# Bioeconomic modeling for decision-support: optimizing early detection and control of invasive pests*

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* This paper comprises a report that I prepared for the United States Department of Agriculture's Animal and Plant Health Inspection Service (USDA-APHIS). It describes a bioeconomic model that I developed and transferred to USDA-APHIS in 2019 to provide input to agency resource allocation decisions related to surveillance and monitoring of invasive species introductions. The report illustrates how bioeconomic modeling can be adapted and implemented to actively inform resource allocation choices. While this draft was not prepared for an academic or economic audience, in on-going work I apply this model to develop management rules of thumb and to examine the value of non-regulatory pest detection sources (e.g. detection and reporting by the general public) for reducing long term management and damage costs from new pest incursions.

**Cost-efficient Surveillance Allocation Tool (CESAT)**
**Overview**

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## CESAT overview:

Cost-efficient Surveillance Allocation Tool (CESAT) was developed as a decision support tool to identify cost-efficient allocation of resources for early detection of new pest incursions. The tool runs the program R (R Corp 2019). Implementing the model requires estimating a range of parameters related to introduction risk, spread rate, detection activities, and damage and control costs across focal pests, sites, and traps. The model can be applied to one or more pests at a time and across multiple sites.

CESAT employs a bioeconomic modeling framework to a) determine the most cost-efficient allocation of survey resources across sites and traps and b) the expected net benefits of allocations across a range of budget options. CESAT can be used to help address questions such as:

1) How should survey resources for pest A be allocated across sites, and what level budget would provide the greatest net returns?
2) What are the net economic costs (or benefits) of changing an annual survey budget from X to Y?
3) How many resources should be allocated to survey for pest B at site A?
4) How many resources should be allocated to pest B versus pest C?
5) Should we continue trapping for Pest A, and if so, at what level?
6) What are the expected benefits of allocating survey resources according to Plan C?

CESAT is intended to provide an additional source of information for resource allocation decisions related to early detection of pests. Output from CESAT can assist in exploring economic trade-offs associated with different allocation options.

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# BACKGROUND:

## CESAT OVERVIEW:

Pest detection programs serve an important role in APHIS' efforts to safeguard U.S. agricultural and environmental resources by ensuring that new introductions of harmful plant pests and diseases are detected as early as possible, to reduce long term impacts and costs of management. However, resources for conducting pest surveys are limited, so understanding how to target resources efficiently (across pests and locations) can improve the effectiveness of these safeguarding investments.

The decision-support tool – Cost-Effective Surveillance Allocation Tool (CESAT) – has been developed to help address this challenge (Epanchin-Niell 2017). CESAT can help inform efficient allocation of pest detection resources to get the "biggest bang for the buck" in terms of reducing long term costs and damages from pest establishment. The tool provides a framework for prioritizing surveillance investments across locations and pest groups (e.g., fruit fly, gypsy moth complex, wood borer/bark beetles, and snails) to minimize costs and damages from new pest introductions across the US or in more localized areas.

The algorithm underlying the CESAT identifies cost-effective resource allocation using information on pests' potential damages, introduction rates, spread rates, eradication costs, quarantine costs, control efficacy, and survey costs and sensitivity. The algorithm is based on a mechanistic model of population establishment, growth, detection, and control, and allocates resources across pests and sites to provide the greatest reduction in long term costs and damages by detecting invasions earlier when they are smaller and less costly to manage (Epanchin-Niell et al. 2012, 2014).

## BACKGROUND ON OPTIMAL SURVEY ALLOCATION

Surveillance for invasive species is conducted in order to learn about invader presence and distribution, and provides value by enabling people, agencies, and communities to respond or adapt to the invader's presence (Figure 1). For example, knowledge of an invader's presence may enable the initiation of an eradication or control program or enable communities to reduce impacts by preparing for an invader's arrival (e.g. preemptive pesticide treatments, quarantine measures, or adjustment of agricultural practices). If learning about the invader's presence through surveillance were not likely to alter responses relative to without knowledge of the invader's presence, then there would be minimal economic value to conducting surveys for early detection.[1] Similarly, active surveillance would provide little value if target species were likely to be detected equally

[1] Surveillance and pest trapping also can be important for providing evidence of maintained pest free status as may be required by some trade agreements and to monitor eradication efforts in order to determine when success has been achieved. These applications are not the specific focus of the effort described here.

early by alternative mechanisms (e.g. public reporting of observed damages or pest sightings). Cost-effective surveillance programs target surveys where there is the highest value of information provided by a given investment – i.e. where the benefits gained from surveillance are greatest relative to the costs. Because the value of information and the costs and effectiveness of survey efforts vary across target pests and locations, cost-effective surveillance effort is heterogeneous across pests and locations.

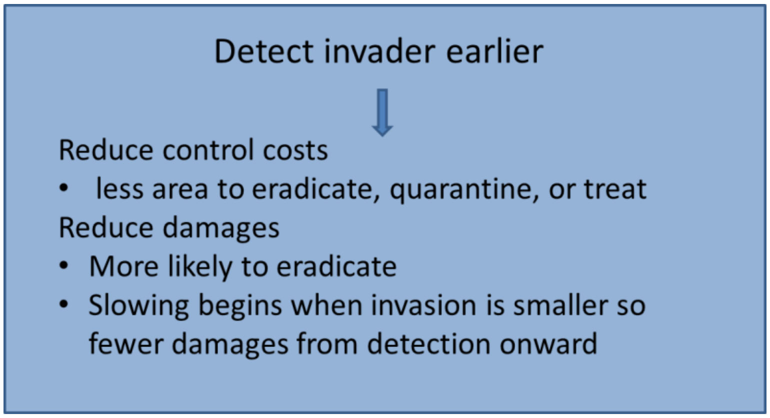


**Figure 1.** How surveillance creates value.

*The resource allocation problem:*

*How many resources should be invested in detecting each target pest group, and where should those resources be targeted across the landscape, in order to minimize the total combined costs of surveillance investments, pest control efforts, and pest damages.*

The overarching resource allocation problem is how to allocate survey resources across pests and locations to minimize long term costs. Such cost-effective resource allocation can be achieved by targeting resources where they provide the biggest bang for the buck (i.e. return on investment), as measured by benefits divided by costs (Figure 2). Anticipated benefits (a.k.a. returns) are the expected reduction in long term invasion control and damage costs with versus without the survey efforts, and costs are the expense of implementing the surveys.

$$\frac{\left[\begin{array}{c}\text{Probability target pest has established}\\ *\\ \text{[pest costs without surveillance – pest costs with surveillance]}\end{array}\right]}{\text{Costs of surveillance}}$$

**Figure 2.** Return on investment from surveillance.

A variety of factors affect the long term costs and damages from an introduced pest, and hence also the value of surveillance investments. These factors include the pest's probability of introduction, when a new population is likely to be detected without formal surveillance, the species' rate of spread, damages posed to at-risk resources, the cost and effectiveness of control options (including eradication, quarantine, and suppression costs) (Epanchin-Niell 2017).

Placing surveys on the landscape increases the likelihood of detecting a population early, when it is less costly to control and causes fewer damages. As the number of traps at a site increases, the probability of (early) detection also increases. As such, the expected cost of an invasion (control costs plus damage costs) generally decreases with increasing trap density (red line; Figure 3). In contrast, total survey costs increase with trap density (blue line; Figure 3). Thus, the total costs (invasion costs plus survey costs) decrease and then increase with trap density (green line; Figure 3). In the absence of a budget constraint, optimal trapping levels are where total costs (green line) are at a minimum (purple circle; Figure 3).

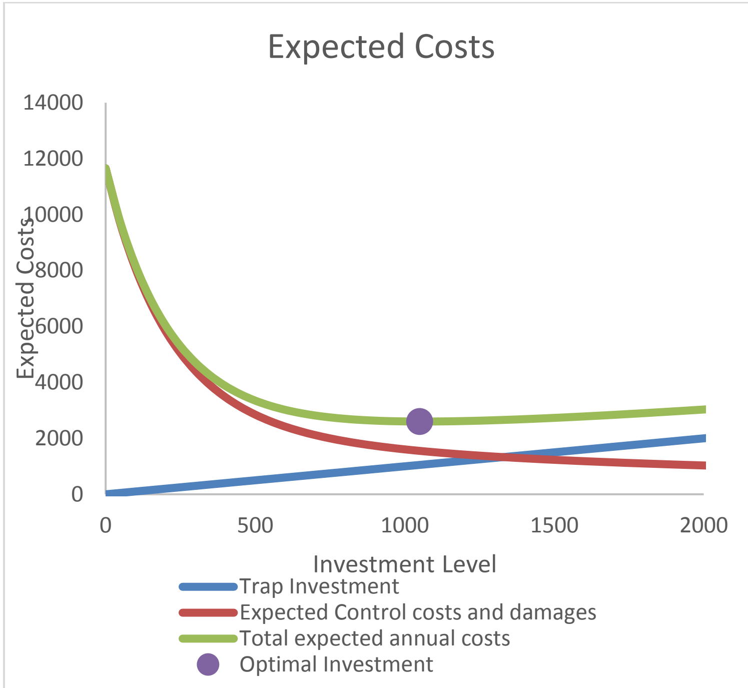


**Figure 3.** Expected survey, eradication, and total costs from pest introduction as a function of survey point density. Eradication cost (and damage and control costs) decline with sampling density. Total survey costs increase with trap density, and total costs (invasion costs plus survey costs) decrease and then increase with trap density. Optimal sampling levels are where total costs are at a minimum.

With a single site and pest, the optimal level of survey investment (i.e. the level that minimizes total expected costs) occurs where the cost of an additional trap just equals the benefits provided by the placement of that additional trap. In economic parlance, the optimal investment in surveillance occurs where the marginal benefits of additional surveillance (i.e. the marginal reduction in costs and damages from earlier detection) equal the marginal costs of the additional surveys.

