Beyond the Lamppost:
Optimal Prevention and Control of the Brown Treesnake in Hawaii

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I. Introduction

The threat of invasive species stems from their ability to change, rapidly and irreversibly, ecosystems and the direct and indirect economic services that ecosystems provide. Species spread both accidentally and intentionally, aided by human travel and exchange. Each of several stages of invasion dictates different human response. In general, policy makers must determine the proper balance between "prevention" expenditures that lower the probability of new introductions and "control" expenditures that limit the growth rate and/or the pest population. Optimal policy regarding invasive species will minimize the expected damages and costs of control within an ecosystem and will include full consideration of the cycle of prevention (or avoidance) and control (or removals) needed over time. Rarely, however, have policy makers or economists integrated prevention and control for optimal intertemporal allocation of resources.

The existing literature on the economics of invasive species has taken several complementary approaches to evaluating policy options, but to date these efforts remain rather fragmented across the timeline of an invasion. Due in part to the complexity of bioeconomic modeling and the specificity of biological factors involved in creating ecosystem changes, most case studies focus on preventing entry of new species as a function of trade (Horan et al. 2002; Costello and McCausland 2003; McCausland and Costello 2004; Horan and Lupi 2005a; Horan and Lupi 2005b; Margolis, Shogren and Fischer 2005), preventing or controlling a single invading species (Olson and Roy, 2002; Eiswerth and Johnson 2002; Knowler 2005; Knowler and Barbier 2000; Settle and Shogren 2002; Buhle, Margolis, and Ruesink 2005) or on broader ecosystem damages at a particular location and time (Kasulo 2000; Turpie and Heydenrych 2000).

With few exceptions (Kaiser and Roumasset 2002; Burnett et al. 2006), prevention and control have been handled separately so far in the empirical literature. Typically either prevention or control policies are investigated, but a full characterization of the threat has not yet been laid out. From these efforts, an economics of prevention and control (e.g. Kaiser and Roumasset 2002; Pitafi and Roumasset 2005; Olson and Roy 2005; Perrings 2005; Finnoff et al, 2006) is slowly evolving in which insights and tools of optimal control theory are combined with biological and economic parameters to solve for the optimal expenditures on avoidance and removal over time. Applications, when attempted, have been mainly illustrative to date. In this paper we will illuminate theoretically how expenditure paths change in response to various parameters, and solve for expenditures for every population level and each time period for the real-world case of the Brown treesnake (BTS). We find that the conventional wisdom that "an ounce of prevention is worth a pound of cure" does not reveal the whole story. Depending on the interaction of biology and economics, the message may be much richer than this.

The case of the snake is used to illustrate dynamic policy options for invasive species that may or may not be present, but has a high likelihood of arriving and continuing to arrive, in a new location (Hawaii) and that will cause extensive economic damages if established. For BTS, these concerns include damages to Hawaii's fragile ecosystems and biodiversity, human health concerns, and infrastructure for power supply.

II. Case Overview: Brown Treesnake (*Boiga irregularis*)

Hawaii faces several threats from invasive species, all of which must be considered simultaneously for optimal avoidance and removal efforts to minimize expected damages to the state's ecological assets and economy. Perhaps the most dramatic candidate for Hawaii's top pest is the Brown treesnake (*Boiga irregularis*). This native of Australia and New Guinea, upon establishment in Hawaii, would introduce snakes[2] to the islands and create a list of damages that include direct economic impacts as well as widespread ecological disaster.

We infer potential damages from Guam, where the snake was introduced to the previously snake-free island in the 1950s. Since then, high-density populations of 12,000 snakes per square mile have arisen, sending thousands to the hospital with venomous bites over the last 10 years. The snakes have been blamed for the extirpation of 11 of 18 bird species, and currently generate power outages 1.5 hours every other day (up from one every 3-4 days in 1997). Finally, poultry productivity has been adversely affected (See USGS 2005 for recent overview of damages. Detailed power and medical data are courtesy of Stephanie Shwiff, USDA).

