Designing cost-efficient surveillance for early detection and control of multiple biological invaders

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Abstract. Wood borers and bark beetles are among the most serious forest pests worldwide. Many such species have become successful invaders, often causing substantial, costly damages to forests. Here we design and evaluate the cost-efficiency of a trap-based surveillance program for early detection of wood borers and bark beetles at risk of establishing in New Zealand. Although costly, a surveillance program could lead to earlier detection of newly established forest pests, thereby increasing the likelihood of successful eradication and reducing control costs and damages from future invasions. We develop a mechanistic bioeconomic model that relates surveillance intensity (i.e., trap density) and invasion size to probabilities of detection and control. It captures the dynamics of invasive species establishment, spread, and damages to urban and plantation forests. We employ the model to design surveillance programs that provide the greatest net present benefits. Our findings suggest that implementing a surveillance trapping program for invasive wood borers and bark beetles would provide positive net benefits under all scenarios considered. The economically optimal trapping strategy calls for a very high investment in surveillance: about 10,000 traps in each year of the 30-year surveillance program, at a present value cost of US$54 million. This strategy provides a 39% reduction in costs compared with no surveillance, corresponding to an expected net present benefit of approximately US$300 million. Although surveillance may provide the greatest net benefits when implemented at relatively high levels, our findings also show that even low levels of surveillance are worthwhile: the economic benefits from surveillance more than offset the rising costs associated with increasing trapping density. Our results also show that the cost-efficiency of surveillance varies across target regions because of differences in pest introduction and damage accumulation rates across locales, with greater surveillance warranted in areas closer to at-risk, high-value resources and in areas that receive more imported goods that serve as an invasion pathway.

Key words: bark beetles; bioeconomic model; biological invasions; biosecurity; cost-efficiency; eradication; monitoring; New Zealand; pest management; risk management; search effort; wood borers.

INTRODUCTION

Invasive species cause significant ecological and economic harm to natural and human systems worldwide, affecting biodiversity and ecosystem services, agriculture, industry, and human health and incurring significant expenditures for control (Pimentel et al. 2005, Olson 2006, Aukema et al. 2011). The costs from invasive species introductions are predicted to continue to rise as new invasions occur and spread, facilitated by increasing human travel, trade, and climate change (Simberloff 2000, Liebhold et al. 2012). Resources for reducing invasion damages can be invested at various stages: to prevent new introductions, eradicate established invaders, or reduce the spread or damages from established invaders.

International trade is an important pathway for invasive species introductions, and prevention along this pathway often includes inspection or treatment of imports (Liebhold et al. 2012). However, such efforts cannot effectively prevent all new introductions. When prevention does not succeed, early detection of new invasions can increase the likelihood of control and reduce control costs and damages (Epanchin-Niell and Hastings 2010). However, early detection requires investment in surveillance efforts that can be costly, and thus involves inherent economic trade-offs.

Government, resource management agencies, and other stakeholders must decide whether (and how much) to invest in surveillance or monitoring efforts to increase the probability of detecting potential invaders earlier. This resource allocation decision is complicated by a variety of factors, including uncertainty about which invaders may establish and when, the damages they may cause, and the likelihood and the costs of detection and control. In addition, surveillance costs are incurred
immediately and with certainty, whereas the benefits of surveillance are less certain and generally occur in the future. Also, target species may not yet be present when surveillance begins. These factors can reduce the perceived urgency and motivation for investing in surveillance, but the question remains: How much should be spent searching for new invasions?

The problem of surveillance design for early detection of invaders has been approached from a variety of perspectives, most of which do not explicitly consider costs. Strategies have included targeting based solely on risk, with allocation of surveillance to the highest-risk areas (e.g., Wylie et al. 2008), and maximizing the power of detection for a given level of investment (e.g., Barrett et al. 2010, Jarrad et al. 2011). The latter goal minimizes the probability of failing to detect a population if it is present. However, to obtain the greatest benefits from investing scarce resources, surveillance design must explicitly balance the cost of surveillance with the costs of allowing invading populations to go undetected longer. Greater surveillance intensity (e.g., numbers of traps deployed or visual surveys conducted to detect new populations) requires larger upfront investment but also increases the likelihood of detecting invasions earlier, when their control is less costly and more likely to be successful. Consequently, there is an optimal level of surveillance that minimizes the total combined costs of invasion management and damages. This trade-off among surveillance costs and invasion costs and damages is inherent to this decision context, but rarely is considered explicitly in actual management planning.

Past research on designing cost-efficient surveillance for locating established invaders has taken various approaches, generally focusing on identifying the optimal level of surveillance to implement for locating populations of an invader for which eradication or control, when attempted, is certain (e.g., Mehta et al. 2007, Bogich et al. 2008, Hauser and McCarthy 2009, Homans and Horie 2011, Epanchin-Niell et al. 2012, Horie et al. 2013). Some studies have also considered the optimal location of these efforts (e.g., Hauser and McCarthy 2009, Cacho and Hester 2011, Homans and Horie 2011, Epanchin-Niell et al. 2012, Horie et al. 2013). Each study has relaxed particular assumptions of previous studies to increase the realism and applicability of the modeling approach for designing surveillance programs. The existing body of work provides not only useful frameworks for designing surveillance for detecting new invasions, but also qualitative guidance identifying when surveillance is most worthwhile. Specifically, greater investments in surveillance are generally warranted when establishment rates or numbers are high, expected invasion damages are high, and surveillance is less costly.

In this study we extend the existing literature on designing cost-effective invasive species surveillance programs in four ways that allow for practical and general application of our approach. First, we consider surveillance efforts that target detection of new populations of multiple pest species simultaneously, rather than considering a single-species program. This is relevant because, at any point in time, a very large number of potential invaders could be introduced, and in most cases it is not possible to predict which one will be introduced next. Targeting a suite of invaders, as we consider in this paper, can therefore increase the efficiency and effectiveness of surveillance efforts, particularly when resources are limited or species can be sampled jointly at lower costs than when sampled independently, such as via visual surveys or multispecies traps (Brockerhoff et al. 2013). Second, we account for the possibility that eradication may not be feasible or may fail, such that an invasion may continue to spread and cause damages despite the investment in eradication efforts. This is the case for many invaders, particularly ones for which effective control measures have not been developed or whose populations become widespread prior to detection. Third, we assume that managers attempt eradication only if the investment is expected to provide positive net benefits despite the potential for failure. In this way, we account for the endogeneity of the eradication decision in the design of the surveillance system (e.g., Homans and Horie 2011). Fourth, we employ a mechanistic approach to estimating spatially varying damages from invasions based on the likely establishment locations and spread patterns of invaders and the location of susceptible resources across the landscape. This approach can help to target surveillance to areas where the benefits from effective surveillance are greatest.

We apply our approach to designing and evaluating the cost-effectiveness of surveillance for wood borers and bark beetles arriving in New Zealand. These species are among the most serious forest pests worldwide, and many have become successful invaders beyond their native range (e.g., Brockerhoff et al. 2006a, Haack 2006, Aukema et al. 2011). Damages from wood borers and bark beetles can be extremely costly (Turner et al. 2004, Colautti et al. 2006, Kovacs et al. 2010). In the United States, this guild of insects was identified as the most damaging, causing an estimated $1.7 billion in local government expenditures and $830 million in lost residential property values annually (Aukema et al. 2011).

International trade in logs, timber, and other forest products and the use of wood packaging materials, in particular, are important pathways for the introduction of wood borers and bark beetles (e.g., Brockerhoff et al. 2006b). These pests can be detected through visual inspections (for the insects themselves or the damage they cause) and approaches that use specific or generic beetle attractant traps to sample species. Trap-based surveillance programs for wood borers and bark beetles are in operation in several countries, including Australia and the United States (Rabaglia et al. 2008, Wylie et al. 2008, Augustin et al. 2012). New Zealand has well-
developed forest health and high-risk site surveillance programs that rely on visual insect and damage detection (Stevens 2008). New Zealand also tested a targeted trap-based system (Brockerhoff et al. 2006b), but discontinued it because of uncertainty about the net benefits and a shortage of funding. An external evaluation of New Zealand’s Forest Health Surveillance program recommended implementing a trapping surveillance program for wood-boring insects for earlier detection and, therefore, a higher likelihood of eradication and containment (Brockerhoff et al. 2010; A. M. Liebhold and B. Callan, unpublished manuscript). However, no quantitative analysis has been done to determine whether the risks posed by wood borers and bark beetles and the benefits of an additional surveillance program justify its potentially high costs. Here we develop a novel modeling approach for designing cost-effective surveillance for detecting populations of potential new invaders across multiple regions. We apply the model to evaluate the cost-efficiency of surveillance trapping for early detection of invasive wood borer and bark beetles that may establish in New Zealand.