While a "simple" rule (equate marginal benefits with marginal costs) can be used to determine the optimal number of traps to deploy for a given pest at a given location, the problem is more challenging when allocating a fixed amount of resources across multiple pests or multiple locations. Resource constraints may not allow the optimal level of surveillance to be achieved for all targets. Instead, resources are allocated across the set of targets to get the "biggest bang for the buck". This is achieved when resources are allocated such that a shift in resources from one target to another cannot increase overall benefits. This occurs when survey effort is allocated such that the marginal benefit of an additional trap divided by the marginal cost of the trap is equated across all targets. Conceptually, this optimal allocation can be found by taking "scoops" of resources sequentially from a fixed "pot" of resources (i.e. the total survey budget), and allocating each scoop to the site and pest for which it will provide the greatest benefits, given the allocation of scoops previously doled out. This “greedy algorithm” results in the equalization of marginal benefits divided by marginal costs across targets and provides the greatest bang for the buck from available resources.

# MODEL OVERVIEW

## CONCEPTUAL CESAT MODEL DESCRIPTION

The basic model assumes that the landscape is divided into sites that vary in their risk of invasion by pests across several pest groups. We aim to determine how pest detection resources should be allocated across pests and sites to minimize long term costs and damages from invasions. We assume that pests are optimally controlled following detection, and the value of detection results from reduced costs and damages from slowing pest spread, damage mitigation, or eradication of established pests.

Figure 4 shows the basic components of the CESAT model for a single species and site. The manager is choosing the amount to invest in surveillance (green box). This investment amount, as well as the rate of population spread and probability of detection by the public determines the probability that a population would be a give size at detection. The size of the population at detection determines the long term costs and damages from the invasion for each control option: eradication, quarantine (i.e. slow the spread programs), damage mitigation measures, or no control. The model then assumes that the most cost-effective control option is selected, based on the population size at detection. By combining the expected control and damage costs associated with pest establishment and the annual probability of pest establishment, the model estimates the long term expected costs and damages from invasive pest introduction dependent on investment in survey effort.

The single species/site submodel is then aggregated up to account for multiple pests and sites, such that the investment level for each pest by site combination contributes to the overall costs and damages (Figure 5a).

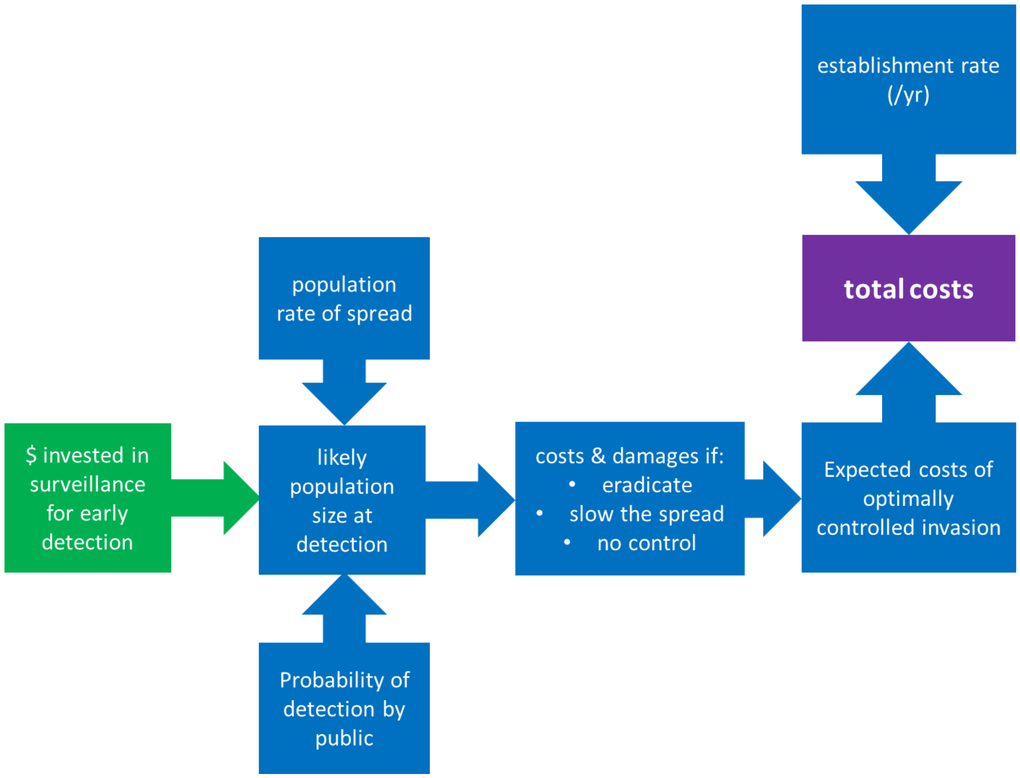


**Figure 4.** Components of the CESAT model for a single species and site

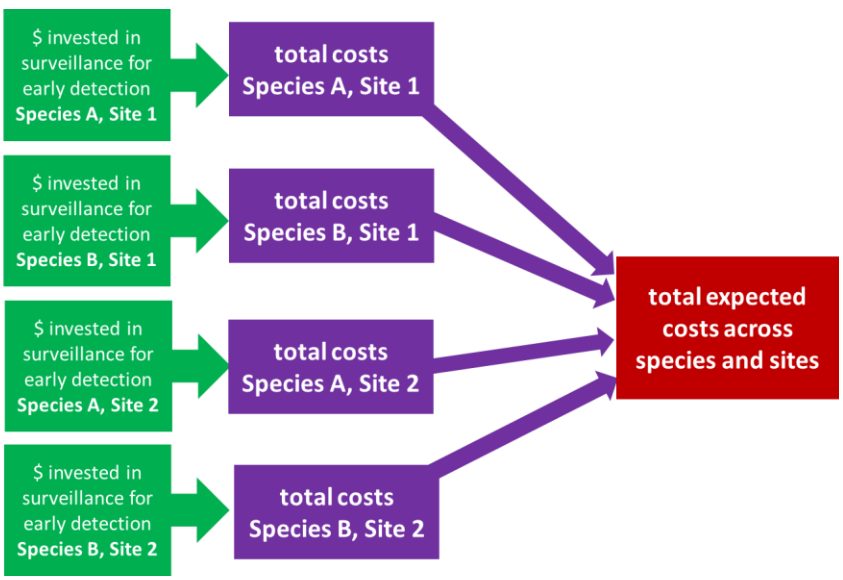


**Figure 5a.** Surveillance investment at each site for each pest determines the overall expected costs and damages from pest introduction. CESAT aims to optimize those investment levels (green boxes) to minimize the total expected costs (red box).

In addition, a single trap type can sometimes target multiple pests, such that the benefits from investments in that trap type are the reductions in costs across multiple targeted pests (Figure 5b).

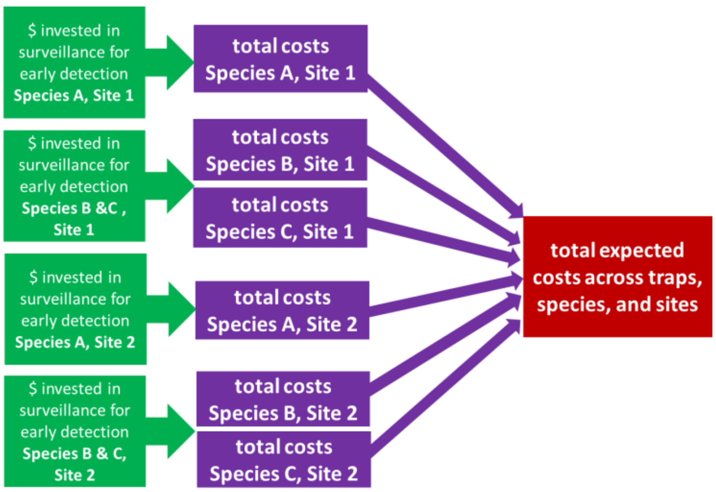


**Figure 5b.** Surveillance investment at each site for trap determines the overall expected costs and damages from pest introduction. CESAT aims to optimize those investment levels (green boxes) to minimize the total expected costs (red box).

Considering a set of pest groups and a set of potential survey sites, we assume that each combination of pest group by site is characterized by an annual probability of pest establishment, an invasion spread function, damages per unit area occupied or new area invaded, cost of eradication per area treated, cost of slowing the spread dependent on the length of invasion front or total area quarantined, effectiveness of slow the spread efforts (% reduction in spread rate), probability of a trap detecting a population if placed within range of the population, probability that the population would be detected by non-trapping methods (dependent on population size), and the cost of deploying each pest detection trap. We represent each parameter in the model using a uniform distribution to capture the uncertainty in species and site characteristics.

The CESAT model recognizes that both pest introduction and detection are stochastic processes, such that these are represented as probabilities. Following establishment, pest populations are assumed to grow and spread over time (e.g., Figure 6).

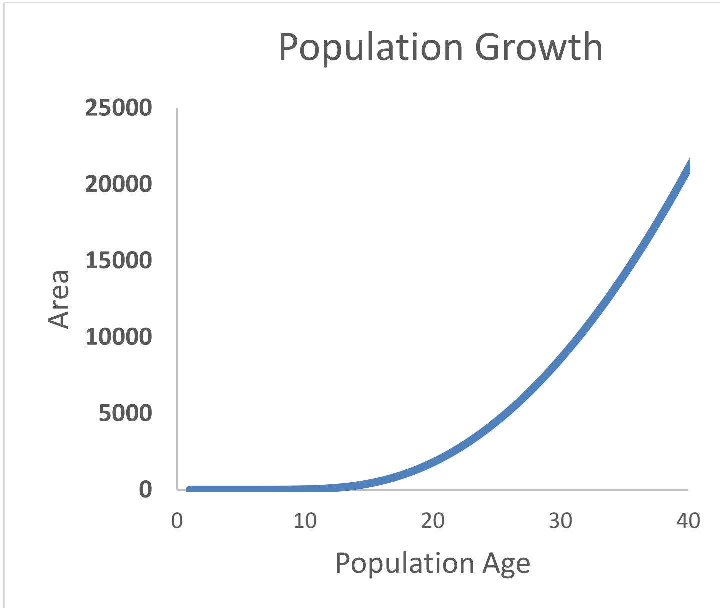


**Figure 6.** Population growth. Populations spread radially, occupying increasing area over time.

In each time period following establishment, the probability of detection depends on the number of traps deployed, trap efficacy, the size of the population, and the likelihood of detection by alternative means (e.g. public reporting), such that surveillance investment determines the probability that a population will be a given size when detected (e.g., Figure 7).

