

Optimal Public Control of Exotic Species: Preventing the Brown Tree Snake from Invading Hawai‘i

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I. Intro

This paper develops a theoretical model for the efficient establishment of economic policy pertaining to invasive species, integrating prevention and control of invasive species into a single model of optimal control policy, and applies this model to the case of the Brown tree snake as a potential invader of Hawaii.

The arrival of a new species to an existing ecosystem has a variety of potential outcomes. These outcomes range from beneficial increases in economic value to destruction of both direct market goods and indirect values for ecosystem services. We investigate here invasive species that arrive unexpectedly and cause economic or ecological damage, in order to determine optimal policy for prevention and control expenditures. Policy options include prevention techniques such as reducing incoming shipments, interdiction at the source, and interdiction at the destination, and control techniques including eradication or population reduction, containment of the population, or adaptation to the new ecosystem resources.

The optimal policy choice combination will depend both on biological and economic concerns. For example, reducing incoming shipments will incur potentially high economic costs, particularly for island populations that may not be able to produce replacement goods locally. Interdiction at the source is effective if the source is known and

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limited, while interdiction at the destination will be preferred if there are multiple sources or if the destination is the only trade partner for the source with a susceptible environment for invasion. Both cases require limited points of entry, as, for example, the multiplicity of routes makes the prevention of interstate land transportation of potentially invasive species virtually impossible. Prevention policy options in such cases are essentially limited to spreading public information about their dangers.

When prevention fails, eradication remains a viable solution unless the population spreads so rapidly, or is so difficult to detect and eliminate (as is the case for most insects, e.g.) that the population cannot be pushed below the extinction rate. Immediate eradication followed by a return to optimal prevention efforts seems as if it should be pursued if economically viable, because this will incur a one-time control cost instead of an infinite stream of control costs and damages. However, this becomes akin to causing a local species extinction as soon as the population is self-sustaining, which suggests that eradication may only rarely succeed against an invader that has already demonstrated the biological adaptability to establish itself in a new environment. Population reduction or containment will therefore be potentially important control mechanisms, where the species is kept from reaching its biological potential for damages by pursuing a removal plan that minimizes the damages from the remaining population subject to the costs of removal. Containment, or spatially controlling the spread of the invasive species, will be particularly useful where ecological damages are not uniform across habitat, as in cases of localized concentrations of valuable threatened resources. Here we concentrate on population reduction, assuming uniform population densities and damages across viable habitat.²

² Spatial considerations could be incorporated by adapting diffusion models Shigesada, N. and K. Kawasaki (1997). Biological Invasions: Theory and Practice. Oxford, Oxford University Press. or density-dependent

Existing models of invasive species and pest species generally show the costs of the invasive species in terms of lost revenues from agriculturally productive assets such as farm or fisheries outputs (Fisher, Krutilla et al. 1972; Babcock, Lichtenberg et al. 1992; Gollamudi 1995; Lynch 1996; Williamson 1996; Eeckhoudt and Godfroid 1998; Sharov and Liebhold 1998; Sharov, Liebhold et al. 1998; Williamson 1998; Williamson 1999; Perrings, Williamson et al. 2000; Shogren 2000; Perrings 2002). A growing concern, however, is the protection of natural resource assets that contribute to economic well-being either indirectly or through non-market interactions. For example, the destruction of endangered species habitat by invasive species is now the second-greatest threat to imperiled species, after direct human destruction of habitat (Wilcove, Rothstein et al. 1998). In these cases it becomes more difficult to measure the costs of the invading species, as the initial value of the natural asset is not known or easily quantifiable.

Shogren's (2000) model sets up an appealing general approach to the problem. He suggests that a land manager determine the choice of mitigation and adaptation to maximize expected social welfare, defined as the expected value of the natural asset across potential states of damage from invasive species, net of control expenditures. We expand and refine this model to include prevention expenditures that delay or preclude the need for control.

Questions of investment in prevention and control of invasive species are addressed as a cohesive flow of effort to stem the level of damages from the potential risk of invasion. Investment in prevention is assumed to influence the probability that we enter a state of the world where invasive species cause damage to economic and ecological values. Successful

models to include economic considerations and boundary constraints where control costs become quite high for valuable locations, suggesting prevention through containment is even more worthwhile. This possibility is left for future work.

prevention delays establishment of the species and accompanying control expenditures, lowering expected costs. By establishment, we assume that it is uneconomic to eradicate the existing population.

