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Post-Border Forest Biosecurity in Australia: Response to Recent Exotic Detections, Current Surveillance and Ongoing Needs

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Abstract: Assessing exotic pest response and eradication programs can identify factors that will lead to increased pest detection and provide information for prioritizing and enhancing future eradication attempts. We review the forest-related insect and pathogen detections and responses in Australia between 1996 and 2017. Thirty-four detections of new exotic forest species were made in this timeframe; seventeen each of insects and pathogens. Twenty-nine of the species are now established in mainland Australia and another in the Torres Strait. Four of the established species cause high impact, and three of these were subject to failed eradication programs. Two of the four established high-impact species were not previously recognised as threats; indeed, 85% of all new detections were not considered high-priority risks. Only one forest pest has been successfully eradicated, suggesting a lower success rate of Australian forest eradication programs than the world average. Most of these exotic pests and pathogens were not detected early enough to attempt eradication, or they were not deemed a significant enough pest to warrant an eradication attempt. Early detection is key to successful eradication. We discuss current surveillance programs in Australia and the methods (general, specific), locations (urban, regional, amenity, plantation, nursery, native forest), and surveillance type (public, industry, ad-hoc researcher, forest health surveillance, high-risk site surveillance, pest-specific trapping) that detections were made under. While there has been an increase in detections using specific surveillance since 2010, there remains a need for a structured national approach to forest biosecurity surveillance, preparedness, and responses.

Keywords: invasive species; biosecurity; emergency response; eradication; forest pests and pathogens

1. Introduction

Many exotic plants were introduced deliberately or unintentionally to Australia following the arrival of Europeans in the eighteenth century [1], and with them, many plant pests. However, Australia remains free from many of the devastating invasive insects and pathogens recorded elsewhere (e.g., [2–7]), with strict biosecurity protocols required to preserve this status [1,8]. Australia has a detailed process to respond to exotic pest incursions affecting plant industries—the Emergency Plant Pest Response Deed (EPPRD) [9]—and for pest incursions that primarily affect the environment and social amenity—the National Environmental Biosecurity Response Agreement (NEBRA) [10]. Nonetheless, several reviews highlighted deficiencies in Australia's biosecurity system with respect to forestry [11–13] and environmental biosecurity [8,14,15]. Significant exotic forest pests have already established in Australia, resulting in ecological impact in native forests (e.g., *Phytophthora cinnamomi*) [16] and financial impact to commercial plantations (e.g., sirex wood wasp, *Sirex noctilio*) [17] and amenity forests (e.g., elm leaf beetle, *Xanthogaleruca luteola*) [18]. Exotic forest pests continue to arrive and establish in Australia [19].

Biosecurity authorities require sufficient information to develop effective policy and implement adequate operational procedures. The Australian Government Department of Agriculture and Water Resources (DAWR) is the lead agency for biosecurity in Australia and collaborates with state and territory governments and technical experts to develop policies, strategies, and procedures for biosecurity surveillance, diagnostics, and national and domestic biosecurity regulations. Accurate and up-to-date information on exotic pest threats, likely pathways, and impacts of exotic pests are required to effectively develop pest and pathway risk assessments and ensure adequate preparedness and response procedures are developed. Data on established exotic pests can be used for ex post risk assessments and to inform ex ante risk assessments to improve our understanding of invasion pathways and identify management strategies to prevent invasions of exotic forest pests [20,21]. Furthermore, reviewing responses to previous exotic pest incursions can identify common factors of successful eradication programs [22–25] and assist in understanding whether response procedures, including capacity, capability and stakeholder engagement, are adequate, and identify strengths and weaknesses in the system.

Early response activities to the detection of exotic plant pests in Australia were relatively informal, ad hoc, and conducted on a case-by-case manner, unlike formal procedures in place for animal health [14,15]. Following recommendations by Nairn et al. [15], Plant Health Australia (PHA) was incorporated in 2000 to facilitate preparedness and response arrangements between governments and industry for plant pest incursions [26]. In 2005, Australia ratified a system for coordinated, rapid and comprehensive responses to pest incursions, the EPPRD, which is a legally-binding agreement between the Australian Government, state and territory governments, and plant industry bodies that covers the management and funding (including cost-sharing and owner reimbursement) of agreed responses to the detection of exotic plant pests [9]. A national response plan (PLANTPLAN) was subsequently developed to provide incursion management guidelines in the event of an exotic plant pest detection and outlines procedures, roles and responsibilities for all parties, including government and industry [14,27]. When a suspected exotic pest is detected, delimiting surveys are conducted to determine the distribution of the pest, assess the likely economic, environmental or social impacts, and identify potential control options. This information is then used by a national committee (Consultative Committee on Emergency Plant Pests (CCEPP)) to determine whether the pest is technically feasible and cost-beneficial to eradicate [9].

Eldridge and Simpson [28] summarised early response activities to several forest pest detections in Australia. When *S. noctilio* was detected in Tasmania in 1952, an eradication attempt was made, including destroying 3000 trees in a single plantation, followed by a prolonged but ultimately fruitless effort in the 1960s and 1970s to eradicate the pest from mainland Australia through movement restrictions and tree destruction. Following the discovery of dothistroma needle blight (*Dothistroma septosporum*) in New South Wales in 1974, plans were in place to burn the affected plantation but were delayed due to rain, and the disease was then found further afield. Similarly, a decision was made to try to eradicate poplar rust (*Melampsora medusae* and *M. larici-populina*) following its detection in New South Wales in 1974, but it was subsequently found to have spread further, and eradication was abandoned [29]. All are now significant pests in Australia: *S. noctilio* and *D. septosporum* require ongoing management and control in *Pinus* plantations, and *M. medusae* and *M. larici-populina* "ruined the poplar plantation industry in Australia ... in its infancy" [28].

Since 2005, the implementation of the EPPRD has resulted in more structured and coordinated responses to exotic plant pest detections, including equitable cost-sharing between government and industry for the cost of eradication and response. However, recent reviews identified the need for a more coordinated approach to forest biosecurity in Australia [13,19] and highlighted the risks and costs of exotic forest pests to the Australian forest industry [17,30]. This led to the development of the National Forest Biosecurity Surveillance Strategy (NFBSS) [31] and appointment of a National Forest

Biosecurity Coordinator [32]. A major goal of the NFBSS, "to reduce the risk of establishment of exotic forest pests", provides a timely opportunity to investigate patterns associated with the establishment of recent exotic forest pests and pathogens in Australia. Our aims were three-fold: (1) To collate, analyse and summarise data on detection and response by government and industry to exotic forest pest incursions over the last two decades; (2) to review the success of eradication programs; and (3) to make recommendations to improve early detection of future incursions of exotic forest pests and thereby improve the likelihood of successful eradication.