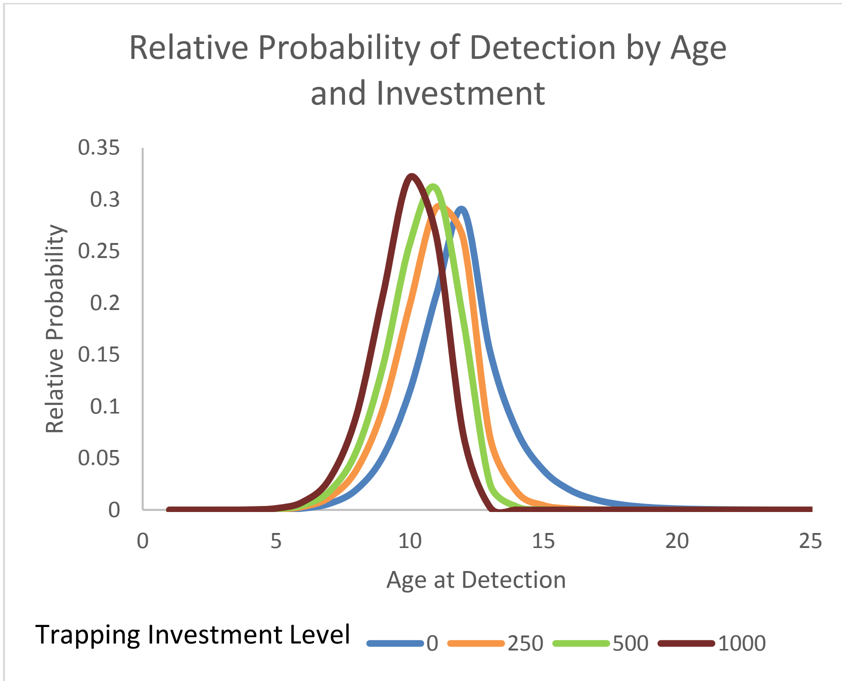


**Figure 7.** Relative probability of detecting a population at a given age, dependent on survey investment amount. As greater traps are placed on the landscape, populations tend to be detected earlier, when they are smaller.

Once a population is detected (by a trap or by some other means), CESAT assumes that managers select the management strategy that minimizes the expected discounted long term costs and damages from the pest. Management options include eradicating the population, slowing its spread, implementing damage mitigation measures, or implementing no control. The expected costs and damages with management depend on the age (size) of the invasion when detected (e.g., Figure 8), and hence on the amount invested in surveillance.

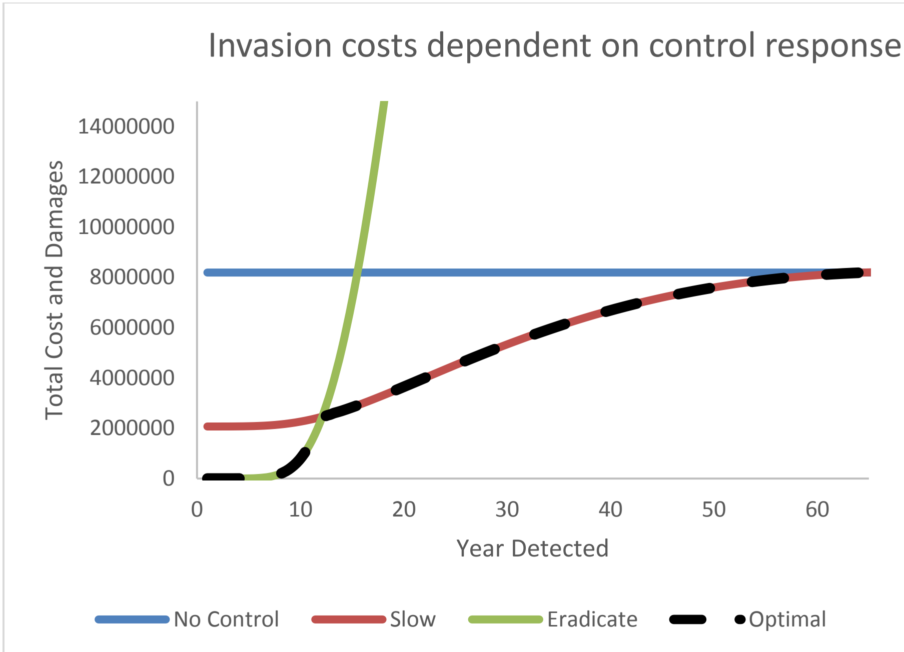


**Figure 8.** Total costs and damages from pest establishment, dependent on age of detection and the management response. With eradication (green line), the long term costs and damages from an invasion increase sharply with age of detection as the area requiring control and incurring damages increases. The expected costs from eradication are lower than the costs of other management responses (red and blue lines) when the pest is detected early. When detected later, the optimal response switches to quarantine (red line), and eventually no control (blue line) if detected very late. The black dashed line indicates the expected long term costs of control and damages for a pest, dependent on the age at which it is detected. Total expected costs increase with time to detection.

By combining information about the relationship between survey investments and the probability distribution of the population age at detection (Figure 7) with the expected costs of populations detected at different ages (Figure 8), one obtains the expected long term costs from pest invasions dependent on the level of surveillance investment (red line; Figure 3), where costs decrease with increasing investment in surveys. However, when summed with survey costs (blue line; Figure 3), one obtains total expected costs, which decrease and then increase with increasing survey investments (green line; Figure 3). The optimal survey investment in this single pest/site example is where total costs are minimum (purple circle; figure 3).

The net benefits from surveillance equal the difference between the expected invasion management and damage costs without trapping surveillance versus with trapping surveillance (Figure 9). Optimal surveillance investment maximizes the net benefits.

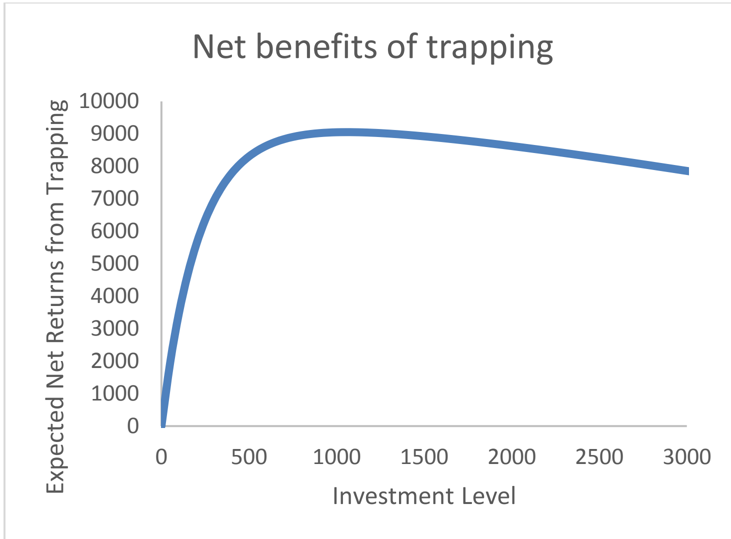


**Figure 9.** Net benefits from survey investment. Net returns increase sharply at low survey investment levels (as costs and damages are reduced through early detection) and then decline with additional traps as additional survey costs outweigh the reductions in pest costs. Optimal investment is where net returns are the greatest.

This framework can then be expanded to consider the optimal allocation of a restricted budget across multiple sites and pests. The management objective represented in CESAT is to allocate resources across sites and trap types to minimize long term costs and damages when summed across all traps, pests, and sites. The model considers implementation of a long term surveillance program that applies a constant surveillance strategy for the duration of the pest detection program (following Epanchin-Niell et al 2014). The benefits of the surveillance program accrue from earlier detection and control of pest populations that established prior to the start of the program but were previously undetected, as well as of populations that establish during the survey program. The model allows specification of surveillance investment levels in prior years, recognizing that past survey effort reduces the likelihood of undetected populations present on the landscape at the start of the focal surveillance program.

To determine optimal investment levels across targets, we begin by calculating the expected net benefits for each pest group and site for a wide range of survey investment levels. We then calculate the marginal returns (benefits) from different "scoops" of investment, where the marginal benefits are the additional benefits (reduction in costs and damages) from each additional unit of survey investment. We identify the optimal, unconstrained survey investment level for each pest group at each site as the investment level that produces the highest expected net benefits (expected total benefits minus total investment costs) for that pest and site. To allocate limited survey resources across pests and sites, we use a "greedy" algorithm that sequentially allocates scoops of resources across targets in order of decreasing marginal benefits, until all of the resources have been allocated.

Because all parameters in the model are described by distributions, we use Monte Carlo draws of these parameters to create sets of parameters that represent the range of uncertainty in underlying characteristics for each target. For each set of Monte Carlo draws, we calculate the expected total and marginal benefits of survey investments, accounting for optimal post-detection management choices. Thus, for each target (pest group by site), we develop a distribution of potential expected benefits from survey investments based on underlying parameter uncertainty. We use several metrics to summarize these distributions and to serve as inputs into the optimal resource allocation algorithm. Specifically, we consider resource allocation based on the mean, median, and 5$^{th}$ and 95$^{th}$ percentiles of the distribution of marginal benefits for each investment level. A focus on the 95$^{th}$ percentile essentially represents a risk averse strategy as it focuses on the Monte Carlo draws for which survey investments can provide the greatest reductions in costs and damages.