If eradication is economic when the population growth rate is positive, then the expected result is cyclical: preventative measures should be taken until they fail, eradication should occur rapidly, and then a return to preventative measures should be instated. Many cases of invasions, however, pass the point of eradication before they are identified, and in these cases established populations should be managed much like fisheries, but in reverse. One wishes to remove as many species as is economically possible to reduce the damages from the population.

As a quantitative example, we begin to examine the case of the Brown Tree Snake, a potential invasive species to Hawaii that could cause economic damages, mainly in the forms of ecological change and loss of biodiversity, power outages from snake-power line interactions, and health concerns.

II. The theoretical model

A. Characterizing the threat

Nature and economy combine to determine the threat from species introductions. Nature determines the biological characteristics of species and economic activity provides transport pathways for species introductions. Prevention and control efforts are predicated on the assumption that change in the existing state of natural capital would decrease well-being. Policy determines the optimal level of prevention expenditures, conditional on the imperfect information gleaned (at some cost) from nature and the expected progression of

an invasive, and failed prevention results in the need for eradication or control. Eradication will return society to the state in which prevention delays damages from further invasion; control requires minimization of social costs that accommodate the new species.

Our model integrates prevention and control as a potentially cyclical optimal control problem for a comprehensive strategy to minimize the social costs of invasive species. As a first step in understanding the mechanics of these interrelated processes, we describe the conditions that would create cycles and then focus more precise analytical attention on the case where failed prevention leads to an ineradicable invasive population.

Though this model will take as given the “invasibility” of any given species, it is useful to describe briefly the ways in which one might characterize a potential invader. With better knowledge on each species, one could expand our model to encompass multiple species for the optimal allocation of resources across them. We assume a spectrum of biological and economic characteristics that determine two species- and location- specific probabilities:

- 1) The probability that a new specimen will arrive and become established, (ξ_t) , starting a viable population (n) , and
- 2) The probability that an established species will convey real economic and ecological change (ω_t) . We assume here that this economic change may take on two possible states: one in which there are damages from the new species, (D) , with probability ω_t , and one in which there are no damages.

We divide the problem into two steps to induct the optimal prevention and control levels. Once a species is established, the present value of the damages, given an optimal

control policy, are taken as known. The present value of the damages is thus calculable beginning from any future time period at which establishment occurs.

With optimal prevention expenditures, there is an ever increasing cumulative probability, ξ , that the species has become established by time, t . This probability goes to one as t approaches infinity.

Determinants of ξ include biological concerns, such as whether the arrival point is a hospitable habitat for the species, and economic concerns such as the rate of speed of transport and the availability of transport vectors (Cohen and Carlton 1998). We assume that species establishment only happens once. In other words, the biological, radial growth of the newly established species will expand the population so much more rapidly than additional arrivals that these would have a negligible effect on both population and damages.

Determinants of ω are also both economic and biological. The extent of viable habitat, as well as the alternative land and resource uses, and the level of existing habitat disturbance and past efforts at human management of the land will influence this probability.³

B. The Control Problem

We begin by modeling the states of the world where the species has become established. Actions at this point are limited to containment of the population and adaptation to the new ecosystem resources, as we define establishment as occurring when eradication is not economically feasible. In this case, we express the objective functional as:

³ Though we expect a stochastic element to these probabilities, based on scientific uncertainty and unpredictable episodes in nature that change the habitat capabilities of the ecosystem and potential invaders, for tractability and exposition we do not model the majority of these uncertainties at this time.

$$W\{x\} = \int_0^{\infty} e^{-rt} \{\omega(n_t, x_t) \cdot D(n_t, x_t) + C(n_t) \cdot x_t\} dt ,$$

and the goal of the social planner as the minimization of this welfare loss to society from a potential invader, or:

$$\text{Max}_x \{-W\{x\}\} \quad (1)$$

subject to

$$\dot{n} = g(n) - x \quad (2)$$

s.t. $0 \leq x_t \leq x_{\max}$, with n_0 given, where $g(n)$ is the biological growth function of the invading species. We assume that unit costs, $C(n)$, are decreasing in population size

$$\left(\frac{\partial C}{\partial n} < 0\right).$$

The current value Hamiltonian for this problem is:

$$H_c = -\omega_t \cdot D_t - C_t(n_t) \cdot x_t + [g(n_t) - x_t] \lambda_{ct}, \text{ where } \lambda_{ct} \geq 0 .$$

