. The model took into account plantation age, thinning status and incident mortality level, and was based on a standardised plantation regime comprising two thinnings and a clearfall harvest at age 32. Indicative yield and timber stumpage values for the model were sourced from the Forestry Corporation of NSW, and based on an average quality *P. radiata* plantation site from central western NSW. By understanding how tree value changed with plantation age and stocking, we were able to reasonably estimate the relationship between Sirex tree mortality level and loss in log product value.

Quantifying the costs of the impacts of the Sirex outbreak in the Green Triangle required a slightly different approach due to the size and complexity of the region's plantations. Detailed records for the region's four plantation growers (Woods & Forests Department SA, Softwood Holdings Limited[2], SE Afforestation Service and Southern Australia Perpetual Forests, and Conservation Forests & Lands

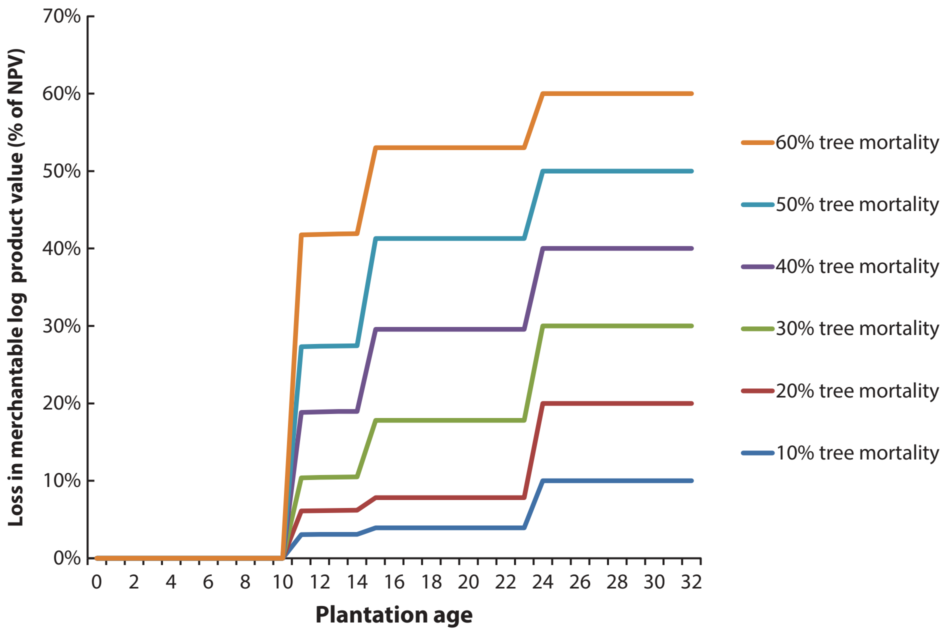

Figure 4. Loss in log product value (% of NPV) for six Sirex tree mortality scenarios applied to a *Pinus radiata* plantation subject to two thinnings, with Sirex risk commencing in year ten

[2]Became CSR Softwoods in 1988.

Victoria[3]) were available for the period of the outbreak (1987–1990). Records included reports on the impacts of the Sirex outbreak including estimates of tree mortality by area and plantation age. Drawing on these records and our knowledge of plantation log values, we were able to estimate the costs of the Sirex outbreak for the region as a whole. Comparison of individual company records allowed for cross-checking.

Using the assembled costs of the three outbreaks we applied the same valuation method that was used for costing the National Sirex Control program (i.e. allocation of costs to years, conversion to 2015$, and application of a NPV formula using 1952 as the baseline and a 5% discount rate). When reporting costs per hectare we used a different method. Rather than using the area of the national softwood plantation estate, we used the actual area of plantation that was subject to Sirex attack. This method generated values that are more meaningful to plantation managers.

Caution is required when comparing the costs per hectare at Pittwater, Delatite and Green Triangle. In the case of Pittwater and Delatite, the outbreaks occurred in discrete plantations that were similar in size (1097 and 1184 ha, respectively) but of different ages. In contrast, the Sirex outbreak in the Green Triangle impacted 56 522 ha of plantation comprising many different age classes within a much larger plantation estate.

Results

Investment in Sirex control

Total expenditure on Sirex management and control in Australia was valued (NPV, 2015$) at $24.8 million or $90 ha^{-1} (based on the total area of national softwood plantation at the time of the expenditure). We found that the cost of control was sensitive to the discount rate, and ranged from $17.8 million at a 7% discount rate to $71.6 million undiscounted (Table 1).