2. Detection and Responses to Exotic Forest Pests and Pathogens in Australia

2.1. Methods

We compiled data on the national response activities following the detection of exotic forest pests in Australia from 1996 to 2017 (Table 1); prior to this date, information is incomplete. Data were obtained from published sources, including the annual Plant Biosecurity Status Reports (e.g., [33,34]), International Plant Pest Convention Pest Reports (https://www.ippc.int/en/countries/australia/pestreports/), GERDA (b3.net.nz/gerda) [35] and elicitation from biosecurity personnel. We ascertained the type of surveillance [36] undertaken to detect the pest as: (a) general ('passive') surveillance, where new detections were reported by the public, researchers, diagnostic laboratories, or industry; or (b) specific ('active') surveillance, where new pests were detected via targeted surveillance programs for early detection, such as high-risk site surveillance (HRSS), forest health surveillance, or surveillance during an emergency response. A six-point scale was further used to reflect surveillance type for each detection with increasing levels of intensity/specificity: (1) public; (2) industry; (3) researchers during non-surveillance activities; (4) forest health surveillance; (5) HRSS or emergency response; and (6) pest-specific trapping (e.g., Asian gypsy moth/*Lymantria* delta traps). Detections were compared between states and divided into urban and regional detections, as well as whether they occurred on amenity, plantation, nursery, or native forest trees. Species were categorised as low, medium, or high impact according to literature and expert knowledge (Table 1). Low impact species were those where no intervention, management, or damage records were found; medium impact species had evidence of damage, management or control but this was either short-term, localised or minor; and high impact species were those that required ongoing management, and/or had significant economic or environmental effects recorded. Where appropriate, frequencies were compared using one- and two-way Chi-square tables.

Table 1. Exotic forest pests detected in Australia 1996 to 2017.

Species	Common Name	Division/Order (Family)	Year	Main host/s	Surveillance Type [a]	Surveillance Level [b]	Detection Location [c]	Detection Region [d]	State	Response [e]	Status [f]	Impact [g]	References
Arhopalus rusticus	longicorn beetle	Coleoptera (Cerambycidae)	2000	*Pinus*	S	5	A	U	Vic	N *	E	L	[37,38]
Austropuccinia psidii	Myrtle rust	Basidiomycota/ Pucciniales	2010	Myrtaceae	G	2	N ^	R	NSW	E	E	H	[38–41]
Bursaphelenchus aff. *vallesianus/sexdentati*	pinewood nematode	Nematoda (Aphelenchidae)	2016	*Pinus*	S	5	A	U	NSW	N	E	L	[42,43]
Bursaphelenchus hildegardae	pinewood nematode	Nematoda (Aphelenchidae)	2016	*Pinus*	S	4	P	R	NSW	N	E	L	Carnegie et al. unpublished
Bursaphelenchus hunanesis	pinewood nematode	Nematoda (Aphelenchidae)	2000	*Pinus*	G	1	A	U	Vic	E	Er	n	[37,38]
Chaitophorus leucomelas	Black poplar leaf aphid	Hemiptera (Aphididae)	2011	*Populus*	S	5	A	U	NSW	N	E	L	[44], P. Gillespie (NSWDPI) pers. comm.
Cinara pilicornis	Spruce shoot aphid	Hemiptera (Aphididae)	2008	*Picea*	G	2	N	U	Vic	N	E	L	APPD; D. Smith (AgVic) pers. comm.
Colletotrichum salicis	Willow black canker	Ascomycota/ Glomeralles	2005	*Salix*	G	3	A	R	NSW	N	E	L	[45,46]
Corythucha ciliata	Sycamore lace bug	Hemiptera (Tingidae)	2006	*Platanus*	G	3	A	U	NSW	N	E	M	[47], P. Gillespie (NSWDPI) pers. comm.
Cryphonectria parasitica	Chestnut blight	Ascomycota/ Diaporthales	2010	*Castanea*	G	2	P	R	Vic	E	U	H	[42,48]
Diplodia africana	Diplodia canker	Ascomycota/ Botryosphaeriales	2009	*Pinus*	G	1	A	U	Vic	N	E	L	[49], D. Smith (AgVic) pers. comm.
Essigella californica	Monterey pine aphid	Hemiptera (Aphididae)	1998	*Pinus*	G	3	A	U	ACT	N *	E	H	[50]
Grosmannia huntii	blue stain	Ascomycota/ Ophiostomatales	1998	*Pinus*	G	3	P	R	NSW	N *	E	L	[51]

Table 1. *Cont.*

Species	Common Name	Division/Order (Family)	Year	Main host/s	Surveillance Type [a]	Surveillance Level [b]	Detection Location [c]	Detection Region [d]	State	Response [e]	Status [f]	Impact [g]	References
Hylotrupes bajulus	European house borer	Coleoptera (Cerambycidae)	2004	*Pinus* (dead)	G	1	H	U	WA	E	E	H	[35,52]
Kybos lindbergi	Birch leafhopper	Hemiptera (Cicadellidae)	1998	*Betula*	G	1	A	R	NSW	N *	E	L	[53]
Lophodermium conigenum	Lophodermium needle cast	Ascomycota/ Rhytismatales	2001	*Pinus*	G	3	P	R	Vic	N *	E	L	[54]
Marchalina hellenica	Giant pine scale	Hemiptera (Margarodidae)	2014	*Pinus*	G	1	A	U	Vic/SA	E	E	H	[34,42]
Nematus oligospilus	Willow sawfly	Hymenoptera (Tenthredinidae)	2004	*Salix*	G	3	A	U	ACT	N *	E	M	[55,56]
Olivea tectonae	Teak leaf rust	Basidiomycota/ Pucciniales	2006	*Tectona*	G	2	P	R	NT	N	E	L	[57,58]
Ophiostoma angusticollis	blue stain	Ascomycota/ Ophiostomatales	2017	*Pinus*	S	4	P	R	NSW	N	E	L	NMG 2018 [#]
Ophiostoma pallidulum	blue stain	Ascomycota/ Ophiostomatales	2016	*Pinus*	S	4	P	R	NSW	N	E	L	NMG 2018 [#]
Phytophthora niederhauserii	dieback	Oomycota/ Peronosporales	2002	Polyphagous	G	3	N	R	NT/WA	N *	E	M	[59]
Psyllopsis fraxinicola	Ash leaf psyllid	Hemiptera (Psyllidae)	2003	*Fraxinus*	G	3	A	U	Vic	N *	E	L	APPD
Quadrastichus erythrinae	Erythina gall wasp	Hymenoptera (Eulophidae)	2013	*Erythina*	S	5	A	R	Qld	N	E *	L	[33], M. Ashton (QDAF) pers. comm.
Rugonectria castaneicola	Rugonectria canker	Ascomycota/ Hypocreales	2015	*Quercus*	G	3	A	U	NSW	N	E	L	[34], Carnegie et al. unpublished
Shivaphis celti	Asian woolly hackberry aphid	Hemiptera (Aphididae)	2013	*Celtis*	S	5	A	U	NSW	N	E	L	[60], R. Rickard (DAWR) pers. comm.