## MODEL DETAILS

Model details are first described for a single pest type and site, and then expanded to consider multiple pest groups and sites. Specific functional forms assumed for population spread, control, and costs are shown in Table 1.

### POPULATION ESTABLISHMENT, GROWTH AND DETECTION.

Consider a pest that has probability $e(t)$ of arriving and establishing at the focal site of area $M$ in each time period $t$. Following establishment, the population grows and spreads across the landscape according to an underlying growth function, such that in the absence of any control measures the population occupies an area $A(a)$, dependent on its age $a$. In each time period, the population may be detected by deployed traps or non-trapping methods (e.g. the public). Following detection, the population is eradicated, quarantined, or uncontrolled, dependent on which strategy minimizes the expected long term costs and damages from the invasion over the $a_{max}$ years that the invader may cause damages. The size of a population that is subject to quarantine depends on the current population age $a$ as well as its age $r$ when first detected enabling quarantine efforts to begin. The area of a quarantined population is indicated as $A^q(a,r)$.

We model population dynamics using an age-class model, in which we define a set of population age classes $a \in \{1,2,\ldots,a_{max}\}$, and $x^a(t)$ is the expected probability of an undetected population of age $a$ present at the focal site at time $t$. For a population of age $a = 1$ this equals the probability of establishment $e$ in each time period. Any established populations transition to age class $a$+1 in the following time period if undetected. Thus, an age class model for undetected populations can be specified as:

$$\begin{aligned} & x^1(t+1) = e(t) \\ & x^a(t+1) = x^{a-1}(t)(1-p_{detect}(a-1,I)) \qquad \text{for } a = 2,\ldots,a_{max} \end{aligned} \tag{1}$$

where $p_{detect}(a,I)$ is the probability of detecting a population of age $a$ given an investment $I$ in pest detection surveys. Following detection, a population will transition to an uncontrolled, detected population, to a quarantined population, or be eradicated, dependent on the optimal control policy.

Thus an age class model for detected, uncontrolled populations $z^a(t)$ can be specified as

$$z^1(t+1)=0$$

$$z^a(t+1)=x^{a-1}(t)(p_{detect}(a-1,I))(d^{*n}(a-1))+z^{a-1}(t) \qquad \text{for } a=2,...,a_{max} \tag{2}$$

where $d^{*n}(a)=1$ if it is not cost-effective to control (i.e. eradicate or quarantine) a population of age $a$, and equals 0 otherwise.

The age class model for populations subject to quarantine efforts must also be specified with respect to the age of detection ($r$), as the age of detection affects the size of a population at a given age. For all $a,r=1,...,a_{max}$ the age class model for quarantined populations $w^{a,r}(t)$ can be specified as:

$$\begin{aligned} w^{a,r}(t+1) &= 0 && \forall r \geq a \\ w^{a,r}(t+1) &= x^{a-1}(t)(p_{detect}(a-1,I))(d^{*q}(a-1)) && \forall\, r=a-1 \\ w^{a,r}(t+1) &= w^{a-1,r}(t) && \forall\, r<a-1 \end{aligned} \tag{3}$$

where $d^{*q}(a)=1$ indicates that a quarantine policy to slow invasion spread is optimal for a population detected at age $a$.

The probability $p_{detect}(a,I)$ that a population is detected in a given time period increases with survey investment $I$ at the site, the size of the population $A(a)$ (measured as areal extent), trap sensitivity $y_{trap}$, and the effectiveness of detection by the public $y_{public}$. Analogous to Epanchin-Niell et al. (2012, 2014), we assume that traps have a baseline sensitivity $y_{trap}$, measured as the likelihood that a trap will detect the population if the trap is placed within the invasion's areal extent. We also assume that trap placement is random with respect to the location of each established population, through one or both being random in space. The probability that a given population is detected by a trap (i.e., at least one deployed trap successfully detects the population) can therefore be estimated as a binomial distribution, where the number of trials equals the number of deployed traps (investment level $I$ divided by trap cost $C_t$), and the probability of success for each trial equals the trap sensitivity ($y_{trap}$) times the probability of the trap intersecting the population (the area of the population divided by the area of the focal site $A(a)/M$, or 1 if the population is larger than the site). We assume that detection by the public follows a similar probabilistic process as detection by traps, where the probability of detection increases with the size of the population and the sensitivity of public detection, but public detection can occur across the site, as opposed to being limited to specific trap locations.[2] We assume $y_{public}$ is the probability that a population of a unit size would be detected by the public in a single time period. Therefore, the probability $p_{detect}(a,I)$ that a population present at a site is detected by a trap or the public in a single time period equals

[2] In past work (e.g., Epanchin-Niell et al. 2012, 2014), we addressed the role of detection by the public by assuming that pest populations would be detected with certainty after a fixed number of years. However, there is large uncertainty and variability in the likelihood of detection by the public, which depends on the size of the population, the characteristics of the pest, and even the characteristics of the site and the people living and working in the area.

$1 – (1 - y_{trap}A(a)/M)^{(I/Ct)}(1 – y_{public})^{A(a)}$ for populations whose area is less than or equal to the area $A$ of the focal region, and equals $1 – (1 - y_{trap})^{(I/Ct)}(1 – y_{public})^{M}$ for populations larger than the focal, surveyed region.

COSTS, DAMAGES, AND IDENTIFICATION OF OPTIMAL SURVEILLANCE.

We assume that the total costs of surveillance at a site depend linearly on the number of traps deployed at the site, with the cost per trap deployed equalling $c_t$ and total annual survey investment at the site indicated by $I$. $C_d(A(a))$ is the total damage costs (e.g., damages to crops or forests) in a single time period from a population of area $A$. When a population is detected, eradication can be attempted at a cost that increases with the population's size, $C_e(A(a))$. Alternatively, quarantine efforts may be applied that slow the rate of invasion spread and whose costs depend on the size of the invasion, $C_q(A^q(a,r))$. Thus, the present value of expected costs from an uncontrolled population detected in the current time period at age $r$ equals

$$\sum_{a=r}^{a_{max}} \frac{C_d(A(a))}{(1+\delta)^{a-r}} \qquad (4)$$

with discount rate $\delta$. The present value of total costs from detection onward of a population subject to quarantine equals:

$$\sum_{a=r}^{a_{max}} \frac{C_d\left(A^q(a,r)\right)+C_q(A^q(a,r))}{(1+\delta)^{a-r}} \qquad (5)$$

The total present value costs for a population detected and eradicated at age $r$ equals $C_e(A(a))$.

The choice of management (no management, quarantine, or eradication) is based on which strategy has the lowest present value costs (long term discounted costs). In general, the optimal strategy shifts from eradication, to quarantine, to no control with increasing population size at time of detection.

Based on this model, the net present value of expected costs and damages resulting from invasion establishment, detection, and management can be determined dependent on the level of investment in pest detection surveys. We consider application of a constant surveillance strategy (i.e., a constant investment level) 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 and those that were present on the landscape (but not yet detected) at the start of the program.

We assume that, prior to the start of the surveillance program, populations were arriving at a background rate $e(t)$ and probability of detection $p_{detect}(a,0)$. Thus, the expected number of undetected populations present on the landscape at the start of the program ($t$=1) can be calculated by recursively solving the following equations beginning at $t$=-$T_{past}$ (where $T_{past}$ is the oldest population considered for detection at the start of the surveillance program) and iterating until reaching $t$=1:

$$x^1(t) = e(t)$$
$$x^a(t) = x^{a-1}(t-1)(1-p_{detect}(a-1,0)) \qquad \text{for } a = 2,...,a_{max} \tag{6}$$

If surveillance was already being applied prior to the start of the survey program under consideration, then initial conditions are determined using the previously applied investment level, rather than $I$=0 as indicated above.

Recognizing that $x^a(t)$, $z^a(t)$, and $w^{a,r}(t)$ are all functions of $I$, we can rewrite them as $x^a(t,I)$, $z^a(t,I)$, and $w^{a,r}(t,I)$. We can then calculate the net present value of total expected costs and damages (with discount rate δ) of investing $I$ in pest detection surveys for $T$ consecutive time periods (excluding surveillance costs) as:

$$TC^{\mathrm{D}}(I) = \sum_{t=1}^{T}\left(\begin{array}{l}\sum_{a=1}^{a_{max}} x^a(t,I)C_d(A(a)) + \sum_{a=1}^{a_{max}} z^a(t,I)C_d(A(a)) \\ + \sum_{a=2}^{a_{max}}\sum_{r=1}^{a-1} w^{a,r}(t,I)\left[C_d(A^q(a,r)) + C_q(A^q(a,r))\right] \\ + \sum_{a=1}^{a_{max}} x^a(t,I)p_{detect}(a,I)d^{*e}(a)C_e(A(a))\end{array}\right)(1+\delta)^{1-t}$$
$$+ \sum_{t=\mathrm{T}+1}^{T+a_{\max}}\left(\begin{array}{l}\sum_{a=t-T+1}^{a_{max}} x^a(t,0)C_d(A(a)) + \sum_{a=t-T+1}^{a_{max}} z^a(t,0)C_d(A(a)) \\ + \sum_{a=3}^{a_{max}}\sum_{r=1}^{a-2} w^{a,r}(t,0)\left[C_d(A^q(a,r)) + C_q(A^q(a,r))\right] \\ + \sum_{a=t-T+1}^{a_{max}} x^a(t,0)p_{detect}(a,0)d^{*e}(a)C_e(A(a))\end{array}\right)(1+\delta)^{1-t} \tag{7}$$

The terms in each of the large summations (over time) are, in order, damages from undetected populations, damages from uncontrolled, detected populations, damage and control costs from quarantined populations; and eradication costs. The first large summation addresses costs incurred over the duration of the survey program, while the second large summation accounts for the costs and damages from populations that were present at the end of the survey program and that accrue costs until they reach age $a_{max}$. We assume that populations detected after the survey program ends are nonetheless managed to minimize their long term costs. The costs of surveys over this time horizon are calculated as:

$$TC^{\mathrm{Su}}(I) = \sum_{t=1}^{T} I(1+\delta)^{1-t} \tag{8}$$

If decisions were focused on determining how much to invest in surveys for a single pest type at a single site, one would solve for the investment level $I$ that minimizes the total expected costs of surveillance, eradication, and invasion damages: Equation 7 plus 8.