The snake is an imminent threat to Hawaii. Eight snakes have been intercepted and verified as BTS in the state since 1981 (Rodda et al. 1999 and Rodda 2005, personal communication). Many more sightings of snakes that were neither caught nor identified have occurred as well. Between 1969 and 1988, over 150 snakes were credibly discovered in the state, with 21 in 1987 alone. Thus experts are unsure of the exact population of BTS in Hawaii, but estimate there may be between 0 and 100 individuals. Trade between Guam and Hawaii is extensive and Hawaii now pays to support Guam's efforts to prevent the Brown treesnake from escaping the island. We use the considerable information from Guam's infestation and expenditures on avoidance to model an integrated avoidance and removal strategy for minimizing expenditures on and damages from the snake.

III. Methodology

We employ optimal control theory to determine the paths of expenditures that minimize the present value of removal costs, avoidance expenses, and damages over time. For the sake of computational simplicity and clarity of exposition, we use a deterministic model. Each period, the snake population is known and new entrants arrive on a continuous basis. The solution involves a steady state population of snakes and corresponding time paths of expenditures on avoidance and removals.

The problem is to:

$$Max \int_0^\infty -\left(\int_0^x c(n)d\gamma + D(n) + y \right) e^{-rt} dt \qquad (1)$$

[2] With the exception of *Ramphotyphlops braminus*, a harmless blind snake present in Hawai`i since 1930.

subject to

$$\dot{n} = g(n) - x + f(y) \tag{2}$$
$$x \geq 0 \tag{3}$$
$$y \geq 0 \tag{4}$$
n_0 given,

where n is the population of snakes, c is the unit cost of removal, $D(n)$ is the damage function, y is avoidance expenditures, $g(n)$ is the growth function, x is the harvest level and $f(y)$ describes how many new snakes are added to the current population as a function of investment in avoidance. The total cost of removal, x, is written as the integral of its marginal cost, $c(n)$. Unlike the standard resource literature's reliance on linear harvest costs, this cost function reflects the cumulative burden of removals, much like the reverse of a marginal benefit curve. In this case in particular, where marginal costs may change rapidly at low population levels, it is important to illuminate how the problem changes if marginal costs are no longer functions of the stock levels alone. As such, it is more akin to the textbook description of an abatement cost for pollution than a harvest cost for a resource.

The current value Hamiltonian for this problem is:

$$H = -\int_0^x c(n)d\gamma - D(n) - y + \lambda[g(n) - x + f(y)]$$

Application of the Maximum Principle leads to the following conditions:

$$\frac{\partial H}{\partial x} = -c(n) - \lambda \leq 0 \tag{5}$$
$$\frac{\partial H}{\partial y} = -1 + \lambda f'(y) \leq 0 \tag{6}$$
$$\frac{\partial H}{\partial n} = -c'(n)x - D'(n) + \lambda g'(n) = r\lambda - \dot{\lambda} \tag{7}$$
$$\frac{\partial H}{\partial \lambda} = g(n) - x + f(y) = \dot{n} \tag{8}$$

For all internal solutions, we get the following:

$$\lambda = -c(n) = \frac{1}{f'(y)} \tag{9}$$

Equation (9) states that at every period where there is positive spending on prevention and control, we set the marginal costs of each equal to the shadow price of snakes. However, we also note that since removal costs are linear with respect to x, we arrive at a bang-bang solution where removal only occurs at the optimum steady state.

Thus, if we have a population smaller than our optimal steady state, then we only spend on prevention until equation (6) holds with equality. As time continues and n increases, λ increases according to:

$$\dot{\lambda} = D'(n) - \lambda g'(n) + r\lambda \tag{10}$$

In order to better understand where the optimum steady state lies, let us define total costs of maintaining a given population of snakes to be:

$$TC(n, x^*(n), y^*(n)) = \int_0^{x^*} c(n) d\gamma + D(n) + y^* \tag{11}$$

where x* and y* are the optimal allocation of removal and prevention expenditures to maintain a population level of n. We note that x*(n) and y*(n) solve the following equations:

$$c(n) f'(y^*(n)) = -1 \tag{12}$$

$$x^*(n) = g(n) + f(y^*(n)) \tag{13}$$

The partial derivative of this total maintenance cost function is therefore:

$$\frac{\partial TC(n, x^*(n), y^*(n))}{\partial n} = c'(n) x^* + D'(n) \tag{14}$$

which we can combine with equation (7) at the steady state where x=x*, y=y*, and $\dot{\lambda}$=0 to get:

$$\frac{\partial TC(n, x^*(n), y^*(n))}{\partial n} - \lambda g'(n) = -r\lambda \tag{15}$$

However, this is easier to interpret if we notice that:

$$\frac{\partial TC(n, x^*, y^*)}{\partial n} = \frac{dTC(n, x^*, y^*)}{dn} - \frac{\partial TC(n, x^*, y^*)}{\partial x^*} \cdot \frac{dx^*}{dn} - \frac{\partial TC(n, x^*, y^*)}{\partial y^*} \cdot \frac{dy^*}{dn} \tag{16}$$

Where:

$$\frac{\partial TC(n, x^*, y^*)}{\partial x^*(n)} = c(n) = -\lambda \tag{17}$$

$$\frac{dx^*(n)}{dn} = g'(n) + f'(y) \frac{dy^*(n)}{dn} = g'(n) + \frac{1}{\lambda} \cdot \frac{dy^*(n)}{dn} \tag{18}$$

$$\frac{\partial TC(n,x^*,y^*)}{\partial y^*(n)}=1 \tag{19}$$

Equation (19) confirms the intuition that the two policy options need to generate equal returns at the margin if they are being used optimally. Rewriting (15), we notice:

$$\frac{dTC(n,x^*,y^*)}{dn}+\lambda[g'(n)+\frac{1}{\lambda}\cdot\frac{dy^*(n)}{dn}]-\frac{dy^*(n)}{dn}-\lambda g'(n)=-r\lambda \tag{20}$$

$$\frac{dTC(n,x^*,y^*)}{dn}=-r\lambda \tag{21}$$

Thus, equation (21) tells us that our steady state is simply when the amount of additional money we would spend to maintain a higher level of snakes is just equal to the interest received by letting that one extra snake live.

IV. Empirical Investigation

The immediate obstacle to estimating economic impacts to Oahu, as with any potential invasive species in a new habitat, is that we have no direct evidence on which to base cost, damage, and growth function parameters. Instead, we obtain rough estimates based on indirect evidence from Guam and the subjective assessments of invasive-species research scientists and managers.

The resulting parameters are discussed below, followed by results.

i. Growth function

We utilize the logistic function,

$$g(n)=bn\left(1-\frac{n}{N_{MAX}}\right), \tag{22}$$

to represent the potential growth of the snakes. In this case, the intrinsic growth rate, *b*, is 0.6, based on based on estimated population densities at different time periods on Guam (Rodda et al. 1992 and personal communication 2005). The maximum elevation range of the snake may be as high as 1,400 m (Kraus and Cravalho 2001), which includes the entire island. There are approximately 150,000 hectares of potential snake habitat on Oahu. Assuming a maximum population density of 50 snakes/hectare, carrying capacity N_{MAX} for Oahu is 7,500,000.

ii. Damage function

Major damages from BTS on Guam include lost productivity and repair costs due to power outages, medical costs from snakebites, and lost biodiversity from the extirpation of native bird species. Using data obtained from Guam, and positing a linear relationship between damages and number of snakes, we derive an equation for damages as a function of snakes.

$$D = 122.31 \cdot n_t . \tag{23}$$

For a more complete look at the derivation of this function, see Appendix 1.

iii. Removal cost function

While to date there has yet to be a successful capture of BTS in Hawaii, we were able to obtain success rates for various capture techniques in an enclosure in Guam. Using this data, we constructed a marginal cost function that is decreasing in n, but independent of x.