Following Kamien and Schwartz (sections 8 and 10), the necessary conditions for an optimal solution are:

$$\dot{n}_t = \frac{\partial H}{\partial \lambda_{ct}} = g(n_t) - x_t \quad (3)$$

$$\dot{\lambda}_{ct} = r\lambda_{ct} - \frac{\partial H}{\partial n_t} = r\lambda_{ct} + \left[\frac{\partial \omega_t}{\partial n_t} \cdot D_t + \omega_t \frac{\partial D_t}{\partial n_t} + C'(n_t) \cdot x_t - g'(n) \lambda_{ct} \right] \quad (4)$$

$$\frac{\partial H}{\partial x_t} = \frac{-\partial \omega_t}{\partial x_t} \cdot D_t - \omega_t \cdot \frac{\partial D_t}{\partial x_t} - C_t(n_t) + \lambda_{ct} \leq 0, \quad \text{if } <0 \text{ then } x_t=0 \quad (5)$$

From this problem, we can derive an optimal control policy path for the case where it is uneconomic to eradicate the new population. Removals, x_t , should occur until the marginal welfare cost from the invasive species population, net of removals, today is equal to the discounted increase in welfare costs of the remaining population tomorrow. This can be seen through rearrangement of equation (4):

$$\dot{\lambda}_c - \frac{\partial \omega_t}{\partial n_t} D_t - \omega \frac{\partial D_t}{\partial n_t} - C'(n_t) \cdot x = (r - g'(n)) \lambda_{ct} \quad (6)$$

Since the harvest of these pests earns no market price, the marginal net benefits are composed of the change in expected damages from the change in expected damages from a lower population $\left(\frac{\partial \omega}{\partial n} D > 0 \right)$, and lower damages, $\left(\omega \frac{\partial D}{\partial n} > 0 \right)$, from a reduced population, net the marginal cost of achieving this lower population. On the RHS, discounted shadow costs for tomorrow are increased by biological growth of the remaining population.

When an internal solution exists, we solve for the optimal relationship between the discount rate and the removal path:

$$g'(n) + \frac{\frac{\partial \omega}{\partial n} D + \omega \frac{\partial D}{\partial n} + C'(n) \cdot g(n)}{\frac{\partial \omega}{\partial x} D + \omega \frac{\partial D}{\partial x} + C(n)} = r \quad (7)$$

This result matches the intuition that if eradication is cost-prohibited, one will “harvest” invasive species so that the opportunity costs of removal equal the discount rate, similar to other renewable resource harvesting. Alternatively, if $x > g(n) \quad \forall t$, then the optimal

solution drives the population to zero, and the result is a cyclical return to prevention. This, as expected, is more likely as the discount rate decreases.

Since costs of capturing the last remaining snakes are likely prohibitive, we assume that there exists a steady state such that where the expected damages and costs are minimized. This is expected to occur at a relatively low population rate, as opposed to occurring near the maximum sustainable yield, as we are minimizing damages rather than maximizing profits. Furthermore, if $n > N_{msy}$, we expect that there will not be a steady state with $x > 0$, as the continuing damages from the existing population will so outweigh the removal costs when $x = g(n)$ that it will always be cost effective to reduce the population below $n > N_{msy}$.

From these findings, we may determine a minimum level of welfare loss over time, W_E , given a species' establishment and optimal control efforts.

C. The prevention problem

Optimal prevention efforts, then, will minimize the *expected* welfare loss to society over time, by delaying the expected welfare loss subject to the prevention costs to society:

$$Max_p \left(- \int_0^{\infty} e^{-rt} (\xi_t \cdot W_E + C_{I_t}(\xi_t) \cdot p_t) \right). \quad (9)$$

(10)

s.t. $p_t \geq 0$, with ξ_0 given, where $F(\xi_t)$ is the cumulative probability function describing the likelihood that the invading species has become established by time t. Note that

$$F(t) = \int_0^t f(s) ds, \text{ where } f(s) \text{ is the density function for } \xi_t \text{ and } F(t) \rightarrow 1 \text{ as } t \rightarrow \infty.$$

Prevention is not expected to change the number of new arrivals (a_t) per se, only their

probability of successful establishment⁴. Though optimal prevention may be the same each year, the cumulative probability of establishment will grow over time until prevention fails.