One also can calculate the expected net benefits of any given investment level as the reduction in expected costs and damages with surveillance investment $I$ relative to without:

$$NB(I) = TC^D(I = 0) - TC^D(I) - TC^{Su}(I) \tag{9}$$

**Table 1.** Model functional forms used in CESAT.

| Model function | Notation | Units | Baseline assumptions |
|---|---|---|---|
| Radial population growth without control | $g(a)$ | km/yr* | $g(a) = \frac{ga^m}{h^m + a^m}$ |
| Radial population growth under quarantine | $g^q(a)$ | km/yr* | $g^q(a) = \left(\frac{ga^m}{h^m + a^m}\right)q$ |
| Population size (area) without control | $A(a)$ | km² | $A(a) = \pi\left(\sum_{i=1}^{a} g(a)\right)^2$ |
| Population size (area) if quarantine begins at age *t* | $A^q(a,t)$ | km² | $A^q(a,t) = \pi\left(\sum_{i=1}^{t-1} g(i) + \sum_{i=t}^{a} g^q(a)\right)^2$ |
| Population radius if quarantine begins at age *t* | $r(a,t)$ | km | $r(a,t) = \sum_{i=1}^{t-1} g(i) + \sum_{i=t}^{a} g^q(a)$ |
| Eradication costs | $C_e(A(a))$ | $/population | $C_e(A(a)=c_e\, \pi\, (r(a,t)+b_e))^2$ |
| Damage costs pre-detection | $C_d(A(a))$ | $/ population/yr | $C_d(A(a)=c_d\, A(a)$<br>or<br>$C_d(A(a)=c_d\, (A(a)- A(a-1))$ |
| Damage costs post-detection | $C_d(A(a))$ | $/ population/yr | $C_d(A(a)=c_d\, A(a)*d$<br>Or<br>$C_d(A(a)=c_d\, (A(a)- A(a-1))*d$ |
| Slowing costs | $C_q(d,A)$ | $/ population/yr | $C_q(A^q(a,t))= c_q 2\pi\, (r(a,t)+b_q)$<br>*Or*<br>$C_q(A^q(a,t))= c_q \pi\, (r(a,t)+b_q)^2$ |

### CONSIDERATION OF MULTIPLE PESTS AND SITES.

We now expand this approach to consider multiple pests and sites by summing the expected costs and damages (Equation 7) across potential invaders $p \epsilon P$ and sites $s \epsilon S$. We also allow that multiple pests can be targeted by a single trap type *tr*, such that the benefits from that trap depend on the expected reduction in costs across all targeted species.

The overall objective of the resource allocation decision is to identify the optimal investment $I_{tr,s}$ in each trap *tr* at site *s* to minimize costs and damages across all pests and sites, including surveillance costs, or to maximize the net benefits. All parameters and survey investments ($I$) can be indexed by species or trap type and site. $TC^{Su}{}_{p,s}(I_{tr,s})$ is the present value of total expected costs for pest $p$ and site $s$ given investment $I_{tr,s}$, following equation 7 (excluding the costs of surveys). Thus, across all sites, trap types, and species, the total costs is:

$$TC = \sum_{s \in S} \sum_{tr \in Tr} \left( TC^{Su}(I_{tr,s}) + \sum_{p \in P_{tr}} TC^{D}{}_{p,s}(I_{tr,s}) \right) \quad (10)$$

If a region-wide budget constrains surveillance efforts, the following constraint applies:

$$\sum_{s \in S} \sum_{tr \in Tr} I_{tr,s} \leq B \quad (11)$$

where $B$ is the total annual surveillance budget. Optimizing this problem (Equations 10 and 11) finds the level of investment in traps at each site for each pest type that minimizes the total expected costs from surveillance, eradication, and invasion damages, given any budget constraint.

The expected net present benefits of implementing the optimal surveillance program or any other potential surveillance program (as defined by investment levels $I_{t,s}$) relative to doing nothing, is calculated as the difference in total costs under the specified program and when all $I_{t,s}=0$ (Equation 9).

To solve for the optimal investments in traps in the absence of a budget constraint, one can simply identify the surveillance investment level that maximizes net benefits for each site and trap individually, because the optimal trapping for each trap by site combination is independent of optimal trapping levels at other sites or for other traps. However, when resources are constrained, the survey investments are dependent across sites and lures, and the optimal investment levels equalize the marginal benefits of additional investments across sites and traps, such that reallocation of resources from one site or trap to another cannot improve outcomes. To solve for this outcome, we 1) solve for the marginal benefits of investments for each site by trap combination for a range of investment levels, and 2) use a greedy algorithm to allocate investments to sites by trap combinations in order of decreasing marginal benefits of investment, until resources are fully allocated.

If we define *i* as the marginal cost of survey investment (i.e. a "scoop" of investment in surveys), then the marginal benefit of a scoop of additional investment in trap *tr* at site *s* is:

$$MB = TC^{D}{}_{tr,s}\left(I_{tr,s}\right) - TC^{D}{}_{tr,s}\left(I_{tr,s} + i\right) \quad (11)$$

Similarly, in the absence of a budget constraint, a manager would invest in traps at a site until the marginal benefits of additional investment just equals the cost of the additional investment. This is the investment level that maximizes the total net benefits (benefits of the investment minus the costs of investment).

### Incorporation of parameter uncertainty

As noted above, we define all model parameters as distributions, rather than as point estimates, to account for uncertainty in underlying parameters. We therefore use Monte Carlo draws of each parameter to create sets of characteristics that represent the distribution of uncertainty in underlying characteristics for each target. For each Monte Carlo representation, we calculate the expected total and marginal benefits of survey investments, accounting for optimal post-detection management choices. Thus, for each target (pest group by site), we calculate a distribution of potential expected benefits from survey investments. We use several metrics to summarize these distributions and to serve as inputs into the optimal resource allocation algorithm. Specifically, we consider resource allocation based on the mean, median, and 5$^{th}$ and 95$^{th}$ percentiles of the distribution of marginal benefits for each investment level. A focus on the 95$^{th}$ percentile essentially represents a risk averse strategy as it focuses on the Monte Carlo draws for which survey investments can provide the greatest reductions in costs and damages.

### Parameter Specification:

CESAT requires estimation of numerous parameters for each focal pest, trap, and site (Table 2; Appendix A). Parameters can be specified by drawing on a variety of data sources, including, among others, published literature, reports, historic data, and expert judgement, as described ion Appendix A (e.g. Epanchin-Niell et al 2012, 2014, 2017).

**Table 2.** Model Parameters. Description of model parameters, symbols used in model description, example units, and the parameter abbreviation used in CESAT's R code and data input files.

| Model parameter | Symbol | Potential Units | Parameter abbreviation in CESAT | Description |
|---|---|---|---|---|
| Investment level | *I* | \$/(site by pest) | Model Output | The \$s invested in each trap at each site is determined by CESAT to minimize total costs and damages across the landscape |

| | | | | |
|---|---|---|---|---|
| Site area | $M$ | $km^2$ | Specify in: Site_areas.csv | The area of each site – where sites are identified as contiguous areas of relatively homogenous risk with respect to establishment and damages. |
| Introduction (establishment) rate | $e$ | populations/ $yr^*$ | IR | The probability that a population arrives and establishes at a site in single time period |
| Asymptotic Population growth rate | g | $km/yr^*$ | SR | The maximum radial rate of spread that a pest is likely to achieve (i.e. if population modeled as a growing circle, how quickly could the radius grow) |
| Half time to reach asymptotic growth rate | $h$ | $yr^*$ | h | The number of time periods following introduction before a population's growth rate reaches half of its maximal radial rate. |
| Growth function shape parameter | $m$ | --- | m | Growth function shape parameter that determines how rapidly the growth rate increases following establishment |
| Trap sensitivity | $Y_{trap}$ | ---- | SuE | The probability that a trap would detect a population if placed in an infested area (i.e. in an area where the species is present) |
| Marginal survey cost | $c_t$ | $/trap | SuC | The annual cost of a trap, its placement and servicing, and associated pest identification |
| Public detection efficacy | $Y_{public}$ | ---- | PDpub | The probability that a pest that has spread across a unit area (e.g. $km^2$) would be detected by the public or other means in a single time period (e.g. year) |
| Marginal damage costs | $c_d$ | $\$/km^2$ | DC | Damages per unit invaded area arising from a pest (e.g. lost revenues from crop damage, lost harvest or ecological values from tree damage, etc). Damages should represent average damages per unit area invaded – averaged both within focal site as well as across other nearby sites in the landscape. |
| AreaNew | | 0 or 1 | AreaN | Indicator variable that is set to 0 if damages accrue annually across entire invaded area or to 1 if damages only accrue in newly invaded area. |
| Post-detection damage change | $d$ | proportion | DR | The proportional increase or decrease in costs incurred following detection (reduction in damages, net of management costs). |
| Marginal eradication costs | $c_e$ | $\$/km^2$ | EC | The expected cost per unit area required to respond to and successfully eradicate a population, |