$$c(n) = \frac{1.547 * 10^7}{n^{0.8329}} \tag{24}$$

For a more complete look at the derivation of this function, see Appendix 2.

iv. Arrival function

We assume that avoidance expenditures buy a reduction in the number of snakes that arrive and become established. According to our sources, under current avoidance expenditures of $2.6 million, Oahu faces an approximate 90% probability that at least one snake will arrive over a ten-year time horizon. If expenditures increased to $4.7 million, the probability of at least one arrival would decrease two-fold, to about 45% over the ten-year horizon. Finally, if we increase preventative spending to $9 million per year, the probability of an arrival decreases another two-fold, to about 20%. We convert these probabilities to expected values using the Poisson distribution.

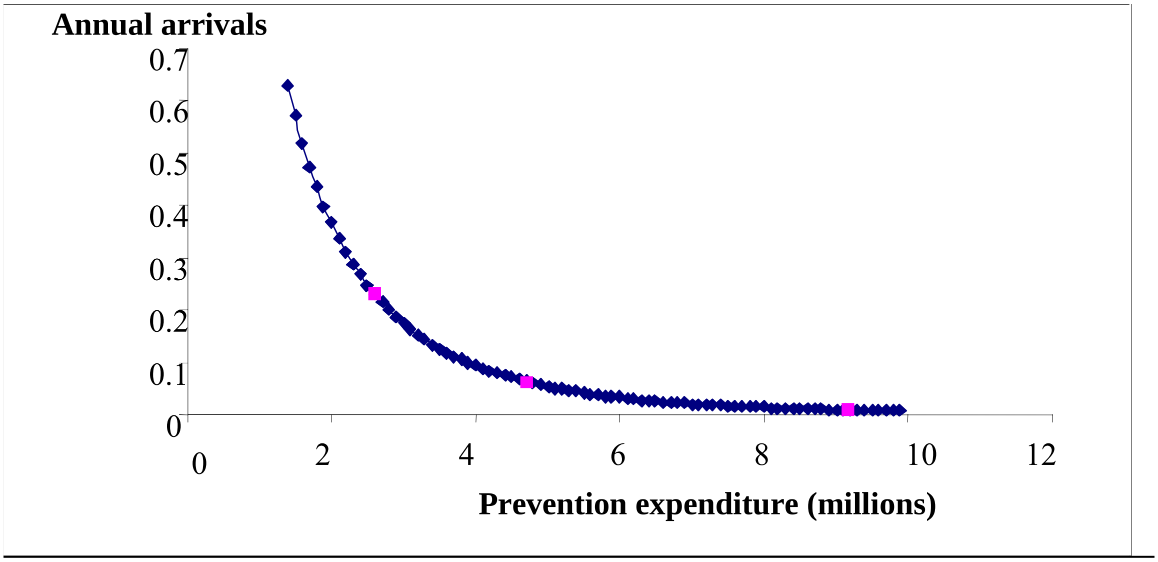
We then use the Weibull curve to fit the arrival function because of its flexible shape and ability to model a wide range of failure rates (e.g., in engineering, such as capacitor, ball bearing, relay and material strength failures). Here, the Weibull describes failure of the avoidance barrier. The resulting function is

$$\lambda(y) = \exp(2.3 - 0.00224 y^{0.5}) \tag{25}$$

Figure 1 illustrates this function.

For more explanation on the Poisson distribution and the Weibull function, see Appendix 3.

Figure 1. Arrivals as a function of avoidance expenditures



v. Optimal avoidance and removal results

As mentioned previously, there is great uncertainty surrounding the present population of snakes in Hawaii, although the number is estimated to be between zero and 100. For this reason, we look at two cases, first, optimal policy if there are no snakes in Hawaii and second, optimal policy given an initial population of 50 snakes.

Given our functional forms, if the current population is zero, then today it is optimal to spend $11.1 million only on avoidance. With this level of prevention, it takes about 7 years to reach n=2.21, at which point we begin removal expenditures to keep the population in a steady state. In the steady state, we spend $12.5 million to remove 1.57 snakes every year and $2.79 million to keep all but 0.238 snakes from entering the island. The marginal costs of these activities are equal at $521 million per snake.