The current value Hamiltonian for the problem of prevention is:

$$H_p = -\xi_t \cdot W_E - C_{It}(\xi_t) \cdot p_t, \quad (11)$$

and the necessary conditions for an optimal solution require that the Hamiltonian take the same value each period:

$$\xi_t \cdot W_E + C_{It}(\xi_t) \cdot p_t = \xi_{t+1} \cdot W_E + C_{It+1}(\xi_{t+1}) \cdot p_{t+1} \quad (12)$$

$$\dot{\lambda}_{pt} = r\lambda_{pt} - \frac{\partial H_p}{\partial \xi_t} = r\lambda_{pt} - \left[-W_E - C'_{It}(\xi) \cdot p_t + \lambda_{pt} \left(f(\xi) \left(1 - \frac{p_t}{a_t} \right) \right) \right] \quad (13)$$

$$\frac{\partial H_p}{\partial p_t} = \frac{-\partial \xi_t}{\partial p_t} \cdot W_E - C_{It}(\xi_t) + \lambda_{pt} \left[f(\xi) \frac{\partial \xi_t}{\partial p_t} \left(1 - \frac{p_t}{a_t} \right) + F(t) \left(\frac{-1}{a_t} \right) \right],$$

$$\lambda_{pt} \leq 0, \text{ if } <0 \text{ then } p_t=0 \quad (14)$$

Assuming $p_t > 0$ and rearranging equation 14 leads to an intuitive rule for the optimal level of prevention in any given time period that sets the reduction in marginal damages accrued today and tomorrow from the reduced probability of establishment equal to the marginal costs of prevention:

$$-\frac{\partial \xi_t}{\partial p_t} W_E - \lambda_{pt} \left[f(\xi) \frac{\partial \xi_t}{\partial p_t} \left(1 - \frac{p_t}{a_t} \right) + F(t) \left(\frac{-1}{a_t} \right) \right] = C_{It}(\xi_t). \quad (15)$$

⁴ Assume, for example, that arrivals increase at the average rate of increase in trade, so that $a_t = (1 + \varphi)^t a_0$, where φ is the average rate of trade.

The connection between the prevention problem and the control problem is clearly seen by solving for p_t in equation (13):

$$p_t = \frac{\dot{\lambda}_p - \lambda_p \left[r - \left(f(\xi) \left(1 - \frac{p_t}{a_t} \right) \right) \right] - W_E}{C'(\xi_t)}. \quad (16)$$

Here, prevention should follow a path such that the captures are equal to the ratio of the rate of change in the *in-situ* value of the asset under prevention net of the change in the shadow value from discounting, the change in the likelihood of successful prevention and the minimum expected damages from optimum control if the species is introduced, to the change in the marginal cost from the change in probability. In other words, the marginal dollar spent on prevention in the form of postponement should equal the marginal benefit in control costs and damages avoided.

Any steady state will require that $p_t = a_t$, from equation (12) and the fact that the cumulative probability of prevention failure will increase over time⁵. However, if a_t grows at the rate of trade, exogenous to the system, there can be no steady state level of prevention, as prevention should increase at the level of arrivals. Prevention cannot eliminate the threat, but it will buy time from needing control expenditures, reducing expected damages by postponing them.

III. Case Study: The Brown Tree Snake

A. Overview

⁵ The alternative possibility, that $F(t)=0$, will only occur if $\xi = 0$ in the steady state. In this case, the steady state is a prevention level of zero.

Brown tree snakes (*Boiga irregularis*) were accidentally introduced to Guam in the 1940s, via shipping from their native Australia. They cause an average of one power outage every four days. If O'ahu faced similar conditions, the expense of power outages would be significant. A conservative estimate of the cost for one major O'ahu power outage triggered by a fallen tree branch in 1991 was \$13 million (Committee 1996).

Brown tree snakes have also devastated Guam's native bird population, causing the loss of 9 of Guam's 11 native bird species. Though snakes usually do not have sufficient numbers to eat themselves out of their prey base, on Guam snake density reached over 50 snakes per hectare, when the normal range for snake densities is about 1-10 snakes per hectare (Rodda, Fritts et al. 1996). As Guam's island ecosystem had evolved without the presence of snakes, this aberration was possible and appears sustainable. Hawaii shares many of Guam's island traits, including a current absence of snakes, making the islands' bird populations susceptible to this same devastation.