Analysis of expenditure revealed that two-thirds ($16.3 million) was directed to operational management and one-third ($8.5 million) to research and producing biological control agents (Fig. 5).

Much investment in operational management occurred in two distinct investment spikes (Fig. 2). The first was generated by a state-wide Sirex surveillance and (physical) eradication program across Victoria, with over 4500 properties quarantined due to Sirex infestation (Eldridge & Simpson 1987; Neumann et al. 1987). The first investment spike peaked in 1965 at $5.3 million or $29.47 ha^{-1} (based on 181 000 ha, the total area of national softwood plantation at the time of the expenditure), and then tailed off over the following eight years. The second investment spike in the late 1980s occurred in response to the major Sirex outbreak in the Green Triangle region (Haugen 1990). The second spike was relatively short-lived, lasting for only two and a half years, but a massive control operation was put in place and in some plantations every Sirex-attacked tree in every fifth row was felled and inoculated (Haugen & Underwood 1990). At its peak the investment reached $4 million y^{-1}. This amount equated to $71.53 ha^{-1} if applied just to the plantations in the Green Triangle that were attacked, or $4.71 ha^{-1} if applied to the total area of the national softwood plantation estate at the time.

Of the $8.5 million (NPV) invested in Sirex research and development, most (85%) was directed to the CSIRO (1962–1971) for the establishment and running of a Sirex biological control laboratory at Silwood Park, UK. A smaller Sirex laboratory was located in Hobart, Tasmania. This laboratory served as a quarantine station to receive parasitoids from Silwood Park (Carnegie & Bashford 2012). The main products arising from this research included the identification and release of a range of biological control agents, including parasitoids (Taylor 1976) and the nematode *B. siricidicola* (Bedding & Atkurst 1974). Research by the Forestry Commission of Victoria led to the development of an efficient trap tree technique to attract Sirex and transferred the

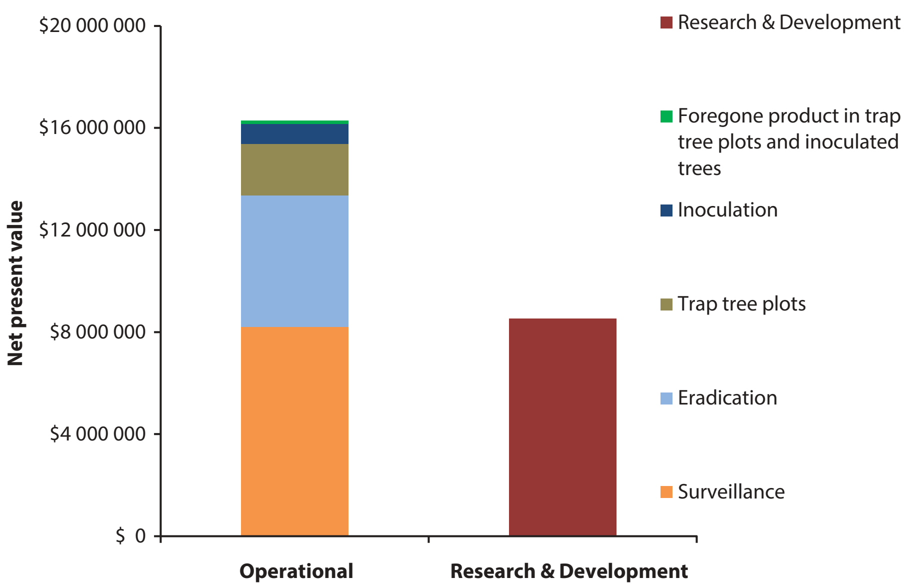

Figure 5. Net present value of national Sirex expenditure (1952–2014), by expenditure type, using 1952 as baseline year for discounting and a 5.0% discount rate. All values adjusted to 2015$

[3]Became Department of Conservation & Environment in 1990.