| | | | | |
|---|---|---|---|---|
| | | | | including the costs of delimitation, quarantine, monitoring, and control. |
| Eradication buffer width | $b_e$ | km | EBuff | The additional width around the population to which eradication effort is applied and eradication costs are incurred |
| Quarantine efficacy | $q$ | ---- | SlE | The proportional reduction in a population's radial rate of spread likely to be achieved by implementing a quarantine or slow-the-spread program |
| Marginal quarantine cost | $c_q$ | \$/km or \$/km$^2$ | SlC | The cost per year associated with slowing or containing the spread of the pest, measured either as a function of quarantined area or quarantined circumference |
| Quarantine buffer width | $b_q$ | km | SlBuff | The additional width around the population to which quarantine effort is applied and costs are incurred |
| SlowAreaCost | | | SAC | Indicator variable that is set to 0 if quarantine costs depend on quarantined area circumference, and set to 1 if quarantine costs depend on the total area of the quarantined location. |
| Length of planned survey program | $Y_t$ | yr | Specify in R program: yrs_trapping | This number should be set to at least 20 or 30 if considering a long term trapping program. Set for shorter if a short-term program is being planned. |
| Prior survey investment | $I_p$ | \$/yr | PTI | The amount of resources invested in surveys in past years (which is be used to determine prior trapping levels and the likelihood of undetected populations being present at the start of the current trapping program). |
| Years of prior establishment | $Y_e$ | yr | Specify in R program: yrs_prior | The number of years ago that a population conceivably could have established and not yet been detected. (use longest estimate across pests and sites, since this is a single value across species and sites) |
| Years of prior trapping | $Y_p$ | yr | YPT | The number of years that prior surveys have been ongoing. |
| Maximum age of invasion considered | $A_{max}$ | yr | Specify in R program: max_age | This represents the time horizon over which damages from new establishments are considered. As a default 50 or 75 years can be used. |
| Discount factor | $\delta + 1$ | proportion | Specify in R program: discount_factor | A discount factor of 1.02 places greater value on future costs, while a value of 1.05 discounts future values more. |

| Model Run Parameters | | | | |
|---|---|---|---|---|
| Number of Monte Carlo draws | obs | --- | Specify in R program: obs | Number of draws from uncertainty distributions for each parameter. Larger numbers better encompass the full range of uncertainty, but processing time increases. 100 observations is reasonable baseline. |
| Size of "investment scoops" | inv_scoops | $ | Specify in R program: inv_scoops | The size of the investment allocated sequentially across traps and sites in the allocation algorithm. This may be selected as the smallest amount likely to be allocated to a trapping programs at a site in a single time period. |
| Number of "investment scoops" | Num_inv_levels | -- | Specify in R program: Num_inv_levels | The maximum number of "investment scoops" considered for allocation to any single trap at a site. This number times the size of the investment scoop is the maximum allocation considered for any given trap at a site. |

## ILLUSTRATIVE APPLICATION

To illustrate the model, we applied CESAT to allocating resources across three pest groups that may establish across 4 types of sites (Tables 3, 4 and 5). This example is not parameterized to particular species, but intended to illustrate application of CESAT. It considers three species groups that are similar in their trap sensitivity and quarantine costs and effectiveness, but vary in their spread rates and costs of eradication (Tables 3, 4). The magnitude of damages, rates of introduction, and probability of detection by the public vary across sites (but are similar across pest groups at a site) (Tables 3, 5).

**Table 3.** Model parameters used in the generalized analysis, and in optimization of surveillance.

| Model parameter | Symbol | Potential Units | Parameter abbreviation in CESAT | Case Study Values | |
|---|---|---|---|---|---|
| | | | | Low | High |
| Investment level | *I* | $/(site by pest) | Model Output | Optimized | |
| Site area | *M* | $km^2$ | Specify in: Site_areas.csv | 100 | |
| Introduction (establishment) rate | *e* | populations/ $yr^*$ | IR | 0.0001-0.0005 | 0.001-0.005 |

| | | | | | |
|---|---|---|---|---|---|
| Asymptotic Population growth rate | g | km/yr* | SR | 1-3 | 7-10 |
| Half time to reach asymptotic growth rate | *h* | yr* | h | 8-12 | |
| Growth function shape parameter | *m* | --- | m | 4-6 | |
| Trap sensitivity | $Y_{trap}$ | ---- | SuE | 0.5-0.8 | |
| Marginal survey cost | $c_t$ | \$/trap | SuC | 30-75 | |
| Public detection efficacy | $Y_{public}$ | ---- | PDpub | 0.05 - 0.1 | 0.4 - 0.5 |
| Marginal damage costs | $c_d$ | \$/km² | DC | 5-150 | 3,750-5,000 |
| AreaNew | | 0 or 1 | AreaN | 0 | |
| Post-detection damage change | *d* | proportion | DR | 0 | |
| Marginal eradication costs | $c_e$ | \$/km² | EC | 10,000-15,000 | 80,000-100,000 |
| Eradication buffer width | $b_e$ | km | EBuff | 0 | |
| Quarantine efficacy | *q* | ---- | SIE | 0.4-0.6 | |
| Marginal quarantine cost | $c_q$ | \$/km or \$/km² | SIC | 6,000-14,000 \$/km | |
| Quarantine buffer width | $b_q$ | km | SIBuff | 0 | |
| SlowAreaCost | | | SAC | 0 | |
| Length of planned survey program | $Y_t$ | yr | Specify in R program: yrs_trapping | 15 | |
| Prior survey investment | $I_p$ | \$/yr | PTI | 0 | |

| | | | | |
|---|---|---|---|---|
| Years of prior establishment | $Y_e$ | yr | Specify in R program: yrs_prior | 5 |
| Years of prior trapping | $Y_p$ | yr | YPT | 0 |
| Maximum age of invasion considered | $A_{max}$ | yr | Specify in R program: max_age | 20 |
| Discount factor | $\delta + 1$ | proportion | Specify in R program: discount_factor | 1.05 |
| **Model Run Parameter** | | | | |
| Number of Monte Carlo draws | obs | --- | Specify in R program: obs | 50 |
| Size of "investment scoops" | inv_scoops | $ | Specify in R program: inv_scoops | 200 |
| Number of "investment scoops" | Num_inv_levels | -- | Specify in R program: Num_inv_levels | 70 |

**Table 4a.** Characteristics of 3 focal pest groups. (See Table 3 for parameter value ranges)

| Parameter | Pest groups | | |
|---|---|---|---|
| | **Pest 1a** | **Pest 1b** | **Pest 2** |
| Trap sensitivity & Cost | Medium & Medium | Medium & Medium | Medium & Medium |
| Quarantine efficacy & Cost | Medium & Medium | Medium & Medium | Medium & Medium |
| Growth rate | High | Low | Low |
| Eradication cost | High | High | Low |

**Table 4b.** Characteristics of 4 focal sites. (See Table 3 for parameter value ranges)

| Parameter | Site | | | |
|---|---|---|---|---|
| | **Site 1** | **Site 2** | **Site 3** | **Site 4** |
| Damages | Low | High | High | High |
| Probability of detection by public | High | High | Low | High |
| Introduction Rate | Low | Low | High | High |

We apply CESAT to determine the most cost-effective allocation of survey resources across the four focal sites and three pest groups, accounting for uncertainty. Because of the uncertainty in the underlying parameters, the expected benefits of surveys, as well as the optimal level of investment in surveys across sites and pests, are also uncertain.

Figure 10 shows the optimal proportional allocation of resources across species and sites for a range of budget levels (x-axis). The figure shows that pest groups 1a and 1b at site 3 demand the highest investment in surveys, followed by pest 2 at site 3. Site 3 arises as a site needing more resources to detect pests because of the low likelihood of detection by the public. Pest 1a has a high spread rate and costs of eradication, and pest 1b has a high cost of eradication. These findings fit with the intuition provided by previous work (Epanchin-Niell 2017).

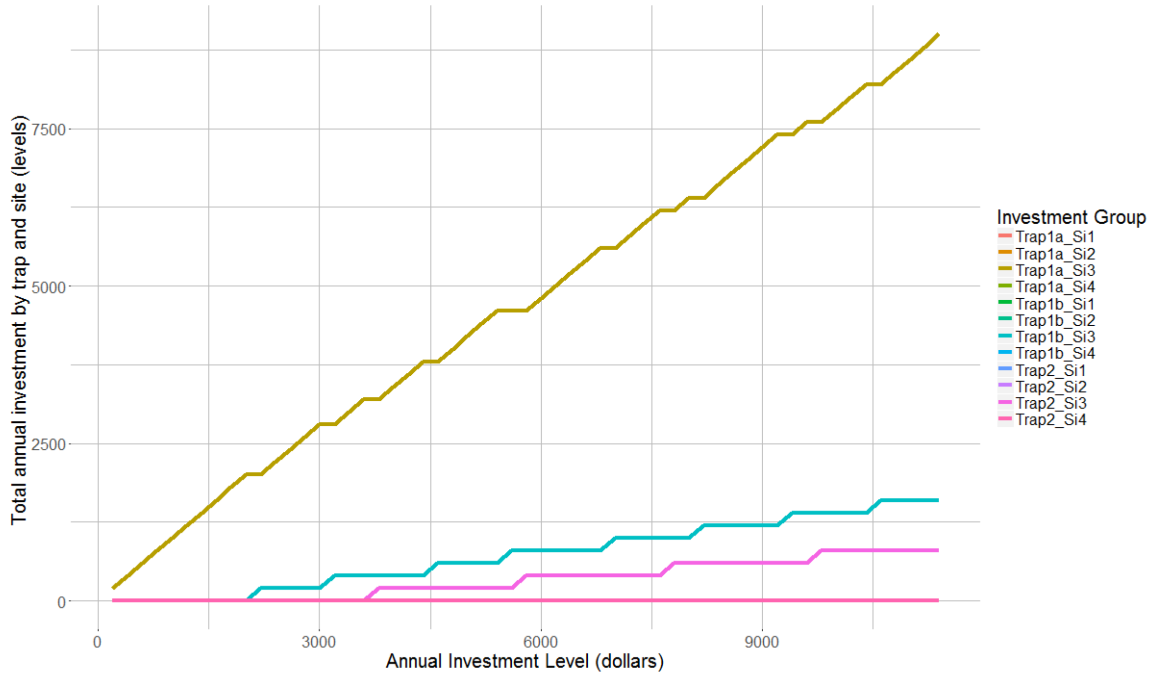


**Figure 10.** Investment allocation across species and sites. For any given annual budget level along the x-axis, the colored lines show the optimal amount of that budget that should be allocated to each trap and site to maximize the net benefits of the surveillance investment. The three pest by site combinations that optimally receive the highest proportions of the survey budget are, in decreasing order, pest 1a, 1b, and 2 at site 3.