There are health costs associated with these snakes, too. Over 200 people, mainly sleeping children, in Guam have been treated for bites from the snake since the mid-1980s (Fritts, McCoid et al. 1990; Fritts, McCoid et al. 1994). Predation also includes poultry and small domestic animals (Fritts and McCoid 1991).

The threat of the snake's arrival in Hawaii is imminent. Live specimens have been intercepted in Honolulu (Fritts 1995). The remainder of this section analyzes the expected damages and costs from an arrival that is followed by a successful adaptation into the environment.

B. Application to the model

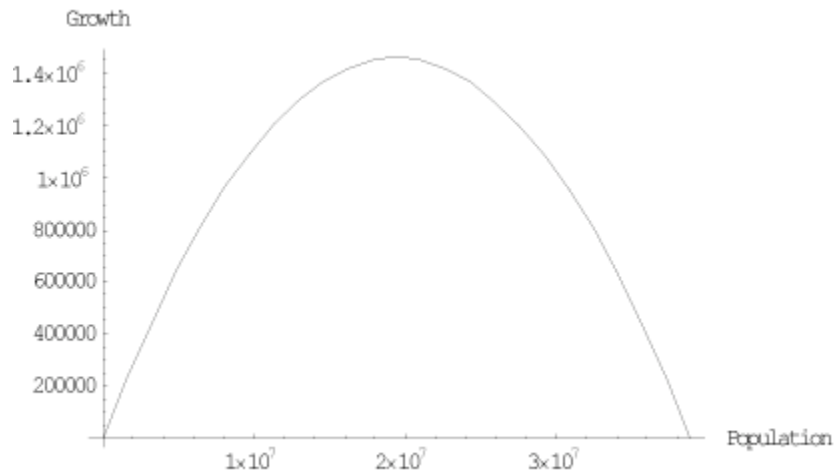
1. Biological growth

We choose the logistic growth function to describe the biological potential of the invading species:

$$g(n) = bn\left(1 - \frac{n}{N_{\max}}\right),$$

where $b = 0.15$, based on the average percentage of hatchlings found in sample populations on Guam (Rodda, Fritts et al. 1996). The maximum elevation range of the snake may be as high as 1,200 m (Fritts 1988). We estimate that there are approximately 3000 square miles of potential snake habitat on Hawaii, so that N_{\max} for Hawaii is estimated at 38,850,000. Figure 1 is a graph of the expected growth function:

Figure 1: Logistic Growth Function for BTS in HI



2. Damages

Guam has a land area of approximately 53,900 hectares, with a maximum elevation of about 400 meters. With a population density of 50 snakes/hectare, we estimate a potential maximum population level (N_{\max}) for the island to be 2.695 million snakes. With approximately 100 power outages per year attributable to the snakes, we estimate that there

are 3.7×10^{-5} power outages per snake per year. Annual electricity generation capacity per capita in Guam is virtually the same as on Hawaii, at 2kW/capita. We estimate that an hour-long power outage on Oahu causes \$1.2 million in lost productivity and damages (Fritts and Chiszar 1997). Positing a linear relationship between snake population and power outages, the expected damage per snake, in terms of power outage costs, is \$44.53.

Guam has experienced a snake-bite frequency average of 3 bites per month, at an average cost of \$70 per hospital visit (Fritts, McCoid et al. 1990; Fritts, McCoid et al. 1994). Thus the expected level of bites per snake per year is at least 1.34×10^{-5} , with an expected cost of $\$9.3 \times 10^{-4}$ per snake. Hawaii's population density below 1200 m is approximately $\frac{1}{2}$ that of Guam's. Snake/human interactions should occur less frequently per square mile. However, Hawaii's population is 8 times greater than Guam's, so we adjust the expected costs for Hawaii to $\$3.72 \times 10^{-3}$ per snake.

While it is known that snakes prey on poultry and eggs, the extent of this predation is unknown. In locations where snakes are believed to prey on eggs, rat populations seem to be decreasing (Fritts and McCoid 1991). Thus we assume that it is unlikely that snakes are greatly increasing predation on eggs, and we estimate these damages as zero.

The Brown tree snake has extirpated 75% (9 of 12) of Guam's native bird population since its arrival (Fritts 1988). Contingent valuation studies have estimated the average value of the continued existence of an endangered bird species at \$31 per household per year for Hawaii (Loomis and White 1996).