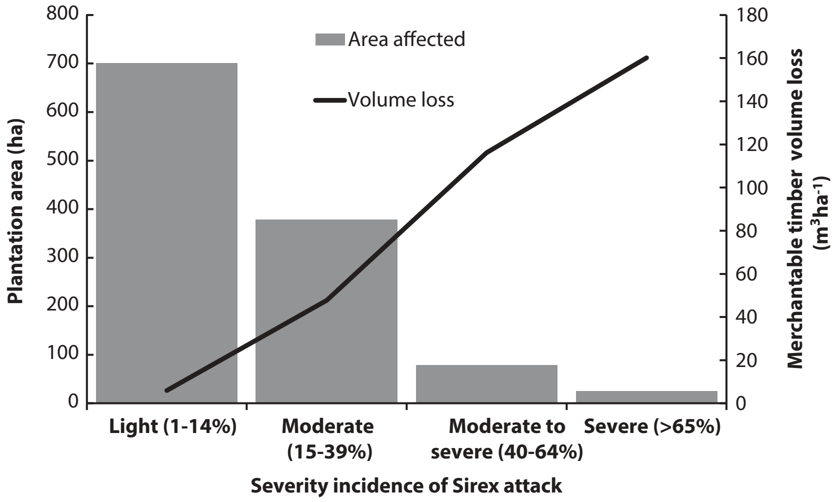

Figure 6. Area attacked and estimated merchantable timber volume loss by severity incidence from a Sirex outbreak in a *Pinus radiata* plantation (1184 ha) at Delatite, Gippsland, Victoria (1972–1979)

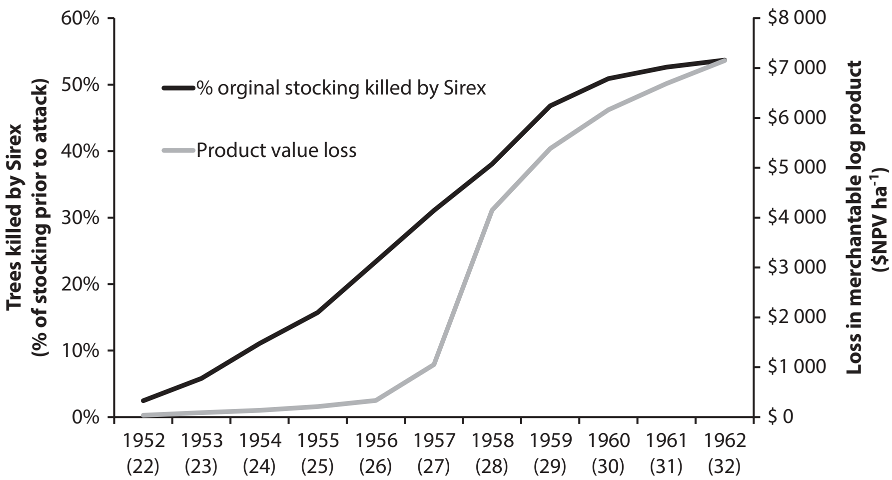

Figure 7. Tree mortality and estimated merchantable timber loss from a Sirex outbreak in *Pinus radiata* plantation (1097 ha) at Pittwater, Tasmania (1952–1962)

nematodes (Neumann et al. 1982). The deployment of these products occurred in the 1970s and 1980s.

Since the early 1990s, investment in the National Sirex Control program has levelled off and now consists of the annual trap tree program, monitoring of biological control efficiency, forest health surveillance and ongoing research. The current annual cost is \$587 000 or \$0.57 ha^{-1} when spread over 1.02 million ha. The bulk of these funds are dedicated to the operational trap tree program.

Cost of Sirex outbreaks

Based on our modelling of age and thinning status and various incidence levels of Sirex attack, we found that Sirex has a relatively minor impact on the product value of an unthinned plantation at mortality levels of 15% or less. At 40% tree mortality levels, the loss of product value is substantial (Fig. 4). Applying this model to the mostly young unthinned plantation at Delatite revealed that 1080 ha (90%) of the plantation was subject to 'light' or 'moderate' Sirex attack (mortality). In these stands merchantable timber loses were estimated at 5.9 m^3 ha^{-1} and 47.8 m^3 ha^{-1}, respectively. In contrast, 104 ha (10%) of the plantation incurred 'moderate to severe' or 'severe' Sirex attack which equated to merchantable timber loses of 116 m^3 ha^{-1} and 160 m^3 ha^{-1}, respectively (Fig. 6).

Applying the same costing model to the more mature plantations that were attacked by Sirex at Pittwater, Tasmania, we found that the value of the timber losses was far greater than in the Delatite outbreak. At its peak in 1962, half of all of the trees in the Pittwater plantation had been killed by Sirex resulting in estimated merchantable timber losses of \$7115 ha^{-1} (Fig. 7). These are only modelled figures, but they provide an important guide to the financial impact of Sirex.