Figure 2. Optimal avoidance and removal expenditure paths

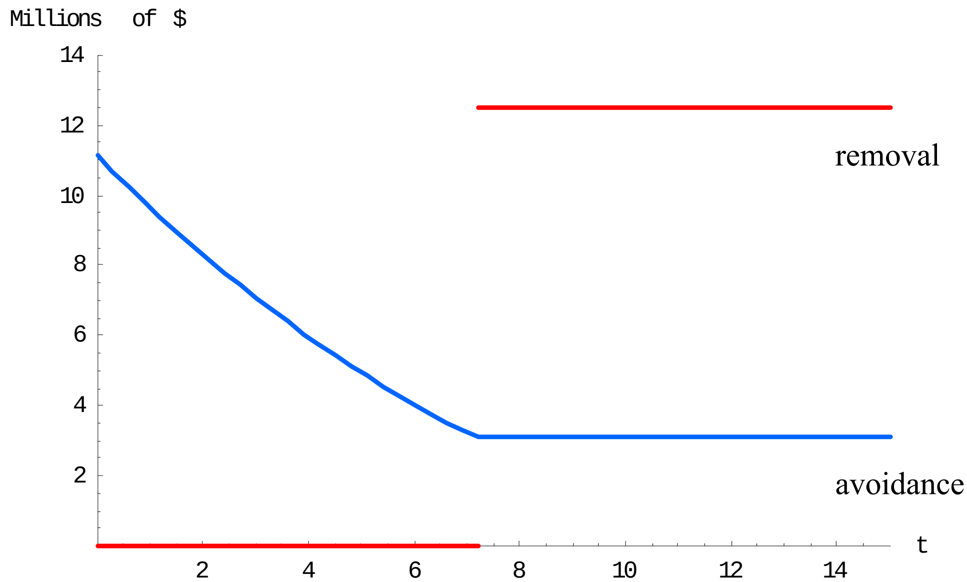


Figure 2 above illustrates the optimal expenditure paths for removing and avoiding snakes on Oahu. The optimal paths require avoidance expenditures that decrease with time and snake population. The steady state level of snakes is 2.21.

Figure 3, below, illustrates the optimal policy if we initially start with 50 snakes on Oahu. After removing 47.79 snakes immediately at a cost of $72.3 million, we spend $12.5 million per year removing snakes and $2.79 million preventing more from entering.