**Methods**

We first introduce a general modeling framework and then parameterize the model to specifically consider surveillance and management of wood borers and bark beetles in New Zealand. We use the model to determine the optimal investment in surveillance, in terms of the numbers and distributions of traps, to minimize the total expected costs of surveillance and management of wood borers and bark beetles in New Zealand, including the costs of surveillance, invasion control, and damages.

**The model**

We begin by developing a model to optimize surveillance for a single location (e.g., a single port region in which invasions may establish) and for a single type of invader (e.g., a single species of wood borer). We then expand the model to consider multiple surveillance locations and multiple potential invaders (e.g., a general suite of wood borer and bark beetle species arriving across multiple port regions). For our application, we focus on surveillance using trap samples baited with insect attractants, but surveillance could alternatively employ visual surveys or other sampling techniques at discrete locations. We define surveillance intensity as the density of traps deployed in a region.

Consider a region in which new populations of a nonnative pest are establishing. The rate at which new populations establish is assumed to be constant, but the actual arrival of new populations in that region is random in space and time, such that the number, size, and location of populations in the region at any point in time are unknown prior to detection. We assume that each new population that establishes occupies a circular area that grows radially at a given rate. To find populations, surveillance is conducted annually with traps distributed at random within the specified region and with cost dependent on the number of traps. In practice, traps are usually deployed in regularly spaced grids, but differences in trap layout do not affect the outcomes from the model when trap sensitivity is low (L. Berec et al., unpublished manuscript). For each trap that intercepts a circular population, the population may be detected with a probability that depends on the sensitivity of the trap. When a population is detected, eradication can be attempted with some probability of success and a cost that depends on the population’s area. If no traps intercept a particular population or if all intercepting traps fail to detect it in a particular year, the population is undetected and continues to grow. Populations also continue to grow if eradication is either not attempted or unsuccessful. Established populations cause damages (e.g., to plantation and urban forests), the magnitude of which depends on the population’s location, size, and the time that has passed since its establishment. The choice of whether to attempt eradication of a detected population depends on the expected net benefit of eradication efforts, which depends on the anticipated success of eradication, the anticipated costs of eradication, and the expected damages from the invader if it is not eradicated. We assume that eradication success and costs depend on population area, ignoring other species-specific characteristics that also can affect these values (Tobin et al. 2014).

We expand this model to consider multiple regions and multiple invader types that differ in their anticipated damages and spread rate. The expected long-term costs and damages associated with any surveillance strategy (i.e., trapping density) can be calculated by employing estimates of rates of population establishment and growth, the probabilities of detecting and eradicating populations, the costs of control, and the damages caused by the invasions. In turn, this framework can be used either to determine the long-term trap densities that minimize the total expected costs of surveillance, eradication, and damages over time, or to evaluate the cost-effectiveness of a proposed strategy. The mathematical details of this framework are described next.

**Population establishment, growth, and detection.**—We define $S$ as the set of population size (age) classes, $S = \{1, 2, \ldots, S_{\text{max}}\}$, where we consider damages accrued over the first $S_{\text{max}}$ years of an invasion. We define $X'(t)$ as the expected number of undetected populations of size class $s \in S$ on the landscape at time $t$ and $Z'(t)$ as the expected number of detected populations for which eradication was either unsuccessful or not attempted. We consider populations establishing within a focal landscape of area $A$. If new invaders establish at an average rate $b$, then the expected number of undetected populations of size class $s = 1$ at any time $t$ equals $b$. In each time period, undetected populations of size class $s$ will transition to size class $s + 1$ if undetected. Suppose
that the probability of detection (subscript “det”) of populations of size class \( s \) given trap density \( d \) is \( p_{\text{det}}(d, s) \), then a size class model for undetected populations can be specified as

\[
x^1(t + 1) = b(t)
\]

\[
x^s(t + 1) = x^{s-1}(t)(1 - p_{\text{det}}(d, s - 1)) \quad \text{for } s = 2, \ldots, S_{\text{max}}.
\]

Similarly, in each time period, populations of size class \( s \) that have been detected but not eradicated will transition to detected populations of size class \( s + 1 \) in the next time period. Thus a size class model for extant, detected populations can be specified as

\[
z^1(t + 1) = 0
\]

\[
z^s(t + 1) = x^{s-1}(t)(p_{\text{det}}(d, s - 1))
\]

\[
\times (1 - \text{erad}(s - 1)p_{\text{erad}}(s - 1))
\]

\[
+ z^{s-1}(t) \quad \text{for } s = 2, \ldots, S_{\text{max}}
\]

(2)

where \( p_{\text{erad}}(s) \) is the probability that eradication (subscript “er”) is successful if attempted, and \( \text{erad}(s) \) indicates whether eradication is attempted when a population of size class \( s \) is detected; \( \text{erad}(s) = 1 \) if eradication is attempted and 0 otherwise. The probability \( p_{\text{det}}(d, s) \) of detecting each population on the landscape increases with density \( d \) of surveillance traps within the focal landscape, population size (measured as areal extent) \( a(s) \), and trap sensitivity \( y \), where we define trap sensitivity \( y \) as the probability that a trap will detect a population when located within its boundaries. If we assume that trap placement is random with respect to the location of each established population, through one or both being random in space, then each trap can be treated as a Bernoulli detection trial. In turn, the probability that any given population is detected (i.e., at least one trial is successful at detecting the population) can be estimated as a binomial distribution, where the number of trials equals the number of traps \( dA \), and the probability of success for each trial equals the trap sensitivity \( y \) times the probability of the trap intercepting the population \( (a(s)/A) \). In this way, the probability \( p_{\text{det}}(d, s) \) that one or more traps are located within and detect each population equals \( 1 - (1 - y a(s)/A)^d \) for populations whose area is less than or equal to the area \( A \) of the focal region, and equals \( 1 - (1 - y)^d \) for populations larger than the focal, surveyed region.

Costs, damages, and identification of optimal surveillance.—We assume that surveillance costs \( C_d(d, A) \) depend on the density of traps and the area \( A \) over which traps are distributed; \( C_d(s) \) is the total damage costs (e.g., damages to plantation and urban forests) in a single time period from a population of size class \( s \), including the costs of any control efforts to reduce damages. When a population is detected, eradication can be attempted at a cost that increases with the population’s size, \( C_d(a(s)) \). The probability of eradication success, \( p_{\text{erad}}(a(s)) \), decreases with the population’s size. We assume that eradication will be attempted only if the expected costs and damages from attempting eradication are less than the expected costs of the population remaining on the landscape and continuing to grow. The expected cost of the population remaining on the landscape (or expected net present value) with no eradication (subscript “noer”), \( \text{ENPV}_{\text{noer}}(s) \), equals the discounted future stream of all costs and damages associated with a population of size class \( s \):

\[
\text{ENPV}_{\text{noer}}(s) = \frac{\sum_{t=0}^{S_{\text{max}}-1} C_d(t + s)}{(1 + \delta)^t}
\]

(3)

where damages are summed across the remaining time periods until the invasion reaches age class \( S_{\text{max}} \), accounting for population growth over time and a discount rate \( \delta \). Thus, eradication is attempted (i.e., \( \text{erad} = 1 \)) if

\[
C_d(a(s)) + (1 - p_{\text{erad}}(a(s)) \times \text{ENPV}_{\text{noer}}(s) < \text{ENPV}_{\text{noer}}(s).
\]

(4)

Otherwise eradication is not attempted (i.e., \( \text{erad} = 0 \)).