Table 1. *Cont.*

Species	Common Name	Division/Order (Family)	Year	Main host/s	Surveillance Type [a]	Surveillance Level [b]	Detection Location [c]	Detection Region [d]	State	Response [e]	Status [f]	Impact [g]	References
Siphoninus phillyreae	Ash whitefly	Hemiptera (Aleyrodidae)	1998	*Fraxinus*	G	3	A	R	SA	N *	E	M	[61]
Teratosphaeria destructans ‡	Eucalypt leaf blight	Ascomycota/ Capnodiales	2006	*Eucalyptus*	G	3	P ^	R	NT	u	n	n	[62,63]
Thyronectria pinicola	canker	Ascomycota/ Hypocreales	2012	*Pinus*	S	4	P	R	NSW	N	E	L	[64]
Tremex fuscicornis	Tremex wasp	Hymenoptera (Siricidae)	1996	*Salix, Populus*	G	1	A	R	NSW	N *	E	L	State Forests of NSW unpublished
Trichoferus campestris	Chineses longhorned beetle	Coleoptera (Cerambycidae)	2016	Polyphagous (*Pinus*)	S	3	A	U	Qld	n	D	n	[42,65]
Tuberolachnus salignus	Giant willow aphid	Hemiptera (Aphididae)	2014	*Salix*	G	1	A	R	Tas	N	E	L	[33], L. Hill (DPIPWE) pers. comm.
Xanthomonas axonopodis pv. unnamed	Mahogany angular leaf spot	Proteobacteria/ Xanthomonadales	2009	*Khaya*	G	2	N	R	NT	N	E	L	[66]
Xylosandrus crassiusculus	Asian ambrosia beetle	Coleoptera (Curculionidae)	2016	Polyphagous	G	3	P	R	Qld	N	E	L	[42]

[a] Surveillance type: G: General, S: Specific; [b] Surveillance level: 1 = public, 2 = industry, 3 = researcher, 4 = forest health surveillance, 5 = high risk site surveillance; [c] Detection location: A: Amenity, H: House, N: Nursery, P: Plantation (exotic host unless ^); [d] Detection region: U: Urban, R: Regional; [e] Response: N: Not technically feasible/cost beneficial to eradicate (N * = prior to EPPRD), E: Eradication attempted, u: unknown; [f] Status: E: Established, Er: Eradicated, U: Under eradication, D: Did not establish (E*established in Torres Strait); [g] Impact: L: Low, M: Medium, H: High, n: not applicable. # NMG = National Management Group Talking Points, unpublished; ‡ The pathogen identified as *Teratosphaeria destructans* was later determined to be a new species [62].

2.2. Detections of Exotic Forest Pests

There were 34 detections (17 insects and 17 pathogens) of new exotic forest pests in Australia between 1996 and 2017; an average of 1.5 ± 0.3 each year. Forty-four percent of all detections were made in New South Wales, and 26% were made in Victoria (Figure 1). Twenty-nine of these species (85%) are now established in mainland Australia (Table 1), and one in the Torres Strait; five have spread to five or more states. Of the four that did not establish, one was eradicated (pinewood nematode, *Bursaphelenchus hunanesis*) [37,38], one is currently under an eradication program (chestnut blight, *Cryphonectria parasitica*) [9], another (initially identified as eucalypt leaf blight, *Teratosphaeria destructans*) was later deemed to be native following taxonomic revision [62,63], and one (Chinese longhorn beetle, *Trichoferus campestris*) was reported from a single trapped male specimen and not found again, despite intensive surveys and trapping in the vicinity of the initial detection [65]. Two of the detections were previously declared High Priority Pests (HPP) in Australia: *C. parasitica* and myrtle rust (*Austropuccinia psidii*), while the European house borer (*Hylotrupes bajulus*) and erythrina gall wasp (*Quadrastichus erythrinae*) were also recognised as exotic threats, but the remaining 85% had not been flagged as significant risks by industry or government prior to their arrival [9,67]. *Teratosphaeria destructans* was also a recognised HPP at the time of detection [63]. However, we found no record that a CCEPP with appropriate technical experts was formed following its detection and subsequent reporting to biosecurity authorities.

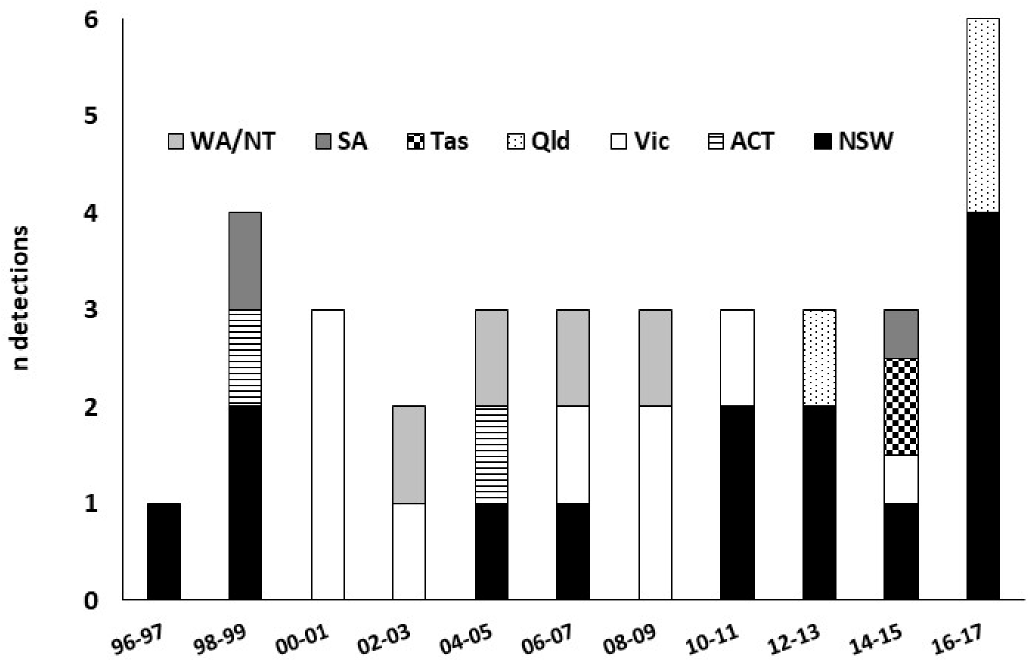

Figure 1. Number of new forest pest detections biennially between 1996 and 2017 in Australia and the state in which they occurred (Queensland (Qld) = stippled; New South Wales (NSW) = black; Australian Capital Territory (ACT) = striped; Victoria (Vic) = white; Tasmania (Tas) = checkered; Northern Territory/Western Australia (NT/WA) = light grey; South Australia (SA) = dark grey).

About half of the recent establishments are primarily pests of amenity trees, twelve are pests primarily in plantations (mainly *Pinus*), and two are pests primarily of hosts in native forests. *Hylotupes bajulus* was found in standing dead pine trees, following its initial detection in structural timber in a dwelling in Perth, and later mostly found in dead *Pinus* in urban areas and plantations [52,68]. *Hylotrupes bajulus* is one of four exotic pests established over the past two decades, causing significant impact. The others are *A. psidii* [41,69,70], Monterey pine aphid (*Essigella californica*) [71,72], and giant pine scale (*Marchalina hellenica*) [8], the latter mainly because of the economic cost of the eradication and 'transition to management' programs. *Marchalina hellenica* and *E. californica* were not considered

HPP to Australia: *M. hellenica* had not previously been recorded as invasive outside its region of origin, and *E. californica* caused little damage in its invaded range [50]. None of the four species with medium level impacts (*Corythucha ciliata*, *Nematus oligospilus*, *Phytophthora niederhauserii* and *Siphoninus phillyreae*, Table 1) were listed as HPPs. Despite comprising around one-third of recent detections and establishments, and half of the eight species causing medium-high impact, no Hemiptera are currently listed as high priority forestry pests in Australia [9,73,74].