There are 15 endangered bird species in Hawaii whose main habitat is below this level (www.hear.org). Of these, 3 are native to small, unpopulated islands that are unlikely to experience the arrival of the snake and 4 are water birds, also users of unlikely habitat

for the arboreal snake. If we assume a 75% chance of losing each of the remaining 8 species, the expected value of these damages to 403,240 Hawaiian households is \$75 million. If each snake is equally likely to contribute to the extirpation, the expected damages per snake are \$1.93. We consider these the base level for high damages possible from the presence of the snakes. If the snakes do not have the same success at extirpating bird populations, or if there is a bias in the contingent valuation estimates that does not account for the marginal benefit of saving an additional species as being potentially lower than \$31 per household per year (see Loomis (1996)), then this estimate may be too high. We use the certain value to Hawaiians of losing one species, or \$12.5 million, to estimate the base for low damages, with an expected per snake damage level of \$0.32.

Expected damages can be expressed then as:

$$D_H = 46.464212 \cdot (n_t - x_t), \text{ and}$$

$$D_L = 44.85547 \cdot (n_t - x_t).$$

The maximum annual damages that Hawaii faces without control efforts are therefore

$$N_{\max} * D_H, \text{ which equals } \$1.738 \text{ billion.}$$

Since we have defined ω as the probability of damages in general, we take the expectation of the high and low damages, assuming that we have an even chance of error regarding the correct damage specification, to get a damage function of:

$$D = 45.65984 \cdot (n_t - x_t).^6 \text{ Figure 2 shows the annual damages over time as the population}$$

grows to capacity without control efforts.

3. Probability of damages

⁶ Note that the model could be further complicated to include a continuous probability of a range of potential damages.

We assume that ω_t is the success ratio of control in removing species of concern. If

$\frac{x_t}{n_t}$ is the ratio of removed specimens (x_t) to population (n_t), then $\omega_t = \bar{\omega} \left(1 - \frac{x_t}{n_t} \right)$, where

$\bar{\omega}$ is the probability of damages without any control efforts. With no control effort, we assume that damages will occur with a probability of 90%, so that $\bar{\omega} = .9$, based on the similarity to the conditions in Guam.

4. Control costs

We assume that control costs are decreasing in n and linear in x . We choose the

simple function $C(n) = \frac{C_o}{q_n \cdot n^\nu}$, where q_n is a “catchability constant,” here assumed to be

0.175 based on the trap efficacy in Guam. C_o / q_n is set at 73,600, based on the requested funds for snake prevention, and $\nu = 0.73$.⁷ Estimates of the efficacy of state-of-the-art traps are that they exhibit only a 7-28% average probability that a given snake will be caught during a capture event, where an event is a single trap for a single night (Rodda, Fritts et al. 1996), and a study investigating the use of dogs in detecting planted snakes estimates their efficacy rate at 70% (Engeman 1997). Thus the capture of the last few specimens should be very expensive.

5. Probability of establishment and prevention costs

We assume that $\xi(0)$, the probability that a new arrival will start a successful population without prevention, is 90% in this case, based on the similarities of the Hawaiian ecosystem to that of Guam’s. For exposition we choose a straightforward

⁷ We choose 0.73 by using trap cost estimates of \$73,600 to acquire and care for 300 traps per year, covering 3.75 square km. With a snake density of 5,000 per km², it costs \$0.23 cents to capture the first snake and at least \$73,600 to catch the final snake.

discrete relationship between prevention probabilities and the prevention expenditures, based on the experiences in Guam. Current prevention activities at Guam focus on the use of K-9 teams (trained Jack Russell terriers) to inspect outbound cargo and aircraft. In 1996, there were 10 dogs, eight full time handlers, a supervisory trainer, and an assistant district supervisor. This prevention level allowed coverage of all aircraft headed for high risk destinations (e.g., Hawaii) that have been on Guam for 4 or more hours during darkness, and outward cargo shipments to high risk locales of 4000 pounds or greater. The estimated costs for this level of prevention is \$1.6 million (Committee 1996).

We assume that prevention costs buy a reduction in the probability that a snake will arrive and become established. The higher the probability of establishment, the easier it will be to capture any one entrant. We choose the simple function $C(\xi) = \frac{C_{p0}}{q_a \cdot \xi}$, where q_a is a “catchability constant,” here assumed to be 0.3 based on the dog experiments in Guam, and C_{p0} is set at 500, based on the requested funds for snake prevention divided by the number of departures from Guam.