The objective of management is to choose a trapping density to minimize the total net present value of expected future costs from surveillance, invasion damages, and control costs. We consider application of a constant surveillance strategy (i.e., a constant trap density) over a fixed time horizon \( T \) and evaluate the total net present value of costs and damages associated with that strategy, including damages resulting from all populations that establish during the course of the surveillance program or that were present on the landscape (but not yet detected) prior to the start of the program.

We assume that in the absence of surveillance trapping, populations remain undetected for a fixed time horizon, \( f \), at which time they are detected perfectly. We assume that populations were arriving at a background rate prior to the start of the surveillance program. Thus, at the start of the program the expected number of undetected populations already on the landscape equals \( x^f(t = 1) = b \) for all \( s \leq f \) (from Eq. 1).

For all time periods of surveillance program implementation, the number of undetected populations of each age class on the landscape can be determined recursively, using Eq. 1. Recognizing that \( x^s(t) \) and \( z^s(t) \) are functions of \( d \), they can be written \( x^s(t, d) \) and \( z^s(t, d) \).

The net present value of total expected costs and damages for a surveillance program lasting \( T \) years, including the costs and damages associated with all undetected populations at the start of the program and all populations establishing during the program, equals
where the terms in the summation are surveillance costs, damages from undetected populations, damages from detected populations, and eradication costs, discounted at a rate $\delta$. The final cost term is the discounted net present value of all populations remaining on the landscape at the end of the surveillance program. To determine the optimal surveillance intensity, we minimize this function with respect to $d$, thereby choosing the trapping density that minimizes the total expected costs of surveillance, eradication, and invasion damages.

Consideration of multiple invaders and regions.—We now expand this approach to multiple invaders and invader types by summing the expected costs and damages (Eq. 5) across multiple potential invaders that can be detected by the same surveillance mechanisms (e.g., traps). In Eqs. 1 through 5, $TC(d)$, $x$, $C_d$, $z$, $b$, $p_{det}$, $ENPV_{noer}(s)$, and $C_e$ each can be indexed by invader type $i$, where $i \in \{1, 2, \ldots, I\}$ and $I$ is the total number of potential invader types distinguished by a combination of damage intensity and spread rate. In Eq. 1, the arrival rate $b^t$ for each invader type is then calculated as the arrival rate $b$ for the region multiplied by the proportion of new invaders expected to be type $i$. The total expected cost (Eq. 5) of all new invaders over the long term with trapping density $d$ thus equals

$$\text{TC}(d) = \sum_{i=1}^{I} \text{TC}'(d).$$

We also can optimize surveillance across multiple subregions (e.g., ports). Consider a total survey area composed of $N$ subregions, with each subregion indexed by $n \in \{1, 2, \ldots, N\}$. We then choose the optimal sample density $d_n$ for each subregion to minimize the total expected costs and damages (Eq. 6) across all subregions:

$$\min_{d_n} \sum_{n \in \{1, 2, \ldots, N\}} \text{TC}_n(d_n)$$

(7)

where all parameters are indexed by subregion $n$. If a region-wide budget constrains surveillance efforts, the following constraint applies:

$$\sum_{n \in \{1, 2, \ldots, N\}} C_{sn}(d_n, A_n) \leq B$$

(8)

where $B$ is the total annual surveillance budget. Optimizing this problem (Eqs. 7 and 8) finds the distribution and density of trap samples across regions that minimize the total expected costs from surveillance, eradication, and invasion damages, given any budget constraints.

The expected net present benefits of implementing the optimal surveillance program or any other potential surveillance program (as defined by trap densities $d_n$) relative to doing nothing, is calculated as the difference in total costs (Eq. 7) under the specified program and when all $d_n = 0$.

Model parameterization

We apply our approach to designing a trapping surveillance program for bark beetles and wood borers in four major centers of trade in New Zealand: Auckland, Tauranga, Wellington, and Christchurch (the major city associated with the port town of Lyttelton); see Fig. 1. These places are the most likely entry points for new wood borers and bark beetles into New Zealand based on trade volume, as we will describe. We focus on two important types of damages that wood borers and bark beetles cause: damage to plantation forests, because timber export is an important industry for New Zealand, and damage to urban forests and trees, because this can be among the highest damage costs caused by this guild of invasive species (Turner et al. 2004, Aukema et al. 2011).

Application of our model requires information about expected establishment rates of new invaders in the focal regions, the likelihood of different “types” of invaders (as defined by the damages they cause and their spread rate), the chances of detecting and of eradicating populations of different sizes, the costs of surveillance and eradication, and the population spread rates and damage functions. Data for estimating these parameters and functions are limited for wood borer and bark beetle invasions in New Zealand, as they are for many systems and invasion management contexts worldwide. Thus, parameterizing our model requires making many assumptions that represent expert estimation about the dynamics and characteristics of the system. We therefore test the influence of these uncertain assumptions on the conclusions drawn from our results using sensitivity analyses and by comparing the expected net benefits of surveillance under various assumptions and our baseline parameters.

Parameter estimates for the analysis were obtained from data held in Scion’s Forest Biosecurity databases, the Global Eradication and Response Database, GERDA (Kean et al. 2012), a review of the literature (e.g., Bulman et al. 1999, Liebhold and Tobin 2008, Brocker-
Potential invader types.—We do not know exactly which species of wood borer or bark beetle may establish in New Zealand in the future. Therefore we delineate 18 potential invader types (i.e., \( I = 18 \)), as defined by anticipated damages to urban forests, damages to plantation forests, and spread rate, to represent the potential array of future invaders (Appendix B). Each potential invader type is characterized as causing high, medium, or low damage to plantation (P) and to urban (U) forests, and as slow or fast spreading. We assume that the damage subtypes and spread rate subtypes are independent, such that the proportion of each potential invader type is the product of the proportions of each damage subtype (\( p^U \) and \( p^P \)) and spread rate type (\( r' \)), where \( r \) is rate of spread.

The vast majority of new invaders cause low damages, with a smaller proportion causing medium damages, and the smallest fraction causing the largest damages (Aukema et al. 2011). Thus we assume that 80%, 15%, and 5% of potential new invaders cause low, medium, and high damages, respectively, for urban and plantation forests. We assume that 50% of new invaders spread quickly (asymptotic rate of spread equals 50 km/yr) and 50% spread more slowly (10 km/yr). These assumptions mean that approximately one-third of new invaders are the slowest spreading, least damaging invader type and about 0.1% are the fastest spreading, most damaging of the 18 invasion types (Appendix B). We conduct two sensitivity analyses on the fraction of fast- vs. slow-spreading invaders, considering scenarios where 75% of invaders spread slowly and 25% spread slowly.

Establishment rates.—New wood borer and bark beetle species arrive and establish in New Zealand at an average background rate, \( b \). Historically, establishments in New Zealand of wood borers and bark beetles occurred at a rate of about 0.4 species/yr, i.e., 40 introductions in the past 100 years (see Brockerhoff 2009: Table 1, Fig. 3). However, not all of these species would be of concern to New Zealand’s plantation forests or urban trees. Furthermore, the rate of wood borer and bark beetle establishments appears to have declined in recent decades. There were 11 detections of new species from 1950 to 2010, giving an average rate of establishment of 0.18 species/yr. Within this time period, the rate

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**Fig. 1.** Distribution of (a) plantation forest (shaded areas; lighter gray indicates lower density or smaller plantations), and (b) human population density. Urban trees are assumed to be distributed in proportion to human population density.
was 0.30 species/yr from 1950 to 1980 and 0.065 species/yr from 1980 to 2011. The apparent reduction in establishment rate may be due to improvements in border biosecurity. For this analysis, we assume that the recent rate of 0.065 introductions/yr is the baseline establishment rate. We recognize that the introduction of phytosanitary measures for wood packaging material used in international trade (ISPM 15; IPPC 2011) will have reduced rates of pest infestation, but the continuing increase in trade volumes is likely to counteract this reduction. ISPM 15 has been found to be not completely effective, so that future invasions will not be prevented entirely (Brockerhoff et al. 2014). For sensitivity analyses, we consider establishment rates of 0.18 and 0.032 introductions/yr, where the former is the longer-term historical average and the latter is half of the baseline rate.