Seventy-one percent of detections of exotic Australian forest pests since 1996 occurred via general/passive surveillance (public, researchers, or industry), rather than during specific/active surveillance (Figure 2), with insects and pathogens equally likely to be detected by either surveillance type ($\chi^2_1 = 0$, $p = 1$). Likewise, in New Zealand, from 2011 to 2014, a similar proportion (66%) of exotic plant pest incursions were detected by general surveillance (public, researchers, industry) compared with 34% by specific surveillance (biosecurity officers) [75]. By the very nature of general surveillance, pests are often detected only after they have established and spread [76]. Of the 71% of detections made by general surveillance in our study, 24% were made by the public, 35% by researchers, and 12% by industry. Although there is currently no formal national forest post-border biosecurity surveillance program in Australia [11,13], there has been a significant increase in detections of new pests via specific surveillance since 2010 ($\chi^2_1 = 12.1$, $p < 0.001$; Figure 2). Some of these pests were detected in urban areas under national or state biosecurity surveillance programs (Table 1): e.g., black poplar leaf aphid (*Chaitophorus leucomelas*) under the National Plant Health Surveillance Program (NPHSP); Asian woolly hackberry aphid (*Shivaphis celti*) under the National Border Surveillance program; and pinewood nematode (*Bursaphelenchus* aff. *vallesianus/sexdentati*) under the New South Wales Forestry High Risk Site Surveillance Program. Others were detected during forest health surveillance programs in plantations, which have recently incorporated targeted biosecurity surveillance activities to detect exotic or cryptic pests [11]: e.g., the blue stain fungi *Ophiostoma pallidulum* and *O. angusticollis*, and pinewood nematode (*B. hildegardae*)—the first records for these pests in the Southern Hemisphere.

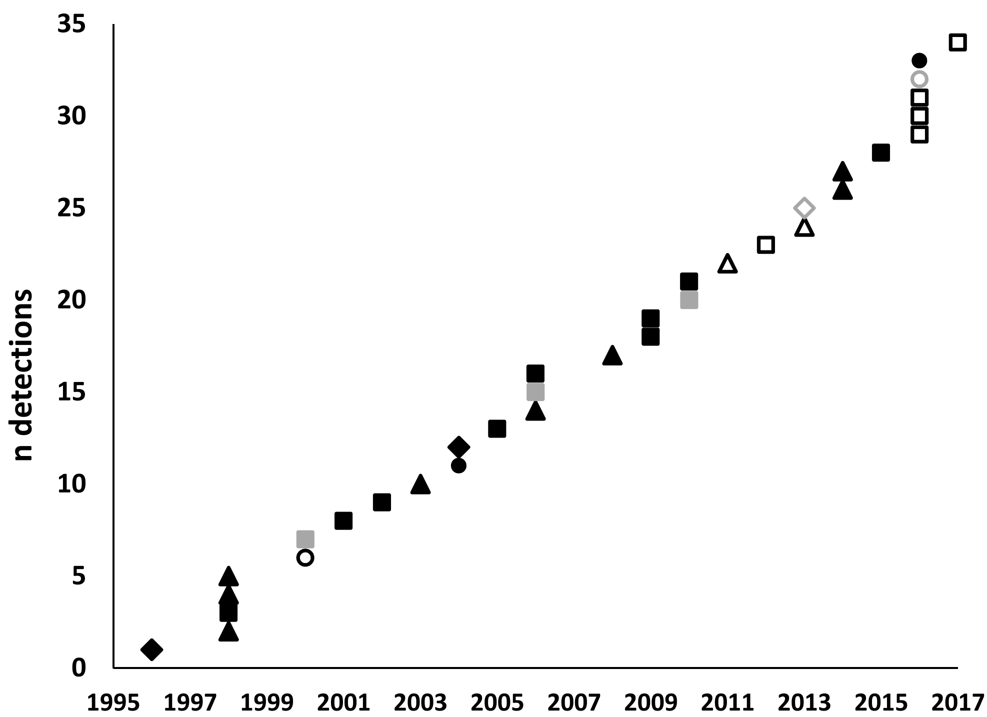

Figure 2. Accumulation of new exotic forest pest species detected in Australia between 1996 and 2017 made by general (solid) and specific (open) surveillance methods as defined by the Food and Agriculture Organization [36]. Insects are designated by Coleoptera = circles ($n = 4$); Hemiptera = triangles ($n = 10$); other = diamond ($n = 3$) and pathogens = squares ($n = 17$). Species that established in mainland Australia are in black, while those that did not establish are in grey.

Detections were equally distributed among urban (15 detections) and regional (19 detections) areas ($\chi^2 = 0.47$, $p = 0.49$), with amenity detections more prevalent within the former and nursery/plantation detections more prevalent in regional areas ($\chi^2_1 = 12.2$, $p < 0.001$). The majority (59%) of all detections were made on amenity trees and accounted for all public and high-risk site surveillance detections (Figure 3). Insects were more often detected on amenity trees than nursery/plantation trees, and pathogens were more often detected on nursery/plantation trees ($\chi^2_1 = 12.1$, $p < 0.001$); only pathogens (4 species) were detected during forest health surveillance activities. Serendipitous or ad hoc discoveries by researchers were made across all host types (Figure 3), and equally between urban and regional areas ($\chi^2 = 0.3$, $p = 0.56$); no detections were made in native forests, or through pest-specific trapping.

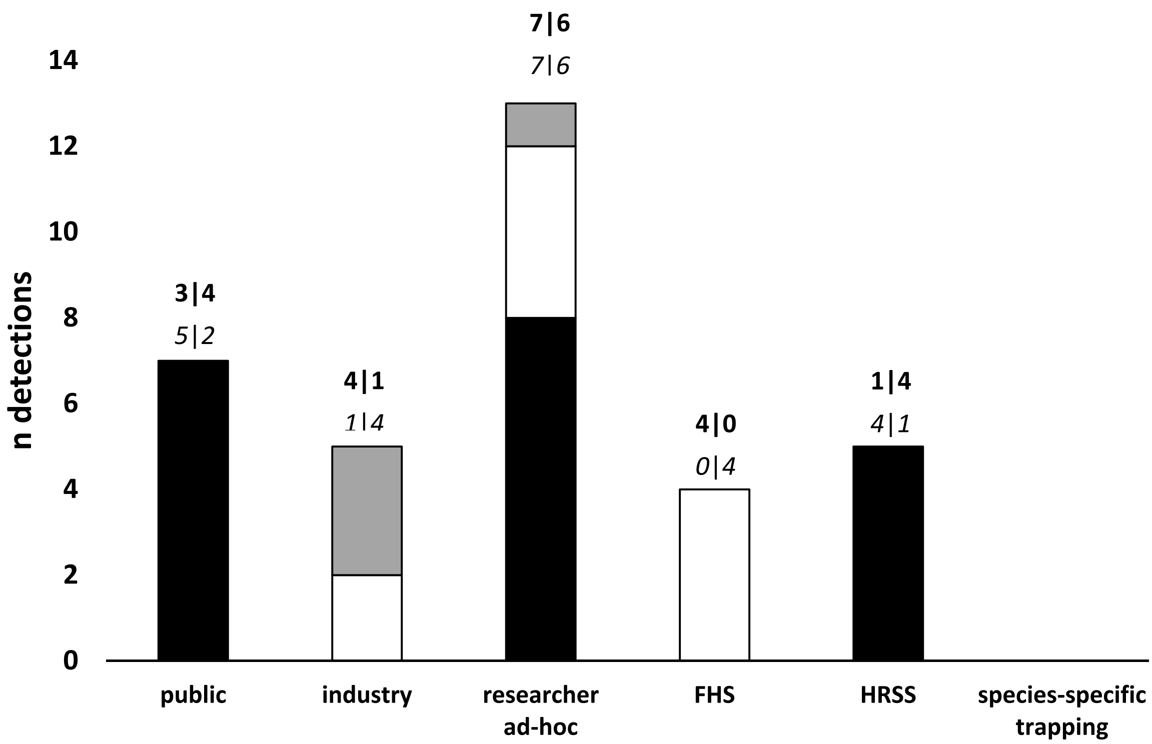

Figure 3. Detections of new exotic forest pest species in Australia since 1996 broken down into surveillance type (public, industry, researcher, forest health surveillance, high-risk site surveillance, and specific pest surveillance) and detection host location types (amenity = black, plantation = white, nursery = grey). Numbers above bars show the number of regional or (|) urban detections (bold), and insects or (|) pathogens (italics), respectively.