Figure 3: Optimal Policy and Removal Paths from n0=50

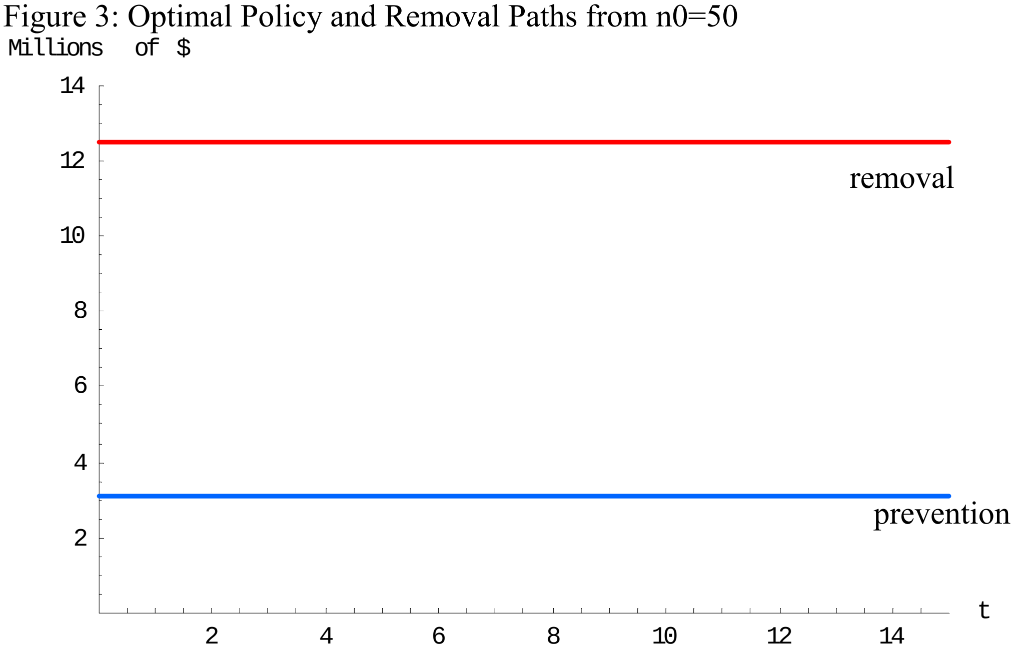


Table 1 reports the optimal policy of avoidance and removal under both of these assumptions.

Table 1. Optimal policy under two initial populations

	1^{st} period		Steady state	Present value	
	n_0=0	n_0=50	n=2.21	n_0=0	n_0=50
Removal, x	0	49.36	1.57		
Cost	0	84.8 million	12.5 million	541 million	697 million
Arrivals	0.00572	0.238	0.238		
y	11.1 million	2.79 million	2.79 million	166 million	139 million
Damage	0	$268	$268	$11,900	$13,400
Total	11.1 million	87.6 million	15.3 million	707 million	837 million

Whether or not we are currently spending "enough" on avoidance or removals depends on the actual number of snakes currently present in Hawaii. If indeed there are no snakes in the state, avoidance expenditures need to be increased more than three-fold, to $11.1 million. However, if there is a small population of close to 50 snakes, optimal policy calls for increased control (from $100,000 to an initial $84.8 million) and approximately the same level of avoidance measures. This result emphasizes the need for better information regarding the current population of snakes in Hawaii.

vi. Status quo vs. optimal policy

It is difficult to compare the optimal program to Hawaii's actual strategy, as we cannot be sure of the government's response in combating BTS at different population levels. We thus derive several alternative scenarios that the government might choose.

Table 2. Losses from following alternative status quo policies

Alternative status quo steady states	Loss vs. Optimal
1	$34.4 m
2.21	$21.1 m
10	$51.9 m
100	$201 m
543	$391 m
10,000	$923 m
N_{MAX}	$24.2 b

In all the scenarios listed in Table 2, authorities continue to spend what they are currently spending each year until they abruptly decide to keep the snake population constant. In the first scenario, the invasive is discovered early (when the population is only 1 snake), and population is maintained at that level. In each succeeding scenario the government switches policy later and allows for a higher number of snakes to remain on the island. Our final scenario observes what happens if the current policy is continued without change.

As we can see, improper management of BTS can easily cost Hawaii tens of millions of dollars. Even if the problem is ignored only until we reach the optimal population of 2.21 snakes, $20 million in value is still lost. The situation is much worse if ignored even longer. If the status quo is maintained until the snake population reaches 10,000 snakes, over $900 million is forgone, which itself is still less than a tenth the cost of letting the snakes roam freely. If the snakes multiply until they reach carrying capacity, we suffer a loss of over $24 billion.

Even though we should not expect that the state would knowingly let BTS reach its carrying capacity in Hawaii, the potential invader is a real threat to our own well-being.

V. Limitations and Directions for Further Research

Using optimal control theory, we generate appropriate comparisons for policy options concerning a potential invasive species. In the cases above, we show that optimal policy will likely require expenditures that differ from current avoidance and removal activities. However, how current expenditures should change is radically different depending on what the starting population is. Because of the massive uncertainty surrounding issues such as initial populations and the probability of arrival and establishment, our analysis suggests early detection of small populations is crucial. Therefore, we recognize that our biggest limitation in assigning an optimal policy is the lack of concrete information, particularly in regards to current population size.

In computing the optimal outcome, we also encountered some quantitative challenges regarding the specification of functional forms for all four essential components: growth, damages, costs of removal, and arrivals. In particular, choosing functional forms that both accurately reflected our understanding of the biological and economic processes and resulted in computationally feasible equations required several simplifications upon which further research might improve.