Collectively, Auckland, Tauranga, Wellington, and Christchurch receive approximately 90% of the trade volume that poses the greatest risk for invasions of wood borers and bark beetles (Appendix C: Table C1). Using methods described in Appendix C, we estimate the relative invasion risk across the four focal ports based on the flow of trade that is likely to use wood packaging material, which is probably the most common introduction pathway for borers (Haack and Petrice 2009; see also Brockerhoff et al. 2006b). We estimate that 48.7%, 23.0%, 8.1%, and 9.3% of wood borer and bark beetle establishments will occur via introduction into Auckland, Tauranga, Wellington, and Christchurch, respectively (Appendix C: Table C1), and thus we apportion our nationwide estimated invasion establishment rate, $h$, proportionately across the four port regions. We further apportion these establishment rates across the 18 identified invader types based on their proportions (Appendix C: Table C2).

Areal extent of regions and proportions of invasion introductions in sampled areas.—The total urban areas of Auckland, Tauranga, Wellington, and Christchurch used for our analysis are 1086 km$^2$, 168 km$^2$, 444 km$^2$, and 450 km$^2$, respectively. Within each of these port regions, the areas of highest risk for wood borer and bark beetle establishment are assumed to be concentrated around the port, and around industrial and commercial areas where imports are unloaded, which may constitute only a small fraction of the region. For our baseline analysis, we assume that trapping efforts are targeted at only 20% of the urban area in each of the four focal regions, thereby focusing surveillance on the highest-risk sites. Furthermore, we assume that 80% of future invaders arriving in a port region establish within that 20% area, such that the remaining 20% of establishment via each port will not benefit from early detection by the targeted surveillance system considered here. These values represent the best understanding of the system, but are uncertain. For sensitivity analysis, we consider four other combinations of trapped area and percentages of establishments occurring within those limited areas. Specifically, we consider trapping of 10% of each port region, which we assume encompasses 60% of establishments; 20% of each port region, encompassing 60% of establishments; 30% of each port region, encompassing 80% of establishments; and 100% of each port region, encompassing 95% of the establishments into those areas.

Cost of surveillance trapping program.—The costs of surveillance, $C_s$, include both fixed and variable costs, where variable costs depend on trap density and the total area surveyed. These costs were estimated using expert opinion (Appendix D). Fixed costs, which include the costs of design, planning and management of the trapping program, data analysis, and writing of reports, are estimated at US$16 250/yr. The estimated per trap variable costs associated with trapping include the costs of traps, attractants, trap deployment and maintenance, sample collection, shipping, and identification; the per trap costs decrease with increasing total trap number and range from US$633 to $328 per trap.

Sensitivity of traps.—The sensitivity of a trap ($\gamma$) is the likelihood that a trap will detect a population (i.e., of an invader’s being caught and identified as such) when a trap intersects the invader population. This sensitivity is likely to vary across species and is highly uncertain. Thus, we assume a baseline sensitivity of 60% and do a sensitivity analysis for $\gamma = 30\%$ and $\gamma = 90\%$ (Appendix D).

Invader population growth.—We assume that each invasion begins near a port and spreads radially according to a growth function such that it occupies an increasingly large circular area over time (Appendix E: Fig. E1). We model the spatial expansion of populations using a sigmoid function that allows for an initially accelerating rate of radial population growth that eventually asymptotes at a rate $g$ (e.g., Epanchin-Niell et al. 2012). Under this assumption, the annual change in the radius of a population is given by $g e^{m(1-(r/m)^{0.5})}$, where $s$ is the size class (or equivalently the age) of the population, $g$ is the asymptotic radial rate of population growth, $m$ is a shape parameter, and $h$ is the time at which half the asymptotic rate of growth is achieved. We employ a shape parameter $m = 5$ and half time value $h = 10$. We consider $h = 20$ for our sensitivity analyses. We consider two asymptotic radial rates of spread to represent the two potential spread types of invaders: 10 km/yr and 50 km/yr.

We chose these spread rates as being within the observed ranges of spread rates for previously established wood borers and bark beetles in New Zealand (E. G. Brockerhoff, unpublished data) and other countries (Appendix E). For example, the great European spruce bark beetle, *Dendroctonus micans*, which was discovered near Ludlow, Shropshire, in 1982, had an average recorded spread rate of ~15 km/yr despite pest control measures undertaken to reduce its further spread (Fielding et al. 1991, Liebhold and Tobin 2008).
Elsewhere, other beetle species have been recorded to spread at an average rate of as little as 5 km/yr and up to 250 km/yr (Muirhead et al. 2006, Liebhold and Tobin 2008), with the higher rates probably capturing uncommon long-distance dispersal events.

**Damages to plantation forests.**—We assume that invaders reduce plantation forest harvest values at a location by a proportion that depends on the invader damage type \( i \) and how long the invader has been present at the location. This measure of damages as reduction in expected harvest value could result from decreased harvest quantity or quality, increases in management costs, or some combination of these factors (e.g., Turner et al. 2004). Our baseline damage assumptions are maximal harvest value reductions of 1%, 10%, and 50% for low-, medium-, and high-damage plantation pests, respectively. For sensitivity analyses, we consider damages of 1%, 5%, and 20% and 1%, 15%, and 75% for low-, medium-, and high-damage plantation forest pests, respectively.

We assume that damages accrue only to forests located within the area occupied by an invader, and thus the amount of forest affected at any given time depends on the age, growth function, and establishment location of the invader, as well as the distribution of plantation forests within New Zealand. New areas of plantation forest are affected over time as an invasive species’ population spreads. We assume a 5-yr delay before damages begin accruing in a newly invaded plantation forest, to account for initially low population densities. Following the 5-yr delay, we assume that damages increase linearly in those areas over the next five years to reach their maximum reduction in harvest value in the 10th year following the arrival of the invader. Maximal reductions in harvest value continue for a fixed time horizon, \( S_{\text{max}} \), following the arrival of the invader in New Zealand or until the population is eradicated.

The distribution of plantation forests in New Zealand is illustrated in Fig. 1a, and the value of future annual plantation harvests for New Zealand is estimated at approximately US$1154 million from 2015 onward (Appendix F). We employ this value as our estimate of total annual harvest value in the absence of any new invasions, and we assume that this value is distributed in proportion to the area of plantation forest (Fig. 1a).

Because of the distribution pattern of forest within New Zealand, plantations are likely to be invaded most rapidly from introductions beginning in Tauranga, followed by Auckland and Wellington (Appendix G: Fig. G1). Damages to plantation forests accrue most slowly for invasions beginning in Christchurch, which has less plantation forest area nearby (Fig. 2a).

**Damages to urban forests.**—We assume that invaders affect a fraction of urban trees that depends on the invader damage type \( i \) and time since arrival at a location. Because there are no data on the distribution and number of urban trees in New Zealand, we follow Turner et al. (2004) by assuming that 20 million urban trees are distributed proportionally with human population density across New Zealand (Fig. 1b; Appendix H). We also assume that each tree affected by invasion...
incurs a one-time average cost of US$2283, which is an estimated average cost of tree removal and replacement (Turner et al. 2004, Haight et al. 2011), but could capture other damages or control costs.

As with plantation forests, we assume that each invasion begins near a port, grows radially, and causes damage to urban forests within the occupied area. Following invasion arrival at a particular location on the landscape, there is a 5-yr delay before damages begin to accrue, after which one-fifth of susceptible trees are affected in each of the following five years. Ten years following the arrival of the invader at a location, the damages to urban forest at that location cease because all susceptible trees have been removed and replaced.

We assume that a total of 1%, 5%, and 20% of urban trees at any location are susceptible to low-, medium-, and high-damage urban forest pests, respectively. We conduct three sensitivity analyses in which we assume that 1%, 5%, and 20% of urban trees have been removed and replaced. We assume that a total of 1%, 5%, and 20% of urban trees at any location are susceptible to low-, medium-, and high-damage urban forest pests, respectively. We conduct three sensitivity analyses in which we assume that 1%, 2%, and 5%; 1%, 3%, and 10%; and 1%, 10%, and 50%, of trees are susceptible to low-, medium-, and high-damage urban forest pests, respectively.