2.3. Response to Detections

For most (85%) pests detected since 1996, eradication was not considered technically feasible or cost-beneficial. That is, most of these pests were deemed unlikely to cause significant damage in Australia due to their low pest status overseas or because their hosts were not important tree species in Australia; or because detection did not occur until post-border establishment and extensive spread [77]. Examples of detections that were subsequently found to be already established include *E. californica* on *Pinus*, lophodermium needle blight (*Lophodermium conigenum*) on *Pinus*, birch leafhopper (*Kybos lindbergi*) on *Fraxinus*, willow black canker (*Colletotrichum salicis*) on *Salix*, and teak leaf rust (*Olivea tectonae*) on *Tectona* (Table 1). Similarly, most plant pests detected in New Zealand from 1990 to 2003 were already widely dispersed prior to detection and established well beyond a level where eradication would be cost-effective [76]. Liebhold et al. [23] noted that eradication is not attempted for the majority of new pest detections, as they are not detected early enough for eradication to be practical. Moreover, many species are not determined to be cost-beneficial to eradicate based on anticipated impacts.

Only one forest pest detected in Australia has been eradicated: *Bursaphelenchus hunanensis*, detected in Melbourne in 2000 and eradicated by 2004 [37,38]. Following detection, aerial and ground surveillance identified over 450 dead trees in metropolitan areas, which were subsequently tested for nematodes. Tree destruction and deep burial were then carried out on nematode-infested trees with 35 trees destroyed. Panel trapping and monitoring of log emergences lead to the detection of the pine longicorn *Arhopalus rusticus*; a new exotic pest detection for Australia. However, a primary vector of *B. hunanensis* was not found. This eradication campaign was successful for several reasons. Firstly, the nematode was detected prior to substantial spread, and a vector for *Bursaphalenchus* spp. is not established in Australia, and none established with the nematode incursion. Secondly, affected trees were easy to detect (dead *Pinus* trees in an urban environment) and destroy. Thirdly, experienced forest-industry health experts were involved in the operational program. Importantly, a cost-sharing arrangement (prior to the formal arrangements made under the EPPRD) was made between industry (at the time the majority were state government growers) and the Australian Government, but the cost of the program is not publicised.

Cryphonectria parasitica is currently under an eradication program under the EPPRD (http://www.outbreak.gov.au/); it had previously been identified as an HPP in Australia because of its significant impact in North America [2]. The pathogen was detected in chestnut (*Castanea* spp.) orchards in regional Victoria in 2010. Surveillance has concentrated on chestnut orchards and amenity trees (*Castanea* spp. and *Quercus* spp.), with all affected trees destroyed and, in some cases, whole orchards destroyed, with compensation provided to growers. In 2016, the response transferred to the 'proof of freedom' phase, following a period of zero detections from surveillance activities [42]; however, more recent detections have raised uncertainty around latent infections and the eradication program is currently being reviewed [9]. The direct cost (i.e., the agreed cost-shared amount of the response, as defined by the EPPRD) of the *C. parasitica* eradication program to date is AU $3.75 million, funded primarily by governments [8], but the total program costs *sensu* Tobin et al. [78] (e.g., in-kind from government and industry) are unpublicised.

Unsuccessful eradication attempts were made for three species over this period. *Austropuccinia psidii* was detected in Australia in 2010 [39], and eradication was attempted but abandoned later that year as it was discovered in native forests [40,79]. The *A. psidii* eradication program involved extensive surveillance, public awareness, host destruction, and movement restrictions of nursery material. The direct cost of the program was AU $3.55 million, funded by governments, with total response costs approx. AU $5 million. The nursery and garden industry estimated the cost of increased fungicide application, intra- and interstate plant movement restrictions, and finding acceptable alternatives to highly susceptible species, was over $9 million in Queensland alone [G. Pegg, pers. comm.]. A further $4.3 million has been spent on research to manage and monitor impact of the disease. *Austropuccinia psidii* has now spread along the east coast of Australia, with localised distribution in Victoria, Tasmania, and the Northern Territory [80], and is causing significant impact to native plant communities [41,69,70]. Several reviews of the emergency response to myrtle rust [41,79,81] identified the haste with which the initial decision that eradication was not feasible was made and the confusion surrounding the taxonomy (name) as key deficiencies in the response.

Marchalina hellenica was detected in Melbourne, Victoria, and Adelaide, South Australia in 2014 ([42], http://www.outbreak.gov.au/). Extensive surveillance and public awareness, including for arborists, was carried out; tree destruction was conducted in Adelaide and appeared successful. Tree destruction was initially conducted in Melbourne, but with over 4300 trees affected, chemical control (imidacloprid) was the preferred option. Chemical control was later found to be ineffective, and the eradication program was halted and moved to a 'transition to management' program, which included research on chemical control, a biocontrol feasibility study, and strategic tree destruction to slow the spread of the pest. *Marchalina hellenica* is currently restricted to trees in Melbourne, with the direct cost of the emergency response and 'transition to management' programs AU $4.4 million, funded equally by governments and the softwood plantation industry [8], and total program costs likely to exceed

AU $6 million. A major reason *M. hellenica* was determined no longer technically feasible to eradicate from Melbourne once chemical control was deemed ineffective is that it was assumed that destroying over 4300 *Pinus* trees in urban areas would not be publicly acceptable [http://www.outbreak.gov.au/], although broad public consultation was not conducted to determine this fact. Almost 100 trees were destroyed to eradicate *M. hellenica* from Adelaide [http://www.outbreak.gov.au/], and tree-destruction was used to successfully eradicate *B. hunanensis* from Melbourne [37,38], albeit smaller numbers of trees. Despite the initial assumptions regarding public acceptance, over 150 trees have been destroyed in Melbourne as part of the *M. hellenica* 'transition to management' program with support from local councils, golf courses, and the public [Australian Forest Products Association Growers Chamber 2018, unpublished]. Liebhold et al. [23] stressed the importance of gaining public support for eradication programs, especially those involving host tree removal or pesticides.