Figure 11 shows the net benefits of investment across a range of potential surveillance budgets. The upper bound of the distribution shows the net benefits based on realizations from the top 95$^{th}$ percentile of Monte Carlo runs. The line indicates the mean net benefits across Monte Carlo draws, and the lowest edge of the distribution represents the lowest 5$^{th}$ percentile of net benefits across Monte Carlo runs. Figure 12 additionally shows the outcomes of prioritization based on a scenario in which resources are distributed equally across targets. In this examples, equal allocation provides substantially lower net benefits than the optimal allocation.

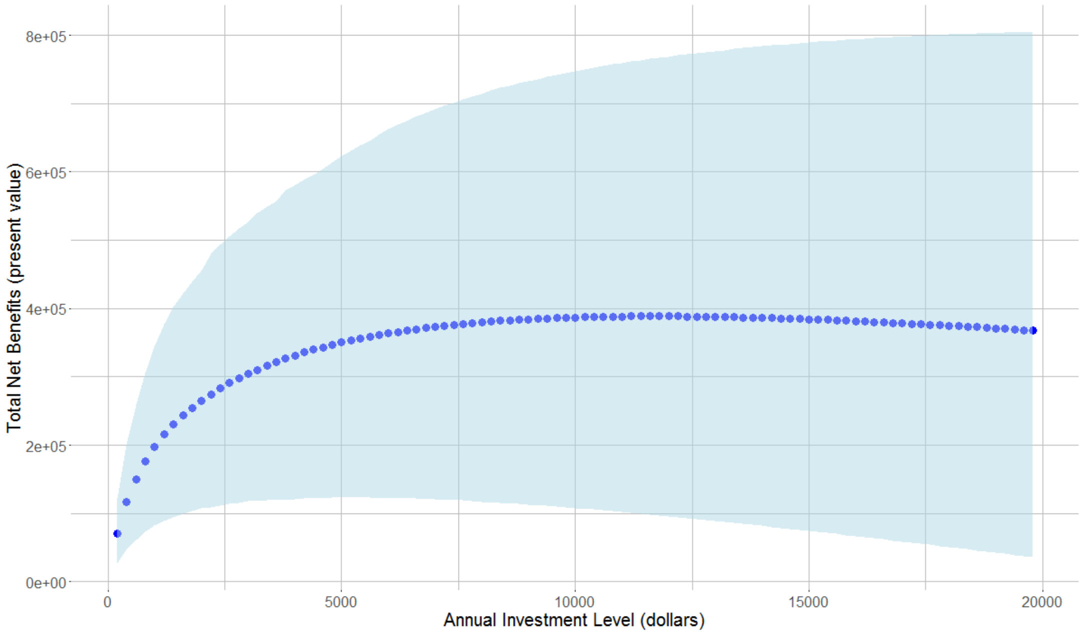


**Figure 11.** Expected net present value of benefits from long term trapping program for a range of potential annual investment budgets (x-axis) under optimal resource allocation. The shaded region shows the range of net benefits across Monte Carlo draws (95%, mean, and 5% outcomes).

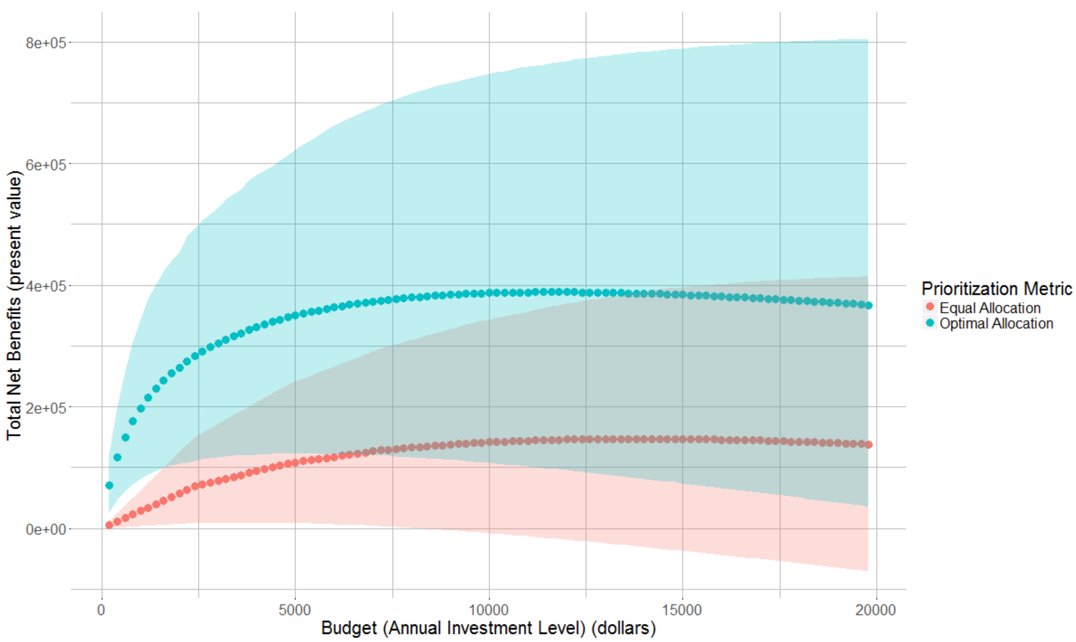


**Figure 12.** Expected net present value of benefits from long term trapping program for a range of potential annual investment budgets (x-axis). The shaded region shows the range of net benefits across Monte Carlo draws (95%, mean, and 5% outcomes). The blue line and shading shows

outcomes under optimal (cost-effective) resource allocation, while the red line shows net benefits if resources are allocated equally across traps and sites.

## CONCLUSIONS

CESAT is a resource allocation decision support tool that can be used to assist with determining how surveillance resources can be allocated across early detection survey programs or across sites to get the biggest bang for the buck from those investments. This flexible tool can be applied to a wide range of pests and traps, and across small to large spatial extents. The model also can be applied to a single pest or across multiple trapping programs.

CESAT can address a wide range of resource allocation questions, such as:

1) How should survey resources for pest A be allocated across sites, and what level budget provides the greatest net returns?
2) What would be the net economic costs (or benefits) of changing the annual survey budget for pest A from X to Y?
3) How much resources should be allocated to survey for pest B at site A?
4) How much resources should be allocated to pest B versus pest C?
5) Should we continue trapping for Pest A, and if so, at what level?
6) What are the expected benefits from implementing a trapping program G?
7) What are the expected benefits of allocating survey resources according to Plan C?

In addition, CESAT can be used to explore the importance of species, site, and economic factors on optimal resource allocation decisions. For example, what would be the benefits of increasing the efficacy of traps for pest A by 25%? What benefits would arise from enhancing private survey efforts? What gains might be realized by from reducing the costs of eradication for Pest C? How much would it be worth to reduce the introduction rate of Pest Z by X%.

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## **APPENDIX A.** CESAT PARAMETER SPECIFICATION

Each parameter is defined as a range, represented by an upper and lower bound estimate. Solving the model for a large number of random draws from each parameter range (assuming a uniform distribution), allows uncertainty in parameter estimates to be accommodated and explored. The time unit used in CESAT is typically one year, and parameters are specified with respect to the chosen time unit (e.g. probability of establishment per year, damages per year, spread per year, investments per year, etc). All parameters should have consistent units (e.g. km vs. miles). We describe parameters with respect to specific pests or traps. However, the user can instead specify generalized “pest types” that group across several species (see e.g. Epanchin-Niell et al 2014.)

*Sites:*

Sites are the areal unit of analysis. Cost-effective resource allocation is determined at the site level, and a number of model parameters are or can be site specific. Delineation of sites for the model may be selected based on existing analysis, such as existing incursion risk maps or host distribution maps. Alternatively, sites may be delineated by a grid overlaid on the focal landscape (e.g. a 10 km x 10 km square grid). Ideally sites should be delineated so that they are relatively homogenous with respect to factors such as establishment probability, etc.

*Site size:*

Site size refers to the total invadable area of a site. In many cases this is simply the total site size. In other cases, some area can be excluded, such as open water. If the analysis is focused on a single pest, the area can be limited specifically to areas where the pest can occur (e.g. exclude forested area for fruit fly focused analyses).

*Introduction rate:*

Introduction rate is the probability that a new incursion of the focal pest will arrive and establish at a site in a single year (or time period). There are several ways to estimate this probability. For species that establish fairly often, establishment probability can be empirically estimated from historic establishment data. Alternatively, one could estimate an annual establishment probability across the entire landscape and then allocate across sites based on relative risk maps for the species, or based on information about arrival (e.g. risk pathways, human population density) and survival likelihoods (e.g. host and climate). See, for example, Epanchin-Niell et al 2012 and Epanchin-Niell 2016.