The proportion of urban forest area affected by invasions is expected to increase most rapidly for invasions that begin in Auckland, because the urban tree density is assumed to be highest in that region. In contrast, Christchurch is located on the much less populated South Island, so the amount of urban forest affected by invaders is expected to accrue most slowly for invaders establishing in Christchurch (Appendix G: Fig. G2).

Baseline detection without surveillance.—Even without implementation of a trapping surveillance program, invaders will eventually be detected, such as through visual observation of insects or damage by surveillance officers or members of the public. We assume that, without surveillance trapping, populations remain undetected for a fixed time horizon following establishment, after which they are detected perfectly. The lag phase for detecting high-damage species is likely to be shorter than for less damaging species because damages are easier to observe. We assume that the lag phase for detection without trapping depends on damages to urban forests, because damages and detection are likely to occur earliest in urban forests. We employ baseline detection lag times of \( f = 8, 10, \) and 15 yr for high-, medium-, and low-damage urban forest pests. We conduct sensitivity analysis using 7-, 9-, and 12-yr detection lag phases for high-, medium-, and low-damage urban forest pests.

Eradication cost and probability of successful eradication.—Relationships between infested area and the cost and probability of eradication success were estimated from values recorded for past eradication programs against wood-boring insects (Kean et al. 2012; see Appendix I). To estimate the costs of eradication, we include only eradication for which costs are known \((n = 25)\). The effect of \( \log_{10}(\text{invasion size}) \) on \( \log_{10}(\text{cost}) \) was fitted using linear regression, where costs were measured in millions of 2011 U.S. dollars and area was measured as \( \text{km}^2 \) (Appendix I: Fig. 11 and Table 11). We use this estimated cost function as our baseline costs and use the upper and lower confidence interval for the fitted line for sensitivity analyses (Appendix I: Figs. 11 and 12).

The probability of successful eradication was estimated from programs with known outcomes \((n = 34)\). Outcomes were classified as either successful \((1)\) or unsuccessful \((0)\). Thirteen of the 34 programs were successful (Kean et al. 2012). The relationship between the log-transformed invaded area \( \text{(measured in km}^2) \) and probability of eradication success was estimated by logistic regression (Appendix I: Fig. 13, Table 12). The baseline parameterization is illustrated in Fig. 14. For sensitivity analysis, we employ the upper and lower 95% confidence intervals for predicted success (Figs. 13 and 14).

**Discount rate and time horizons.**—We use a baseline discount rate equal to 5% and consider 10% and 1% rates for sensitivity analyses. We consider a baseline time horizon, \( S_{\text{max}} \), of 75 yr over which damages accrue from an invader following its establishment, and we conduct sensitivity analyses using time horizons of 50 and 100 yr. We consider a baseline surveillance program of 30 years, but also examine 10- and 50-yr programs.

**Model application**

We evaluate the total expected costs and damages under 10 surveillance scenarios using the baseline parameterized modeling framework. The first five scenarios, which do not optimize trapping across the ports \((\text{Eq. 6})\), include no trapping \((\text{scenario 1})\) and deployment of four levels of numbers of traps \((50, 200, 400, \text{and } 1000 \text{ traps})\) at equal densities across the four ports \((\text{scenarios 2–5})\). The next four scenarios optimize the distribution of a fixed number of traps \((50, 200, 400, \text{and } 1000 \text{ traps})\) across the ports, which is equivalent to optimizing under four budget constraints \((\text{Eqs. 7 and 8})\). The final scenario \((\text{scenario 10})\) identifies the optimal number and distribution of traps across the four ports without any surveillance budget constraints \((\text{Eq. 7})\). We evaluate each of the trapping scenarios \((\text{scenarios 2–10})\) against the no-trapping alternative \((\text{scenario 1})\) to identify the expected net benefits from implementing each trapping strategy.

We also conduct parameterization sensitivity analyses by changing one component of the baseline parameterization at a time. For each sensitivity analysis, we solve for optimal trapping intensity and expected costs and damages for surveillance scenarios 6–10, and the no-trapping alternative \((\text{scenario 1})\). In addition, to see how well the trapping strategies designed as optimal under the baseline parameterization perform if the sensitivity parameterizations are correct, we evaluate the expected costs, damages, and net benefits of implementing the surveillance strategies identified as optimal under the baseline parameterization \((\text{scenarios 6–10})\) when employing the sensitivity analysis parameterizations.
Our sensitivity analyses consider alternative parameterizations of establishment rate ($b$), discount rate ($\delta$), time horizon for damage accrual from invasion ($S_{\text{max}}$), length of the surveillance program ($T$), the probability of eradication success ($p_{\text{er}}$), the cost of eradication ($C_d(s)$), the sensitivity of traps ($\gamma$), the percentage area of each port trapped and the percentage of establishments occurring in that area, damages caused to plantation and urban forests (i.e., the percentage harvest reduction and the percentage of urban trees affected), the spread function (i.e., the time until half of the asymptotic rate of radial invasion spread is reached; $h$), the percentage of slow- vs. fast-spreading species, and the time until detection in the absence of a surveillance trapping program.

The complexity of the modeling approach prevents derivation of analytical solutions, so we solve for optimal trap densities numerically as a constrained optimization using the “fmincon” solver in MATLAB R2010b (MathWorks 2010) with an interior point algorithm.

RESULTS AND DISCUSSION

Some background findings

As expected, the probability of early detection increases with trapping density. The cumulative probabilities of detection for colonies aged 1–5 yr are shown in Appendix J. At densities of 5 traps/km$^2$, populations have a near-zero probability of being detected in the first two years following establishment for fast-spreading invaders, and in the first three years for slow-spreading invaders. At this trap density, there is a 98% probability that a fast-spreading invasion will be detected by its fourth year, and an 85% probability that a slow-spreading invasion will be detected by its fifth year. This rapid increase in cumulative detection probability results from the sigmoidal shape of the population growth function that leads to increasing rates of growth.

The damages caused by invaders in each year following establishment are shown in Fig. 2 for each of the four port regions. Damages to plantation forests generally increase over time as more plantation forest area is affected. Plantation forest damages accrue fastest for populations beginning in Tauranga, followed by Auckland, Wellington, and Christchurch. Damages to urban forests are highly volatile across age classes because of the heterogeneous distribution of urban forests across New Zealand and the short-lived effects of urban damages at any single location. Total damages are the sum of damages to urban and plantation forests; they initially increase steeply with population age, and then level but remain variable over time.

Due to the ports’ differing proximities to urban and plantation forests, the estimated net present value of expected damages from a wood borer or bark beetle establishment (if not eradicated) is highest for establishments beginning in Auckland or Tauranga (~US$560 million) and lowest for Christchurch (US$373 million); see Appendix K. Accounting for the annual probability of establishment in each port, the net present values of expected damages from pests establishing in a single year (without eradication) are US$17.6, $8.3, $2.5, and $2.2 million for establishments beginning in Auckland, Tauranga, Wellington, and Christchurch, respectively (Appendix K).

Surveillance scenario results

Fig. 3 shows how total and component costs and damages vary with trap density for each of four port regions. Surveillance costs increase with trap density, as per definition. Damages to urban and plantation forests decrease with trap density because earlier detection increases the likelihood of eradication by decreasing eradication costs and increasing the probability of success. Expected eradication costs are very low, and increase and then decrease with trap density. At low trap densities, eradication costs are low because populations are detected too late to be worth eradicating. At moderate trap densities, total expected eradication costs are higher because more populations are detected when small enough to make attempted eradication worthwhile. At very high trap densities, total eradication costs are lower because populations are smaller and thus less costly to eradicate when detected. The generally convex shape of the total cost curve, which is the sum of the four component costs, reflects the trade-off between surveillance expenditures and damage costs.