Estimated NPVs of the merchantable timber losses incurred at Pittwater, Delatite and the Green Triangle are detailed in Tables 2, 3 and 4, respectively. Of the three outbreaks we found that, per hectare, the merchantable

Table 2. Net present values of merchantable timber loss, using different discount rates, from Sirex attack at Pittwater, Tasmania (1952–1962)

Discount rate (%)	NPV (\$)	NPV (\$ ha^{-1})
0% (undiscounted)	\$7 804 780	\$7115
3%	\$6 420 473	\$5853
5% (base case)	\$5 661 079	\$5161
7%	\$5 007 790	\$4565

NPV, net present value
All values adjusted to 2015\$. NPV calculations based on 1097 ha

Table 3. Net present values of merchantable timber loss, using different discount rates and baseline years, from Sirex attack at Delatite, Gippsland, Victoria (1972–1979)

Discount rate (%)	NPV (1952 baseline)	NPV ha^{-1} (1952 baseline)	NPV (1972 baseline)	NPV ha^{-1} (1972 baseline)
0% (undiscounted)	$354 660	$300	$354 660	$300
3%	$164 454	$139	$297 022	$251
5% (base case)	$99 745	$84	$264 653	$224
7%	$61 071	$5211	$236 325	$200

NPV, net present value
All values adjusted to 2015$. NPV calculations based on 1184 ha

Table 4. Estimated present values of merchantable timber loss, using different discount rates and baseline years, from Sirex attack in the Green Triangle, Victoria and South Australia (1987–1990)

Discount rate (%)	NPV (1952 baseline)	NPV ha^{-1} (1952 baseline)	NPV (1987 baseline)	NPV ha^{-1} (1987 baseline)
0% (undiscounted)	$23 842 776	$422	$23 842 776	$422
3%	$7 986 923	$141	$22 474 103	$398
5% (base case)	$3 920 602	$69	$21 626 101	$383
7%	$1 950 550	$35	$20 825 204	$368

NPV, net present value
All values adjusted to 2015$. NPV calculations based on 56 522 ha

timber losses (using the 0% discount rate) in the mature plantation at Pittwater ($7115 ha^{-1}) far exceeded those at Delatite and the Green Triangle, being $300 ha^{-1} and $422 ha^{-1}, respectively. In contrast, the scale and total value of the impact of Sirex attack in the Green Triangle ($23.8 million over 56 522 ha using 0% discount rate) far exceeded that of both Pittwater ($7.8 million over 1097 ha) and Delatite ($354 660 over 1184 ha). The three tables also show the effect of using different discount rates and different baselines. The effect of discounting (using a 1952 baseline) was least for the Sirex outbreak at Pittwater which occurred in the 1950s and greatest for the Sirex outbreak in the Green Triangle which occurred over 40 years later.

For the three Sirex outbreaks that we studied, the combined value of the merchantable timber losses was $9.7 million (NPV using a 1952 baseline and a 5% discount rate), refer to Table 5. Table 5 also details the estimated value of the merchantable timber losses using different discount rates. When valued at the time they occurred (i.e. undiscounted), the combined value of the three Sirex outbreaks exceeded $32 million. In contrast, applying a commercial discount rate (7%) reduced the value of the outbreaks to $7 million. Other uncosted Sirex outbreaks that occurred within Victoria in the 1960s and early 1970s would add to these cost estimates; we did not, however, have adequate data for these to be included.

Combining costs of Sirex control and Sirex outbreaks

Two of the three major Sirex outbreaks occurred after a decision had been made to invest heavily in the National Sirex Control program. For this reason, we believe it appropriate to add the costs of these outbreaks to the total cost of the program.

Table 5. Estimated present values of merchantable timber loss, using different discount rates, for the three major Sirex outbreaks at Pittwater, Delatite and Green Triangle

Discount rate (%)	NPV (1952 baseline)
0% (undiscounted)	$32 002 216
3%	$14 571 851
5% (base case)	$9 681 426
7%	$7 019 410

NPV, net present value
All values adjusted to 2015$

Over a 63-year period, we estimate the combined cost of Sirex control and management and merchantable timber losses (from the Delatite and Green Triangle outbreaks) at $28.9 million (NPV using a 1952 baseline and a 5% discount rate).

We were unable to estimate the cost of Sirex under a ‘no control’ scenario, however, the outbreak at Pittwater, Tasmania provided a good indication of the magnitude of merchantable timber losses that can arise under a worst-case scenario. In this case, the Sirex outbreak occurred prior to any major investment in research and development and when there was no effective control available. The NPV of loss due to this outbreak was $5.7 million (Fig. 7). Our analysis of Sirex control costs revealed that a further $5.1 million (NPV using a 1952 baseline and a 5% discount rate) was expended on physical attempts at eradication and quarantine. Hindsight now reveals that attempts at quarantine and eradication were futile. In the absence of investment in Sirex research and development, it may be assumed that these costs would still have been incurred.