The 2004 discovery of the European house borer (EHB) (*Hylotrupes bajulus*) in *Pinus* timber in a dwelling in Perth, Western Australia precipitated an eradication program that involved large scale surveillance of over 12,000 sites (homes and trees), restricted movement zones (quarantine), and destruction of urban and plantation trees to control the pest (https://www.agric.wa.gov.au/ehb/about-european-house-borer, [52,68]). An EHB Emergency Response Plan was nationally agreed and funded to contain and potentially eradicate EHB. However, by 2010 the eradication program was deemed to have failed due to EHB spreading faster than anticipated [35,82], although the infestation may have been present for up to fifty years prior to its detection [52]. The initial program funding was AU $9.7 million, funded by the Western Australian Government, then AU $20.8 million from 2006 to 2011 through a national cost sharing agreement between State and Commonwealth governments, including the forest industry, with a further AU $4.9 million committed by the Western Australian Government in 2014 for containment [83]. Economic analysis of the benefits of ongoing containment activities resulted in a further AU $5 million committed by the Western Australian Government through to 2022 (J. Crisp, pers. comm.).

When *B.* aff. *vallesianus/sexdentati* was detected in 2016, 5 km from a major port facility in Sydney, New South Wales, the initial response involved tree destruction as a precautionary step, while ongoing delimiting surveillance determined whether or not it was established and had spread [43]. These activities were carried out by the state department in charge of biosecurity, but not as part of a national cost-sharing response under the EPPRD. Surveillance was conducted to gather more information on the distribution of the pest to determine whether it was technically feasible and cost-beneficial to eradicate. However, *B.* aff. *vallesianus/sexdentati* was found to be more widely distributed within the Sydney basin, and then later within *Pinus* plantations in regional New South Wales, and the response was abandoned. The nematode has since been determined to not be a primary pathogen on *Pinus* in Australia. This result highlights the need to understand what pests are already present to better inform response decisions [84]. At the time of this detection, targeted sampling for nematodes was not routinely conducted during forest health surveillance, and so the presence of this nematode, already established in regional areas, went undetected.

Similarly, three very recent pest detections (*Ophiostoma pallidulum, O. angusticollis* and *B. hildegardae*) were of pests that had already established and spread (into plantations), and so eradication was determined by CCEPP not to be technically feasible or cost-beneficial. However, if they had been detected at a port-of-entry and not spread far, eradication could have been considered. Historical forest health surveillance and detection of blue stain associated with *I. grandicollis* in Australia has generally assumed the species is *Ophiostoma ips*, based on the association or morphology of fruiting bodies or cultures; rarely are molecular diagnostics conducted. The blue stain pathogen *O. ips* has been in Australia since the 1940s [85] and is the most common fungal species associated with the five-spined bark beetle (*Ips grandicollis*) in *Pinus* plantations [86]. The recent inclusion of biosecurity surveillance within forest health surveillance programs [11] is now detecting cryptic pests that have likely been in Australia for many years, if not decades, and has seen a rise in detections since 2015 (see Figures 1 and 2).

3. Current Biosecurity Surveillance for Early Detection of Exotic Plant Pests

Australia has a robust biosecurity system that includes activities pre-border, at the border, and post border, i.e., encompassing the 'biosecurity continuum' [77]. The Australian Government DAWR funds several national post-border surveillance programs for plant pests, including Asian gypsy moth, fruit flies, and the multi-plant pest National Plant Health Surveillance Program (NPHSP), as well as the Northern Australia Quarantine Strategy (NAQS) [11,13,42]. A review of post-border biosecurity surveillance in Australia identified gaps in surveillance of forest pests, as well as inconsistencies in surveillance targets for the NPHSP [11,13]. Several national inquiries have also identified a lack of biosecurity surveillance for environmental pests [8,14]. In recognition of gaps in the current system and the need for industries to share the cost of biosecurity [8], several plant industries have developed their own biosecurity programs, co-funded by the government, that include post-border surveillance: honey bee industry (http://www.planthealthaustralia.com.au/national-programs/national-bee-biosecurity-program/), citrus industry (http://www.planthealthaustralia.com.au/national-programs/citrus-biosecurity-program/) and grains industry (http://www.planthealthaustralia.com.au/national-programs/grains-farm-biosecurity-program/). The forest industry has recently followed suit, with the National Forest Biosecurity Surveillance Strategy [31].

Current Post-Border Surveillance for Forest Pests

Forest biosecurity surveillance in Australia has recently been reviewed in detail [11–13,19]. Pilot high risk site surveillance (HRSS) programs that included blitz surveys, trapping, and the planting of sentinel trees around port environs were conducted in Queensland and Tasmania in the early 2000s, but funding was discontinued [84,87]. A sentinel site program was initiated in Victoria in the late 2000s utilising local council tree databases [88] and has more recently been utilised in emergency response programs, including *A. psidii* and *M. hellenica*. The Australian Government (DAWR) currently funds the NPHSP and a separate Asian gypsy moth trapping program [42,77]. The NPHSP, which includes host and habitat surveillance, is primarily focused on agricultural and horticultural pests, but in some states includes trapping for forestry pests [13,19]. New South Wales initiated a forestry HRSS program in 2014 that includes monitoring of over 1500 sentinel trees and insect trapping around ports-of-entry. In recognition of a lack of ongoing funding for forest post-border surveillance and gaps in forest pest biosecurity capacity at a national level, DAWR recently funded a project as part of the National Forest Biosecurity Surveillance Strategy that includes HRSS [32].

4. Discussion

The feasibility, cost, and probability of successful eradication is influenced by timely detection of post-border arrival/establishment of exotic species, which is facilitated by effective surveillance systems [22,23]. The Generalised Invasion Curve [http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/protecting-victoria] highlights the benefits of timely detection of an invasive (exotic) pest [89,90]. Prevention of entry is the most cost-effective solution, while successful eradication of an exotic pest incursion, post-border, becomes less likely and more costly the further the pest spreads through time and space. Once established, high-impact pests are likely to require costly and long-term control efforts. In Australia, examples of the latter include *S. noctilio* in *Pinus* plantations, estimated to have cost more than AU $35 million in lost timber production and management interventions since 1952 [17]; *Phytophthora cinnamomi*, which, apart from ecosystem impacts and loss of biodiversity [16], can cost land management agencies and mining companies in excess of AU $1.5 million per annum in prevention and management procedures [91,92]; and *X. luteola*, with surveillance, chemical control, and tree removal costs for local councils up to AU $250,000 pa ([18], D. Smith, pers. comm.).

Here, we introduce a generalised Surveillance Effectiveness Curve to illustrate the benefits of investing in targeted post-border surveillance—to detect new exotic pest incursions—in increasing the likelihood of successful eradication (Figure 4). In parallel with the generalised invasion curve, we can see that investment in structured surveillance increases the chances of early detection, thus reducing the cost—and increasing the probability of success—of eradication. Broadly, surveillance methods to detect new exotic pest establishments involve trapping, visual searches, and reports by citizens [23]. Our curve shows that these methods have different costs associated with them: as a surveillance method, public reporting is less costly than a trapping program. However, as many detections are made through activities that are not dedicated to biosecurity surveillance—by industry, researchers, and forest health surveillance (FHS)—there is not a direct relationship between detection costs and early detection success. For example, FHS is a detection method more costly and less likely to result in eradication because it is conducted in plantations and primarily aimed at mapping the extent and severity of established or endemic pests. The role of the public in early detection should not be underestimated: Australia's only successful eradication in forestry resulted from a public detection, while almost half of New Zealand's new exotic plant pests are reported by the general public [25,75]. In fact, passive detection, such as public reporting, is linked to a higher likelihood of eradication than searching high risk sites [25]. Moreover, the impact of mobilising public interest through biosecurity awareness is two-fold: increasing prevention/detection of exotic species invasions and increasing support for invasion mitigation measures [93]. Engaging and training city and shire councils, arborists, and community groups likewise increases biosecurity awareness and surveillance in regional and urban centres and can further facilitate early detection. The workload involved with public reports is significant, and while a public pest reporting system is important (e.g., in Australia the Exotic Plant Pest Hotline (http://www.planthealthaustralia.com.au/biosecurity/emergency-plant-pests/reporting-suspect-pests/)), biosecurity agencies require adequate surveillance and diagnostic resourcing to be able to respond to these reports. In New Zealand, although the public detected 42% of new exotic pests from 2011 to 2014, this detection involved a positive rate of only 8% from over 2280 reports [75]. The Queensland citizen science project "WeedSpotters" returned a similar positive detection rate (~10% of >3000 samples were notifiable priority weed incursions) and led to eight new exotic detections in a two-year period [94].