Optimal trap density occurs at the minimum of the total cost curve (Fig. 3; open circle). The optimal trap density is highest for Tauranga, followed by Auckland; Christchurch and Wellington have much lower optimal trap densities (Fig. 3, Table 1). The total expected costs and damages are highest for Auckland, followed by Tauranga, with the total expected costs of invasions being much lower for Christchurch and Wellington (Fig. 3). The differences across the four regions result from different establishment rates, rates of damage accumulation, and size (i.e., sampling area). For example, Tauranga has the highest optimal trapping density across the four ports even though the annual expected damage from pest establishment is only half that of Auckland, due to lower introduction rates in Tauranga (Appendix K: Fig. K1). The reason for this unintuitive result is that the Tauranga port region is only about 10% of the size of the Auckland region and therefore has about five times more expected damages per unit area, thus warranting a greater density of traps. However, the optimal number of traps is higher in Auckland.

The optimal surveillance strategy calls for a very high investment in traps: just over 10,000 traps deployed annually for 30 years, at a present value cost of US$54 million (Fig. 3, Tables 1 and 2). This strategy provides an expected net present benefit of about US$300 million by reducing the present value of total expected control costs and damages from US$776 million without surveillance trapping to US$476 million with optimal
surveillance trapping (Tables 2 and 3). This represents an approximate 39\% reduction in expected costs and damages (Table 3).

The expected net present value of benefits from optimally deploying a fixed number of traps across the four port regions is shown in Fig. 4. The net benefits increase steeply with initial investments in surveillance, but increase less steeply for surveillance intensity greater than about 4000 total traps deployed. The maximal expected net benefits are achieved from deploying

<table>
<thead>
<tr>
<th>Trapping scenario</th>
<th>Total traps</th>
<th>Auckland Traps</th>
<th>Auckland Density</th>
<th>Tauranga Traps</th>
<th>Tauranga Density</th>
<th>Wellington Traps</th>
<th>Wellington Density</th>
<th>Christchurch Traps</th>
<th>Christchurch Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>No traps</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Equal trap density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 traps total</td>
<td>50</td>
<td>25</td>
<td>0.12</td>
<td>4</td>
<td>0.12</td>
<td>10</td>
<td>0.12</td>
<td>11</td>
<td>0.12</td>
</tr>
<tr>
<td>200 traps total</td>
<td>200</td>
<td>101</td>
<td>0.47</td>
<td>16</td>
<td>0.47</td>
<td>41</td>
<td>0.47</td>
<td>42</td>
<td>0.47</td>
</tr>
<tr>
<td>400 traps total</td>
<td>400</td>
<td>202</td>
<td>0.93</td>
<td>31</td>
<td>0.93</td>
<td>83</td>
<td>0.93</td>
<td>84</td>
<td>0.93</td>
</tr>
<tr>
<td>1000 traps total</td>
<td>1000</td>
<td>506</td>
<td>2.33</td>
<td>78</td>
<td>2.33</td>
<td>207</td>
<td>2.33</td>
<td>210</td>
<td>2.33</td>
</tr>
<tr>
<td>Optimized trap density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 traps total</td>
<td>50</td>
<td>28</td>
<td>0.13</td>
<td>19</td>
<td>0.57</td>
<td>2</td>
<td>0.02</td>
<td>2</td>
<td>0.02</td>
</tr>
<tr>
<td>200 traps total</td>
<td>200</td>
<td>114</td>
<td>0.52</td>
<td>66</td>
<td>1.97</td>
<td>11</td>
<td>0.12</td>
<td>9</td>
<td>0.10</td>
</tr>
<tr>
<td>400 traps total</td>
<td>400</td>
<td>253</td>
<td>1.16</td>
<td>105</td>
<td>3.12</td>
<td>23</td>
<td>0.26</td>
<td>20</td>
<td>0.22</td>
</tr>
<tr>
<td>1000 traps total</td>
<td>1000</td>
<td>610</td>
<td>2.81</td>
<td>219</td>
<td>6.50</td>
<td>91</td>
<td>1.03</td>
<td>80</td>
<td>0.89</td>
</tr>
<tr>
<td>Optimal trapping</td>
<td>10182</td>
<td>6811</td>
<td>31.36</td>
<td>2149</td>
<td>63.94</td>
<td>650</td>
<td>7.32</td>
<td>573</td>
<td>6.36</td>
</tr>
</tbody>
</table>

Notes: The first row (scenario 1) is the no-trapping alternative. The next four rows (scenarios 2–5) distribute a fixed number of traps at a constant density across the four sites. The next four rows (scenarios 6–9) optimize the distribution of a fixed number of traps across the four sites. The final row (scenario 10) shows the optimal number and distribution of traps without a budget constraint on total trapping effort.
Deploying more than this number of traps leads to decreasing net benefits, as the marginal costs of additional trapping are greater than the marginal benefits from reduced eradication and damage costs.

Although the optimal trap density provides the greatest expected net benefits, there are substantial net benefits from even low (suboptimal) trapping densities (Fig. 4, Table 3). All of the surveillance scenarios with fixed numbers of traps (scenarios 2–5) distribute a fixed number of traps across the four sites. The final row (scenario 10) shows the optimal number and distribution of traps in the absence of a budget constraint on total trapping effort.

TABLE 2. Total costs and damages for various trapping scenarios using baseline parameters, for invasive beetles in New Zealand urban forests and plantations.

<table>
<thead>
<tr>
<th>Trapping scenario</th>
<th>Total</th>
<th>Surveillance</th>
<th>Eradication</th>
<th>Urban forest damage</th>
<th>Plantation forest damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>No traps</td>
<td>776.03</td>
<td>0.00</td>
<td>0.62</td>
<td>404.65</td>
<td>370.76</td>
</tr>
<tr>
<td>Equal trap density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 traps total</td>
<td>705.68</td>
<td>0.73</td>
<td>1.44</td>
<td>364.63</td>
<td>338.87</td>
</tr>
<tr>
<td>200 traps total</td>
<td>651.34</td>
<td>1.68</td>
<td>1.00</td>
<td>333.28</td>
<td>315.38</td>
</tr>
<tr>
<td>400 traps total</td>
<td>614.97</td>
<td>2.57</td>
<td>0.86</td>
<td>312.17</td>
<td>299.37</td>
</tr>
<tr>
<td>1000 traps total</td>
<td>561.21</td>
<td>5.56</td>
<td>0.70</td>
<td>280.10</td>
<td>274.85</td>
</tr>
<tr>
<td>Optimized trap density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 traps total</td>
<td>693.16</td>
<td>0.73</td>
<td>1.39</td>
<td>358.39</td>
<td>332.64</td>
</tr>
<tr>
<td>200 traps total</td>
<td>633.93</td>
<td>1.68</td>
<td>1.01</td>
<td>324.47</td>
<td>306.78</td>
</tr>
<tr>
<td>400 traps total</td>
<td>597.38</td>
<td>2.57</td>
<td>0.85</td>
<td>303.02</td>
<td>290.94</td>
</tr>
<tr>
<td>1000 traps total</td>
<td>549.28</td>
<td>5.56</td>
<td>0.69</td>
<td>273.81</td>
<td>269.22</td>
</tr>
<tr>
<td>Optimal trapping</td>
<td>476.35</td>
<td>54.21</td>
<td>0.51</td>
<td>204.80</td>
<td>216.82</td>
</tr>
</tbody>
</table>

Notes: The first row (scenario 1) is the no-trapping alternative. The next four rows (scenarios 2–5) distribute a fixed number of traps at a constant density across the four sites. The next four rows (scenarios 6–9) optimize the distribution of a fixed number of traps across the four sites. The final row (scenario 10) shows the optimal number and distribution of traps in the absence of a budget constraint on total trapping effort.

TABLE 3. Return on investment for various trapping scenarios using baseline parameters, for invasive beetles in New Zealand urban forests and plantations.