*Pest population spread:*

We model pest spread using a sigmoidal radial spread rate function, which results in slower population growth initially, which increases to reach a linear radial rate of spread. The area of a pest population increases at an increasing rate over time. The model represents populations as an expanding circular area, which can represent spread of small populations well. However, populations also spread through long distance dispersal, creating satellite populations. CESAT abstracts away from this process, but the areal growth of such a spread process could be represented in CESAT's spread model. For example, models such as EXPAT could be useful for estimating spread rates over time. Similarly, information from the literature can be used to parameterize pest spread. Observed spread rates of the same or similar species during past incursions also could be used.

Equation 12 represent the estimated amount of radial population growth in a single year, where *g* is the asymptotic rate of radial growth, *m* is a shape parameter, *h* is the number of years to reach a growth rate that is half of the asymptotic rate of growth, and *a* is the age of the population.

$$g(a) = \frac{ga^m}{h^m + a^m} \qquad (12)$$

Thus, the expected area of a pest population at age *a* can be estimated as:

$$A(a) = \pi\left(\sum_{i=1}^{a} \frac{gi^m}{h^m + i^m}\right)^2 \qquad (13)$$

The asymptotic population growth rate (*g*) is the maximum radial rate of spread that a pest is likely to achieve (i.e. if population modeled as a growing circle, how quickly would the radius grow).

*Trap sensitivity:*

Traps sensitivity is the probability that a trap will detect a population if placed in an infested area (i.e. at a location where the species is present), and is specified between 0 and 1. As examples, pheromone traps, such as those used for detecting gypsy moth, can be highly effective at detecting target species when present, and might be assigned an efficacy of 0.95. In contrast, more generalist lures may be much less effective and have a probability of 0.3 or 0.5.

*Marginal survey cost:*

Marginal survey cost is the estimated annual cost of placing and servicing a single trap, including the associated processing and pest identification costs. If traps are moved periodically during the year (or time step for the model), then the total annual cost of placing and maintaining a trap should be divided by the number of locations in which that trap might be placed during the year, and each placement would be treated as a separate trap in the model. On the other hand, for traps that are serviced multiple times during the chosen time unit, but not moved across locations, the marginal survey costs are the total costs across the year (or time step) for the trap.

*Public detection efficacy:*

Public detection efficacy is the probability that a pest population that occupies a unit area of the landscape (e.g. $km^2$) would be detected by the public in a single time period (e.g. year) at the focal site. This includes the probability of detection by any means other than the investments under consideration in the model. For example, some agricultural pests show highly visible damage that is likely to be detected by farmers and would have a high probability of detection, whereas some species are cryptic and some sites are very remote, likely resulting in low annual probabilities of public detection. If industry groups are likely to conduct surveillance using their own resources, this also could be accounted for in the probability of public detection. This probability is less than one. If one can estimate the probability $p$ of detection by the public for a different sized area $a$, one can solve for the parameter as $1-(1-p)^(1/a)$.

*Marginal damage costs:*

Marginal damage costs are the estimated annual damages per unit invaded area expected to arise from pest establishment. This can include, for example, lost revenues from crop damage or yield loss, increased pest management costs, or losses in ecological value or ecosystem service values, such as recreational losses. Damages should be quantified to represent average per area damages across the focal site as well as nearby sites to which the pest could spread within several decades. Greater weight can be placed on more local damages, as they would accrue earlier. If damages are expected to be delayed relative to the time that an area becomes invaded, damages can be discounted accordingly when estimating this parameter. The marginal damage costs specified here should not include costs that only arise upon detection, such as trade costs.

Total damages can be specified to accrue across the entire area occupied by a pest or only within the portion of the landscape that is newly invaded in each year. Set *AreaN* equal to 1 if damages are limited to the newly invaded area or to 0 if damages accrue across the entire invaded area in each year.

*Post-detection damage change:*

Pest damage costs may increase or decrease following detection. The costs may decrease if detection allows for improved pest management strategies (e.g. through pesticide application, altering production practices, etc.). This reduction in costs is represented as a proportional reduction in per unit area damages following detection ($-1<d<0$) (accounting for the costs and benefits of post-detection responses). For example, $d=-0.05$ corresponds to a 5 percent reduction in annual per unit area damages post-detection. Alternatively, damage costs could increase following detection if, for examples, control or inspection or monitoring measures are required to enable continued trade of goods from the infested area. This increase is represented as the proportional increase in annual per unit area damages ($d>0$) in the absence of eradication. For example, $d$=0 equates to no change in per unit area damages following detection, and $d$=1 equates to per area damages increasing 100%, such that they are 200% of the pre-detection value.

*Eradication costs:*

*Marginal eradication costs:* Marginal eradication costs are the cost per unit area required to respond to and eradicate a newly detected population. Costs include delimitation, quarantine, monitoring, and control costs. Costs of eradication are assumed to be incurred at a single time step in the CESAT, so if costs are expected to be incurred over multiple years of an eradication project, the total present value of those costs, per unit area of an invasion, should be used as the cost estimate. If quarantine or trade costs are incurred during that period, those costs also should be included. Costs should be estimated as the total costs required to have a very high probability of eradication success. All costs associated with the invasion are assumed to cease following eradication, so all post-eradication costs should be included in this parameter.

*Eradication buffer width*: Eradication efforts may be applied in an area larger than the focal population size. If this is the case, an eradication buffer width can be included in the model, which adds an additional radial distance to the population "edge" when calculating the area in which eradication costs are incurred. This is set to 0 if no buffer is needed.

*Quarantine costs and efficacy:*

Here we are defining quarantine as the efforts aimed specifically at slowing or containing the spread of a detected invasion when eradication is not attempted. Examples include the European gypsy moth slow-the-spread program in the eastern United States and efforts to slow the rate of spread of sudden oak death in the western United States. The costs of these activities might include the extra costs of treatment of goods moving out of the infested area or culling or treatment along the population front, etc, that slow the spread of the pest. These are costs that are above and beyond the costs of damages that result from direct damages or control costs to facilitate trade.

*Quarantine efficacy:* The efficacy of the quarantine is measured as the proportional reduction in radial spread likely to be achieved through quarantine measures. Thus, a parameter of 0.3 reduces the radial rate of spread by 30% relative to without quarantine. A parameter of 1 corresponds to perfect containment.

*Marginal quarantine cost*: This is the annual cost associated with slowing or containing the spread of the pest per unit area (e.g., $/km$^2$) of the quarantined area or per unit length (e.g. $/km) of the quarantined area's circumference. The choice of specification will likely depend on the types of relevant costs for a given species. In CESAT, populations may be eradicated, quarantined, or allowed to spread at an uncontrolled rate. Thus, any costs of quarantine that would be incurred under eradication efforts should be included in the eradication costs, separate from the costs considered under this control scenario. Also, only costs that are additional to the baseline damages following pest detection should be included in this cost estimate (i.e. the additional costs necessary to slow the spread, as opposed to costs incurred simply due to detection).

*Quarantine buffer:* Quarantines may affect areas that are larger than the strictly invaded area, so we allow for the marginal quarantine costs to be applied across a larger area or circumference than that occupied by the focal population by including a quarantine buffer width. This buffer adds additional radial distance to the focal population when calculating the area or circumference to which quarantine costs are applied. The parameter *SlowAreaCost* (*SAC*) is set to 1 if costs are applied based on the quarantined area size or set to 0 if costs are based on the length of the quarantined area's circumference.

*Length of planned survey program:*

CESAT identifies cost-efficient allocation of survey resources, assuming a fixed allocation across the duration of a survey program. Unless a specific short term program is under consideration, the program length should be set to a minimum of 20 to 30 years to avoid estimating an overly high optimal annual investment level. A short term trapping program increases the optimal annual investment level because CESAT considers the expected costs associated with any populations remaining undetected at the end of the trapping program. Longer programs allow more time periods for detecting established invaders and discount the costs of populations that establish late in the program more.

*Prior survey investment:*

Prior survey investment is the annual monetary investment in trapping at a site in previous years. This value is used to calculate trapping effort in prior years. Past years' trapping effort affects the likelihood of undetected pest populations being present at a site in the current year.

*Years of prior establishment:*

This is the number of years ago that a population could have established and not yet been detected. In the current version of CESAT this is a single parameter in the model (as opposed to pest or site specific). Thus using the longest estimate across pests and sites is suggested.

*Years of prior trapping:*

This is the number of prior years that surveys have been ongoing at a sites with a particular trap.

*Maximum age of invasion considered:*

This represents the time horizon over which damages from new establishments are considered. As a default 50 or 75 years could be used.

*Discount rate:*

CESAT assumes standard exponential discounting. Lower discount rates place higher value on future costs, while higher discount rates place greater value on short term costs. The discount rate is a choice variable for the analyst, and could potentially be between 0.01 and 0.1.

*Number of Monte Carlo draws (obs):*

This is the number of random parameter draws from parameter uncertainty bounds to capture and examine uncertainty in estimates. Larger numbers better encompass the range of potential uncertainty but also increase processing time and memory requirements. 100 observations is a reasonable baseline, though the analyst may want to initially pick a much smaller number to test things out. Setting this number to 1 induces the model to use the midpoint of each parameter range and produces a single model run using those values.

*Investment scoop size and numbers:*

*Size of "investment scoops"* (inv_scoops): This parameter is the size of the investment scoop (i.e. $ amount) that is allocated across traps and sites based on cost-efficacy. Selection of smaller scoop sizes allows for more refined allocation estimates (including allowing very small total allocations to some sites). As such, this value could be selected as the smallest monetary allocation likely to be allocated to any given trap at a site in a single time period. Smaller scoop sizes, however, require allocation of more scoops to reach the optimal total investment level. Because increasing the number of scoops increases computational time and memory, the analyst may need to try several different scoop sizes and number of scoops to figure out the best configuration.

*Number of "investment scoops"* (Num_inv_levels): This specifies the number of "investment scoops" considered for allocation to a particular trap type at any given site. This number times the size of the investment scoop is the maximum allocation considered for any given trap type at a site. Several hundred scoops can be readily handled in the model.