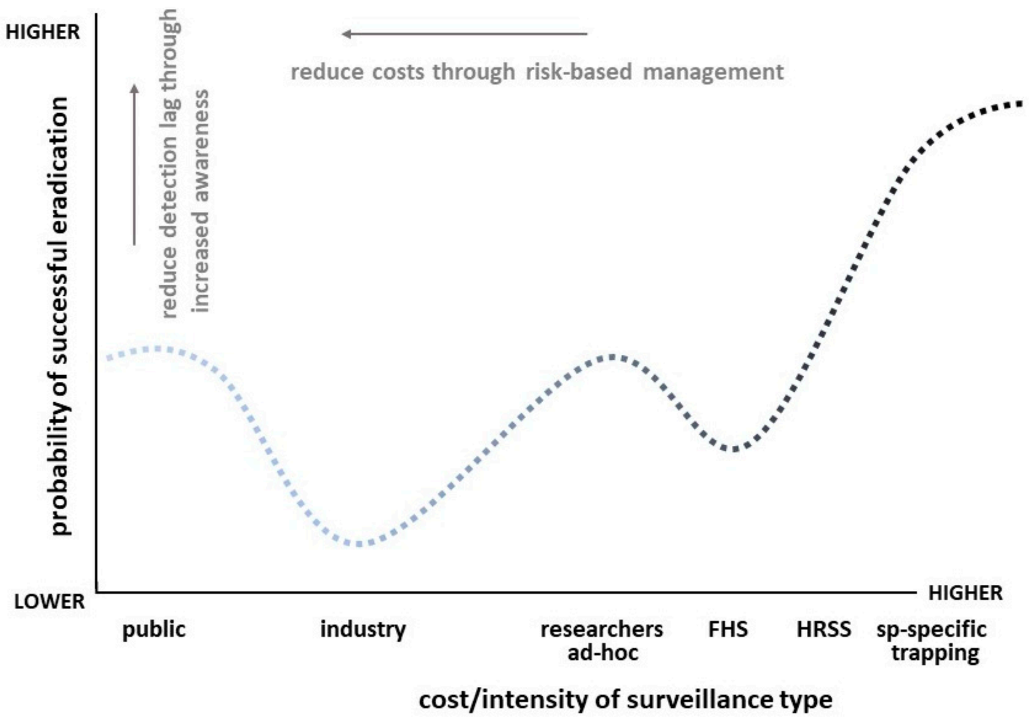

Figure 4. Generalised surveillance effectiveness curve illustrating different surveillance methods for first detections with costs/intensity relative to probability of successful eradication. The colour gradient represents passive surveillance (grey) and active surveillance (black). The former comprises largely visual surveillance, with the grey-black transition illustrating active surveillance via visual searching.

Predictors of successfully eradicable exotic invasions include the size of the infestation, the species' detectability, detection method, and feeding guild [25], with factors such as a low reproductive rate, limited host range, and susceptibility to Allee effects also contributing to the likelihood of eradication [22,25]. Successful eradication also relies on adequate monitoring and control methods, availability of funds, public support, and early detection (a proxy of infestation size) [22,23]. However, most incursions do not warrant the cost and effort of eradication because the pest is considered unlikely to cause a major impact, is too widespread, or lacks suitable treatment options [23,77]. However, for the small number of exotic forest invasions for which eradication is attempted, the majority (53%) are successful [24]. Where eradication was attempted, Australia's eradication success (20%, including the early eradication program against *S. noctilio*, and 25% of completed programs since 1996), therefore, does not reflect this general trend; even adjusted for the over-representation of *Lymantria* eradications, Australia's success rate is almost half that of the global rate (40%, [24]). Improving early detection, and the consequent higher likelihood of eradication, through a coordinated national forest biosecurity program should help to improve Australia's eradication success rate: the long-term benefits of eradication typically outweigh the costs [22,25,95].

As hubs of international activities, including transport, trade, and tourism, urban areas are major hotspots for exotic species arrivals and establishments [96–98]. Urban trees around ports-of-entry have long been recognised as sentinels for early detection of forest pest incursions [84,97,99] and act as 'bridgeheads' for pest invasions to natural forest landscapes or planted forests [96,98]. Indeed, most (59%) detections of forest pests in our study were made through passive visual surveillance via chance encounters (public and ad-hoc researchers), which is less likely to occur at low—and hence eradicable—densities [22]. Increased public awareness and the use of sentinel trees may be methods to improve the efficacy of visual searches, which differ in their cost depending on the mode of deployment (i.e., public and community groups are cheaper than HRSS). Harnessing 'citizen science' via public engagement is an inexpensive and effective post-border surveillance method [25,100,101]. In Australia, as well as providing a quarter of first-record detections, the public assisted with surveillance and reporting of *A. psidii* [40], *H. bajensis* [52], and *M. hellenica* (http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/pest-insects-and-mites/giant-pine-scale) during eradication programs. There is a much larger surveillance capacity in public awareness programs compared to host and habitat search programs which rely on government employees and industry and ultimately result in lower eradication success [25]. This result supports the need for greater awareness and education of the public to garner support and active participation in eradication programs [23].

At the other end of the cost spectrum, HRSS and targeted species-specific trapping around likely points of entry have the greatest chance for early detection of exotic forest species [22]. HRSS involves monitoring at sites identified as high-likelihood entry and establishment points, using a combination of surveillance techniques (i.e., trapping, sentinel tree monitoring, and public awareness). Simultaneous use of traps in ports receiving large volumes of imported commodities, and in their surrounding forests, strongly increases the probability of exotic wood-boring beetle interceptions [102]. Poland and Rassati [101] recommended sentinel tree inspections to detect species for which lures are not available. Australia deploys a targeted network of pheromone traps to detect the Asian gypsy moth (AGM; *Lymantria dispar*) [77]: only sites with a high probability of invasion and greater benefits associated with detection warrant intensive surveillance such as this [103], but to date, there have been no post-border detections of AGM in Australia via any surveillance method. Further, lure-based trapping is costly and only suitable for the mobile stages of particular insect groups [101]; only one Australian forest pest detection (*Trichoferus campestris*) was made by trapping, via a generalist (α-pinene) lure as part of Queensland's NPHSP at high risk sites. Generalist trapping such as this allows detection of low-level populations of taxa groups, rather than individual species, and is often used to target wood-boring Coleoptera which are cryptic and difficult to detect in visual searches [84,87], but results in significant non-target bycatch. Trapping also forms an important component of response plans, with higher eradication success linked to the availability of effective traps for the target exotic pest [25]. However, Hemiptera and pathogens comprised the largest number of detections, and three out of four of the subsequently high-impact species, in our study, but are not generally amenable to trapping [22].