<table>
<thead>
<tr>
<th>Trapping scenario</th>
<th>Expected net benefits (millions of USD)</th>
<th>Reduction in total costs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equal trap density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 traps total</td>
<td>70.35</td>
<td>9.1</td>
</tr>
<tr>
<td>200 traps total</td>
<td>124.69</td>
<td>16.1</td>
</tr>
<tr>
<td>400 traps total</td>
<td>161.06</td>
<td>20.8</td>
</tr>
<tr>
<td>1000 traps total</td>
<td>214.82</td>
<td>27.7</td>
</tr>
<tr>
<td>Optimized trap density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 traps total</td>
<td>82.87</td>
<td>10.7</td>
</tr>
<tr>
<td>200 traps total</td>
<td>142.10</td>
<td>18.3</td>
</tr>
<tr>
<td>400 traps total</td>
<td>178.65</td>
<td>23.0</td>
</tr>
<tr>
<td>1000 traps total</td>
<td>226.75</td>
<td>29.2</td>
</tr>
<tr>
<td>Optimal trapping</td>
<td>299.68</td>
<td>38.6</td>
</tr>
</tbody>
</table>

Notes: The expected net benefits are the difference in total expected costs under the specified trapping scenario relative to no trapping (scenario 1). The percentage reduction in total costs also is relative to no surveillance. The first four rows (scenarios 2–5) distribute a fixed number of traps across the four sites. The next four rows (scenarios 6–9) optimize the distribution of a fixed number of traps across the four sites. The final row (scenario 10) shows the optimal number and distribution of traps if there is not a budget constraint on total trapping effort.

Fig. 4. Expected net benefits of trapping, by total number of traps deployed. In the analysis for this figure, the total number of traps (x-axis) is distributed optimally across the four port regions (Eqs. 7 and 8). The expected net benefits are the difference in total costs and damages with vs. without surveillance trapping, and include surveillance costs, eradication costs, and invasion damages. The circle shows the optimal total number of traps.
Table 4. Sensitivity of expected net benefits of surveillance under alternative parameter specifications for the surveillance programs identified as optimal under the baseline parameterization (Table 1).

<table>
<thead>
<tr>
<th>Sensitivity analysis</th>
<th>50 traps, optimal</th>
<th>200 traps, optimal</th>
<th>400 traps, optimal</th>
<th>1000 traps, optimal</th>
<th>Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>High discount rate ($\delta = 0.1$)</td>
<td>18.49</td>
<td>31.68</td>
<td>39.72</td>
<td>49.21</td>
<td>44.33</td>
</tr>
<tr>
<td>No urban damages; baseline plantation damages (50% low, 10% medium, 1% high)</td>
<td>35.98</td>
<td>61.39</td>
<td>76.53</td>
<td>95.48</td>
<td>99.43</td>
</tr>
<tr>
<td>Low establishment rate ($h$)</td>
<td>40.68</td>
<td>70.04</td>
<td>87.92</td>
<td>110.55</td>
<td>122.72</td>
</tr>
<tr>
<td>Low probability of eradication success</td>
<td>31.98</td>
<td>65.42</td>
<td>87.39</td>
<td>116.10</td>
<td>142.71</td>
</tr>
<tr>
<td>Program length ($T = 10$ yr)</td>
<td>42.38</td>
<td>73.46</td>
<td>92.64</td>
<td>118.11</td>
<td>139.89</td>
</tr>
<tr>
<td>No urban damages; high plantation damages (75%, 15%, 1%)</td>
<td>51.75</td>
<td>88.03</td>
<td>109.78</td>
<td>137.81</td>
<td>163.61</td>
</tr>
<tr>
<td>Delayed (slower) spread ($h = 20$ yr)</td>
<td>53.81</td>
<td>94.40</td>
<td>119.12</td>
<td>152.82</td>
<td>183.57</td>
</tr>
<tr>
<td>Very low urban damages (5%, 2%, 1%)</td>
<td>61.00</td>
<td>104.60</td>
<td>131.14</td>
<td>165.60</td>
<td>206.12</td>
</tr>
<tr>
<td>60% establishment in 20% of port region area</td>
<td>61.38</td>
<td>105.89</td>
<td>133.17</td>
<td>168.60</td>
<td>211.20</td>
</tr>
<tr>
<td>Low plantation damages (20%, 5%, 1%)</td>
<td>64.36</td>
<td>111.81</td>
<td>141.03</td>
<td>179.06</td>
<td>227.49</td>
</tr>
<tr>
<td>60% establishment in 10% of port region area</td>
<td>82.06</td>
<td>133.49</td>
<td>162.10</td>
<td>195.11</td>
<td>235.15</td>
</tr>
<tr>
<td>Higher percentage fast-spreading species (75% fast; 25% slow)</td>
<td>68.72</td>
<td>118.06</td>
<td>147.86</td>
<td>186.97</td>
<td>235.21</td>
</tr>
<tr>
<td>Low urban damages (10%, 3%, 1%)</td>
<td>68.10</td>
<td>117.06</td>
<td>146.97</td>
<td>186.03</td>
<td>237.37</td>
</tr>
<tr>
<td>Time = 50 yr (time over which damages accrue)</td>
<td>71.04</td>
<td>122.87</td>
<td>154.71</td>
<td>196.19</td>
<td>253.70</td>
</tr>
<tr>
<td>Trap sensitivity ($y = 0.3$)</td>
<td>59.52</td>
<td>108.90</td>
<td>140.28</td>
<td>187.47</td>
<td>260.53</td>
</tr>
<tr>
<td>95% establishment in 100% of port region area</td>
<td>44.55</td>
<td>87.23</td>
<td>116.42</td>
<td>162.32</td>
<td>267.67</td>
</tr>
<tr>
<td>80% establishment in 30% of port region area</td>
<td>68.35</td>
<td>121.96</td>
<td>155.71</td>
<td>204.09</td>
<td>276.92</td>
</tr>
<tr>
<td>High eradication costs</td>
<td>80.61</td>
<td>140.91</td>
<td>177.80</td>
<td>226.24</td>
<td>299.40</td>
</tr>
<tr>
<td>Low eradication costs</td>
<td>82.58</td>
<td>141.97</td>
<td>178.53</td>
<td>226.69</td>
<td>299.62</td>
</tr>
<tr>
<td><strong>Baseline</strong></td>
<td><strong>82.87</strong></td>
<td><strong>142.10</strong></td>
<td><strong>178.65</strong></td>
<td><strong>226.75</strong></td>
<td><strong>299.68</strong></td>
</tr>
<tr>
<td>Time = 100 yr (time over which damages accrue)</td>
<td>85.48</td>
<td>147.54</td>
<td>185.68</td>
<td>236.03</td>
<td>313.81</td>
</tr>
<tr>
<td>Trap sensitivity ($y = 0.9$)</td>
<td>97.84</td>
<td>162.97</td>
<td>201.22</td>
<td>247.75</td>
<td>319.89</td>
</tr>
<tr>
<td>Program length ($T = 50$ yr)</td>
<td>97.05</td>
<td>167.49</td>
<td>210.74</td>
<td>267.57</td>
<td>352.43</td>
</tr>
<tr>
<td>High probability of eradication success</td>
<td>171.65</td>
<td>232.93</td>
<td>267.93</td>
<td>311.88</td>
<td>352.66</td>
</tr>
<tr>
<td>High plantation damages (75%, 15%, 1%)</td>
<td>97.85</td>
<td>168.37</td>
<td>211.65</td>
<td>268.98</td>
<td>363.84</td>
</tr>
<tr>
<td>Lower percentage fast-spreading species (25% fast, 75% slow)</td>
<td>95.45</td>
<td>165.44</td>
<td>208.96</td>
<td>266.35</td>
<td>364.14</td>
</tr>
<tr>
<td>High urban damages (50%, 10%, 1%)</td>
<td>121.08</td>
<td>210.84</td>
<td>266.48</td>
<td>340.57</td>
<td>474.52</td>
</tr>
<tr>
<td>High establishment rate ($h$)</td>
<td>230.76</td>
<td>399.22</td>
<td>503.29</td>
<td>643.52</td>
<td>934.94</td>
</tr>
<tr>
<td>Low discount rate ($\delta = 0.01$)</td>
<td>452.63</td>
<td>781.25</td>
<td>986.09</td>
<td>1269.98</td>
<td>1891.42</td>
</tr>
</tbody>
</table>

**Notes:** Results are shown for five different surveillance programs (scenarios 6–10): the optimal distribution of 50, 200, 400, and 1000 total traps, and the optimal, unrestricted surveillance program identified for baseline parameters. Sensitivity analyses are ordered, top to bottom, by increasing net benefits under the optimal program (baseline in boldface). Where three percentages are given for damage, they represent low, medium, and high damages, respectively.