Discussion

When Sirex was discovered on the Australia mainland in 1961, estimated merchantable timber loses of $5.7 million (NPV using a 1952 baseline and a 5% discount rate) had already accrued in a single plantation in Tasmania (under what in effect was a ‘no control’ scenario). With over 20 times more plantation area at risk on the Australian mainland, a decision was made to invest heavily in the research and development of Sirex biological control (in 2015$, an average of $1.27 million y^{-1} between 1962 and 1971). We were not able to predict what the impact of Sirex outbreaks might have been (i.e. under a ‘no control’ scenario) had this investment not occurred; certainly, it would have been greater than the $5.7 million attributed to the plantation timber loses at Pittwater, Tasmania. The $5.1 million that was invested in quarantine and physical eradication may have also been higher had a decision been made to pursue this approach as the only strategy.

Although we were unable to generate a benefit:cost ratio (BCR) for the National Sirex Control program, two earlier cost-benefit studies (McKimm 1975; Marsden et al. 1980) did so, and both produced BCRs greater than one). These studies, however, relied upon simplistic modelling scenarios.

What we can conclude from our study is that under a 'no control' scenario Sirex outbreaks (and their capacity to impact on plantation timber values) would have remained an ever-present risk. Being exposed to the risk of Sirex outbreaks without having an effective system of control may have acted as a deterrent to investment and reinvestment in *Pinus* plantation. This in itself would have been an issue, as attracting investment in new *Pinus* plantations in Australia has been difficult (FWPA 2012; Matysek & Fisher 2016) without having the added uncertainty of an uncontrollable exotic pest.

Under our 'control scenario', we found that investment in Sirex research and development was fruitful, with the successful identification and deployment of a suite of parasitoids in the 1970s and the nematode *B. siricidicola*. Coupled with methods to effectively introduce the nematode, the development of a National Sirex Control strategy (Haugen et al. 1990), and ongoing oversight by the National Sirex Control Committee, investment in research was effectively translated to on-ground control. While the industry awaited the delivery of Sirex research, considerable expenditure was directed to operational management. In the 1960s, much of this expenditure was directed to eradication and quarantine measures. Hindsight shows that attempts at quarantine and eradication were futile.

Since 1990, a more effective system of Sirex monitoring and (biological) control has been put in place, and the costs of managing Sirex in recent decades have plateaued (now averaging \$0.57 ha^{-1}). Plantation growers are now well-equipped to manage Sirex in a cost-effective manner. Current Sirex management includes annual aerial and ground surveys of susceptible stands to identify increases in Sirex activity ('hotspots'), which are then targeted with increased trap tree plot intensity, and inoculation of naturally struck trees with nematodes before an outbreak occurs.

Most Sirex attacks occur at low levels (<10% tree mortality) and are referred to as 'natural thinning' agents by some foresters in Australia, and as such are of no consequence. Our simulated 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 plantation trees that have been thinned twice and final crop trees.

Common attributes of the Sirex outbreaks that we studied included below-average local rainfall, overstocked plantations and control measures that were ineffective and or untimely. In the case of the Green Triangle, all of these factors played a part. At the time of the outbreak, the Green Triangle plantations were managed by four separate entities (two public and two privately owned). The records suggest that knowledge of the emerging Sirex problem held by the plantation managers was not shared in a timely manner (Haugen 1990). A compounding factor was the costly deployment (using trap tree plots and inoculation) of a defective nematode strain that did not act as it was intended (Bedding & Iede 2005). Together these factors resulted in a response that was much more reactionary and costly than it might have been.

Our economic evaluation of the National Sirex Control program over 63 years relied upon detailed examination and interpretation of costs using NPV analysis. Sensitivity analysis revealed that changing the discount rate had a major effect on our final figures. At the higher discount rate of 7%, values after 40 years (1992–2014) were ascribed very little value. When no discounting (0%) was applied, the full magnitude of the expenditure was revealed.

We conclude from our study that the arrival and spread of Sirex in Australia has been costly, imposing costs on plantation growers both from actual timber losses and from developing and implementing control programs. These costs were greatest in the early years when effective control techniques were being developed, but quickly reduced once these techniques were deployed.

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