The forest industry facilitates biosecurity awareness for its members, such as through fact sheets of HPP [104], but detections by industry, particularly in plantations, are only likely to be made in situ once the pest has spread from its initial entry and establishment points. Australia's restrictions on the importation of live plant material [1,19,105] reduce the likelihood of production nurseries being the first establishment points, but if detected at these sites, eradication may be possible prior to substantial spread. First detections in plantations, however, are unlikely to be feasible to eradicate. Likewise, forest health surveillance activities in plantations—largely conducted as visual searches—are unlikely to detect new exotic species early enough to warrant eradication (see Figure 4), as plantations are not generally located proximately to arrival and establishment points. Forest health surveillance costs between AU $0.6-$3/ha, and while industry engages in some specific biosecurity activities, they are not the most effective early detection systems [11,106].

Liebhold et al. [23] stressed the importance of gaining public support for eradication programs, especially those involving host tree removal or pesticides. This involves a concerted effort by biosecurity authorities to ensure the public understands the benefits of stopping new pests from establishing, including the potential long-term economic, environmental, and social impacts (e.g., [107–109]). Biosecurity awareness campaigns can increase public and industry reporting of new incursions (already accounting for 35% of forest-related detections in Australia), in addition to garnering public acceptance of incursion management approaches [93,100], such as tree removal.

5. Ongoing Needs

Our work supports the need for a more rigorous and comprehensive framework for preparedness, surveillance, and response to exotic forest pests in Australia [13]. Here, we highlight ongoing needs to achieve this goal. These activities have been identified through the National Forest Biosecurity Surveillance Strategy (NFBSS), with several projects already underway [31,32], and our work has further stressed the need for the implementation of these activities to improve early detection and increase eradication success.

Early detection of invading plant pests is key to being able to effectively respond and increase the success of eradication of potentially high impact species. A Forest Pests High Risk Site Surveillance Program is being developed under the NFBSS [31,32] and, if fully funded, will enhance early detection of invasive pests before they spread. To this end, the Australian Government and forest industry are investigating a funding model to secure long-term funding for forest biosecurity in Australia [32]. A review of high priority pests for the forest industry, and a pest risk and pathways analysis project, both funded under the NFBSS [32], will improve our understanding of threats and identify gaps in current pest entry pathways that require further controls, and assist in identifying high-risk sites to optimise post-border surveillance. As our study illustrated, harnessing the public to assist in detection of exotic pests will greatly increase our chances for the early detection of pests in urban areas, thus increasing eradication success. Training of local councils and arborists in urban areas around ports in several states is already happening; this process needs to be broadened nationally, and a wider range of public groups need to be targeted. The most common detection method, and the only one that occurred across amenity, plantation, and nursery sites—researchers unexpectedly finding a new exotic species during non-surveillance or even leisure activities—pinpoints the importance of ongoing training and awareness within the scientific community.

Knowledge of the pests already established in Australia is important for surveillance programs and to better inform response decisions [84]. Updating and reviewing pest knowledge to support forest biosecurity has been identified as a key action under the NFBSS [32]. We identified several instances where exotic pests were detected, and their status within the country was unknown because surveillance and identification of detections (e.g., at the molecular level) have historically been inadequate. There is a need to ensure that surveillance and sampling, during both HRSS and forest health surveillance, have sufficient resourcing to (a) target cryptic and seemingly innocuous pests, and (b) ensure diagnosis to the molecular level where needed. We are currently compiling a comprehensive database of established exotic species associated with plantation, amenity and native forest trees in Australia [Nahrung and Carnegie in prep.] to help provide a base-line of established exotic forest pests.

The weighting of trapping success towards Coleoptera and Lepidoptera [22], and Coleoptera in hazard site surveillance in Australia [19,84], combined with the abundance of Hemiptera in detections (this study) and establishments [73] as exotics in Australian forests, suggests effective methods for their early detection, along with pathogens which are untrappable and can be cryptic, are required. Proposed incursion preparedness plans [32] will need to consider surveillance and detection methods for HPP as well as diagnostic protocols, quarantine requirements (e.g., host movement restrictions) and control/eradication methods. In addition, the ability to expect and respond to the unexpected is also paramount, given that 85% of detections in the last 20 years—and 75% of subsequently mid- to high-impact species established—were not HPPs.

The success of an eradication program relies on many factors, as reviewed herein, but a key factor is the ability to kill/control the invading pest. The greatest successes globally have been for pests that can be controlled/killed via trapping or insecticide (e.g., AGM [25]), with less success via host removal, e.g., emerald ash borer (*Agrilus planipennis*), although see the Asian longhorned beetle (*Anoplophora glabripennis*) for success [23]). A key lesson from the *M. hellenica* response is that an independent scientific advisory panel [27] that includes government and industry representatives should be formed during the development of a response plan to ensure that control methods are unequivocal before eradication proceeds.

Eradication programs are often carried out in urban settings, so engagement with the public is essential to gaining acceptance for surveillance and control methods and for a broader understanding of the costs and benefits of eradication [23]. Many of Australia's forest and horticulture HPP and urban tree threats are likely to require tree removal as the primary method of control during an eradication program, e.g., mountain pine beetle (*Dendroctonus ponderosae*), pinewood nematode (*B. xylophilus*), pine pitch canker (*Fusarium circinatum*), polyphagous shot-hole borer (*Euwallacea fornicatus*), and *A. glabripennis*. There is an urgent need to engage social scientists to conduct broad public consultation to gauge the level of social acceptance of the costs and benefits (social, economic, environmental) of eradication programs for invasive forest pests. Not only do we need to measure the social acceptability of biosecurity interventions, we ultimately need to understand what factors affect this, so that biosecurity authorities can educate and empower the public in the most effective way. Critical research is needed to assess the strengths and weaknesses of public vigilance for biosecurity surveillance [100].

Assessing potential reasons for successes and failures in surveillance, detection and eradication during forest pest invasions is critical for managing future incursions in Australia. To adequately examine these patterns and to make recommendations during incursion responses, we require national standardised data collection, including how, when, where and by whom detections are made (e.g., [35]). As invasion processes (arrival, establishment and spread) can best be understood with data at each of these stages, pre-border interception data collected at ports-of-entry, quarantine-controlled premises and post-quarantine detection points should be made available to researchers, as recommended in the Beale et al. [14] biosecurity review.

The inclusion of technical experts from state governments, research organisations and industry in incursion responses is essential, and is considered one of the reasons behind the successful eradication of *B. hunanensis* from Melbourne. Following a review of the *M. hellenica* response, the inclusion of industry experts within the response process has been identified as a factor for success of future programs. Increased diagnostic capacity, including molecular analyses, to ensure that new exotic detections are recognised immediately, is another requirement to improve early response. Increasing Australia's biosecurity surveillance and diagnostic capacity and capability is a key action under the NFBSS [32].

The Australian experience is relevant to post-border biosecurity surveillance and response to exotic detections globally: most continents are also experiencing increasing biological invasions of forests (e.g., [107,110]), with various regulations and recommendations (e.g., [105,111,112]) considered to counter them. We add to this growing collective and reiterate the requirement for global strategies to mitigate and manage exotic forest pest threats and invasions [113].

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