**Factors not included**

Some important stochastic aspects of the costs and benefits of surveillance are not specifically addressed in the current analysis, which is based on expectations. Even though we find that surveillance, on average, can reduce the expected long-term damages from invasive wood borers and bark beetles, the actual realization of future invasions and of detection and eradication success are stochastic. Thus, surveillance increases the probability that new invasions will be detected and eradicated, but does not eliminate risk. In fact, even under the optimal surveillance effort identified in our baseline analyses, only about 70–80% of new invaders arriving in Tauranga or Auckland and 55–65% of those arriving in Wellington and Christchurch are expected to be eradicated (Fig. 5). Nonetheless, the expected net benefits of surveillance are positive and large because surveillance significantly reduces the probability of potentially very bad outcomes by increasing the likelihood that populations will be detected early and eradicated.

The surveillance scenario for alternative parameter sensitivity specifications. Appendix M shows the expected costs and damages, expected net benefits, and percentage savings from optimal surveillance for each trapping scenario and sensitivity parameter specification. For all sensitivity analyses, the greatest net benefits arise from deploying more than 1000 total traps (i.e., more traps than in our highest fixed-effort trapping scenario; see Appendices L and M). The optimal trap densities and total expected costs are most sensitive to the specification of discount rate, with lower discount rates demanding much higher surveillance effort.

Table 4 shows the expected net benefits of implementing the surveillance strategies identified as optimal under the baseline parameterization (scenarios 6–10 in Table 1) for each sensitivity analysis parameter specification. The expected net benefits are positive across all sensitivity analysis parameterizations. Thus, even when accounting for uncertainty in individual model parameters, the surveillance programs identified as optimal in our baseline parameterization are cost-effective.
We did not attempt to estimate potential damages in natural forests or the conservation estate. However, losses of conservation value might amount to costs at least as great as those considered here. A study in the United States (Holmes et al. 2009) suggested the greatest economic harm caused by invasive forest species is likely to be due to losses of nonmarket ecosystem services, including landscape aesthetics and outdoor recreation. Accounting for these damages in the model would increase the net benefits of surveillance trapping and increase the optimal surveillance intensity.

Our approach does not account for trade effects of invasive species (e.g., reduced log exports because of import bans). If New Zealand’s trading partners respond to the presence of a pest invasion by banning or restricting trade in New Zealand logs, this will have an effect above and beyond a harvest yield reduction by reducing demand for these products, thus lowering the price received. Previous studies have sought to estimate the economic impacts of hypothetical trade restrictions resulting from pest establishment and have elucidated qualitative trade implications of invasive species (Prestemon et al. 2006, 2008, Turner et al. 2006, 2007, Li et al. 2007). We have excluded these from our analysis because the trade impact estimation models have limited ability to capture the complex detection, eradication, and control dynamics that will affect both the magnitude and direction of impact (Prestemon et al. 2008). Early detection would incur trade costs earlier but induce a greater likelihood of eradication, which would end the costs of trade impacts. Later detection would delay costs of trade impacts, but those costs would likely be higher and last longer, especially because later detection would increase the size of the quarantine area.

This analysis focused on surveillance in the four port regions representing the import location of about 90% of anticipated future wood borer and bark beetle establishment. Furthermore, we concentrated on the highest-risk areas within those regions. As a consequence, almost 30% of potential future wood borer and bark beetle establishments are not targeted by the surveillance programs considered here because they are expected to occur outside the targeted areas. To design country-wide surveillance trapping (i.e., optimal trapping outside port areas), we would need to expand our analysis to identify region-specific establishment risk across the entire country and estimate damages for invasions beginning in each region. The optimal trap density would be much lower outside the port regions because of the much lower anticipated establishment rates. Determining these trapping densities and the expected net benefits of expanding a surveillance trapping network would be a useful focus for future analyses.

Finally, although this study focused on optimizing and evaluating the expected benefits of implementing a surveillance trapping program, investing in other aspects of invasion control—decreasing arrival and establishment rates, increasing the likelihood of eradication, and increasing the cost-effectiveness of post establishment controls (e.g., containment, biocontrol, chemical pest control)—could also be worthwhile. For example, our sensitivity analyses showed that reducing establishment rates by 50% relative to the baseline assumption would reduce the expected costs and damages from establishment in the four port regions by about US$200 million (Appendix M). Also, in our analysis we estimated the likelihood of eradication and the costs of eradication efforts as functions of invasion size using observed data. In reality, however, eradication success and eradication expenditures are interrelated, such that for any given invasion event, greater investment in the effort is likely to increase the probability of success. Accounting for this correlation between costs and success is a difficult problem that could be the subject of future research and should be considered in the design of on-the-ground eradication efforts.

Conclusions

Our findings show that implementing a surveillance trapping program for invasive wood borers and bark beetles in New Zealand clearly would be beneficial, for all scenarios considered. The optimal 30-year surveillance strategy is expected to provide a net present benefit (i.e., a net present value savings) of about US$300 million. Sensitivity analyses indicate that our findings of positive net benefits of trap-based surveillance for wood borers and bark beetles in New Zealand are robust to our choice of parameters. In addition, although we did not include potential damages to native forests in our analyses, consideration of these damages would increase the returns from surveillance and increase the optimal surveillance intensity.
Our results indicate that surveillance will provide the greatest net benefits when it is implemented at quite high levels. However, our findings also suggest that even low levels of surveillance are worthwhile. We find that the greatest payoffs from surveillance occur for programs in areas that receive large amounts of imports and in areas where damages will accrue most quickly (because of the proximity to high-value, at-risk resources). We expect that these patterns apply to countries beyond New Zealand.

Based on our analyses, we recommend that a trap-based surveillance program for wood borers and bark beetles be implemented in New Zealand. The program’s level of surveillance intensity could be scaled to the available funds, and our model can be used to determine the optimal surveillance strategy, in terms of trap numbers and locations, in relation to the funds available, as well as the expected benefits of augmenting funds allocated to surveillance. Future analyses could focus on identifying optimal surveillance efforts outside core establishment areas (i.e., outside the four port regions) and identifying the distribution of trap locations within each region.

Beyond our specific findings of positive net benefits of implementing a trap-based surveillance program for wood borers and bark beetles in New Zealand, this research outlines a framework for designing surveillance programs across a much broader range of contexts. Our approach is applicable across regions and to single or multiple pest species and specific or general suites of species. Parameterization is probably the greatest challenge to its implementation. However, we have illustrated one strategy for parameterizing and implementing the model for an application that addresses a practical and specific management need. Our results also support the general guidance that investments in surveillance are likely to be most cost-effective in areas that receive high amounts of imports and that are near to high-value, at-risk resources.

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LI T E R AT U R E C I T E D


MathWorks. 2010. MATLAB R2010b. MathWorks, Natick, Massachusetts, USA.

Supplemental Material

Appendix A
Summary of parameters (Ecological Archives A024-075-A1).

Appendix B
Invasive species damage types and proportions (Ecological Archives A024-075-A2).

Appendix C
Estimation of establishment risk, by port and invader type (Ecological Archives A024-075-A3).

Appendix D
Trapping cost estimation and trap sensitivity (Ecological Archives A024-075-A4).
Appendix E
Invader population growth (Ecological Archives A024-075-A5).

Appendix F
Estimation of total annual harvest value for plantation forest (Ecological Archives A024-075-A6).

Appendix G
Invasion of plantation and urban forests over time (Ecological Archives A024-075-A7).

Appendix H
Estimation of urban tree density (Ecological Archives A024-075-A8).

Appendix I
Estimated eradication cost and success functions and data (Ecological Archives A024-075-A9).

Appendix J
Cumulative probability of detection for colonies aged 1 to 5 years (Ecological Archives A024-075-A10).

Appendix K
Expected damages from wood borer and bark beetle establishments (Ecological Archives A024-075-A11).

Appendix L
Optimized trapping densities and numbers for sensitivity analyses (Ecological Archives A024-075-A12).

Appendix M
Costs, damages, and return on investment results for sensitivity analyses (Ecological Archives A024-075-A13).