IV. Results

Table 1 summarizes some of the findings for the control problem. We find that a steady-state equilibrium for control efforts may exist at a very low population level. This equilibrium behaves as predicted. It is not particularly sensitive to the discount rate, though if C_0 is small enough it will be efficient to eradicate or exclude the population from valuable resource areas. Note that this is essentially the result achieved in Hawaii for (easily spotted) wild cattle a century ago, as they were excluded from conservation districts where they were causing significant damage to watershed capabilities.

Figure 2 shows the expected annual damage levels associated with each year of growth from $n = 1$ to $n = N_{\max}$. These are the costs of no control.

We can use the estimates for W_E , or the present value of the controlled damages of an invasion, to determine prevention expenditures once one knows arrival rates and determines a distribution function for the probability of establishment as a function of preventions and arrivals. These calculations are left for future work.

V. Conclusions

A successful invader will have biological and economic characteristics that make control expensive at even small population levels. High population levels of invasion may incur very high damage levels, as the example of the Brown tree snake shows. Eradication is likely to be difficult, and post-invasion control efforts will need to last indefinitely. This potentially ever-present expense is avoided by successful prevention.

Successful prevention, however, is likely only a postponement, as paths for introduction cannot be scrutinized to assure a 100% avoidance of invasion. Over time, the cumulative probability of a successful invasion will tend toward one, and the prevention system will fail.

If control can begin soon after, and establish an equilibrium at a very low population level, the major damages may be avoided. In cases where eradication is possible, this option should be preferred and followed by a return to the prevention efforts that had preceded it.

If populations have grown to exceed the “maximum sustainable yield,” or the point at which the growth rate is maximized, without control, there is no equilibrium level of

control that establishes a cost effective equilibrium at this high population level. Instead it is efficient to “harvest” the invader until the population returns to a low steady state.

The only steady states that occur for prevention are the case where there is no positive probability of establishment (e.g., the species is not suited to the environment or has no arrival vector), or where prevention removals exactly equal arrivals. Since this requirement means that unless arrivals are constant, prevention should keep pace with arrivals rather than be set at some constant level. While the first dollar spent on prevention clearly supports the adage, “an ounce of prevention is worth a pound of cure,” optimal prevention expenditures should continue until the ounce of postponement is equal to the ounce of cure postponed. Thus prevention should continue until its marginal cost outweighs the expected marginal benefit of postponing an invasion.

It is beneficial to spend considerable amounts on prevention and control at early stages of invasions. Costs at these early stages may not be terribly cumbersome compared to the damages that would be incurred without them. Control efforts should be continuous to maintain a low population even if eradication is not feasible. If eradication is biologically and economically feasible, eradication must be followed by continued prevention efforts.

Discontinuous cost or damage functions are likely and might affect optimal prevention and control. For example, it is much less likely that a small population of snakes would cause a bird species extinction than a large population, but we assume here that each snake has an equal contribution to the damages of an extinction, regardless of the population. A more realistic damage function would attempt to establish the threshold at which bird extirpation becomes likely. Biologists, however, do not yet have a description

of this non-linear event. This is just one example of how solid economic estimates will improve with improved scientific knowledge.

If prevention or control cannot be implemented on a small scale, we should expect that the large outlays should go to prevention rather than control efforts as large control expenditures would need to be maintained to control a rather small population, and these large expenditures would likely have a greater impact in successful prevention.

Finally, we note that there is no steady state level of prevention, rather prevention expenditures should track arrivals and depend significantly on the biological possibilities for establishment and the economic possibilities for damage. Precise understanding of these possibilities remains limited, and investment in research on these costs appears warranted.

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Table 1: Findings for Optimal Control of BTS in HI

Specifications				Steady state pop'n	Expected Damages + Costs
b	Cost function	Damage function	Disc. rate		Annual
0.15	$C = \frac{73600}{n^v}, v = 0.73$	$D = 45.65984 * (n - x)$	$r = 0.03$	1300	98830
0.15	$C = \frac{7360}{n^v}, v = 0.73$	$D = 45.65984 * (n - x)$	$r = 0.03$	88	6415
0.15	$C = \frac{73600}{n^v}, v = 0.73$	$D = 45.65984 * (n - x)$	$r = 0.10$	1250	103281

Figure_2

Annual Damages over Time, without Control (Millions of Dollars)