The deterministic arrival of a fraction of snakes per year was used as an approximation for the probabilistic event of a snake's arrival. Ideally, the model would replace this arrival function with an explicit function describing the probability that a snake arrives in any given period. We made this simplification for two reasons. First, because of the uncertainty surrounding the initial population, building a straightforward probability distribution is highly complex. Furthermore, there is imperfect scientific information concerning the probability distribution of a snake's arrival to Hawaii for obvious reasons.

However, additional scientific information might improve the ability to estimate the probabilities associated with successful establishment. In particular, a better understanding of the probability of a snake mating and reproducing would enhance our ability to estimate accurately assess the probability of establishment separate from the probability of arrival. The scientific evidence from Guam does suggest that male-female ratios are not one-to-one, with perhaps many fewer females than males moving into transport zones (Rodda 2005, personal communication). An extended model of the snakes would also consider the extent to which future introductions matter, which should be rapidly decreasing with population size.

Despite all of these limitations, we still feel that we have made significant progress towards the determination of optimal BTS policy. Our results suggest that it is more advantageous to spend money finding the small population of snakes as they occur than attempting to prevent all future introductions.

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Appendix 1. Derivation of the damage function

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 per hectare, the carrying capacity for Guam is 2,695,000 snakes. With approximately 272 hours of power outages per year attributable to snakes, we estimate that there are $1.01*10^{-4}$ power outages per snake per year. Fritts and Chiszar 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 on Oahu, in terms of power outage costs, is $121.11.

Guam has experienced a snake-bite frequency average of 170 bites per year, at an average cost of $264.35 per hospital visit. Thus the expected number of bites per snake per year is at least $6.31*10^{-5}$, implying an expected cost of $0.02 per snake. Oahu's population density below 1,400 m is approximately 3 that of Guam's, so we adjust the expected costs for Hawaii to $0.07 per snake.

The Brown treesnake has extirpated 61% (11 of 18) of Guam's native bird population since its arrival (USGS 2005). 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 8 endangered bird species on Oahu whose main habitat is below 1,400 m and are at considerable risk of extirpation.

To obtain a conservative interval estimate, we assume that the birds are valuable to households on Oahu alone. We assume that at carrying capacity, there is roughly a 98% chance of losing a single species and another 5% chance of losing a second bird species. Using an expected value to 280,000 Oahu households of losing one species of $8.68 million, the expected per snake damage level is $1.13 per year, assuming that each snake is equally likely to contribute to the extirpation.

Thus, expected damages from human health factors, power outages, and expected endangered species losses can be expressed as:

$$D = 122.31 \cdot n_t \,.$$

Appendix 2. The Removal Cost Function

For simplicity's sake we chose to start with a cost function whose marginal cost of removal was dependent of the stock of the invasive, but independent of the harvest rate.

Parameterization of our cost function was entirely based upon information provided by Gordon Rodda (personal communication). Rodda studied an enclosed area of 5 hectares containing roughly average levels of both snakes and prey for over a year. During that time, he observed the life cycle patterns, relative sizes, and most importantly to our study, the success rates of two capture techniques. The first method, setting traps, had a relatively high success rate with larger snakes but was completely ineffective at capturing the smaller ones. Visual searches, on the other hand, had much lower success rates than trapping, but were able to 'catch' all sizes of snakes. In Rodda's enclosure study, all 'capture' data was collected and the individual was recorded and then released back into the enclosure. This enabled a detailed study of individual snake heterogeneity. Results are presented below.

Rodda estimated that were these methods put into practice on Hawaii, each night of trapping would cost roughly $150 per 5-hectare area, whereas visual searches would cost closer to $300 per area per night. We then estimated the expected number of nights to catch a single snake if somewhere on the island by each of the two methods. We also calculated the fraction of a night (or fraction of the island searched) before the first of 100 snakes were found by each of the two methods. Because in a steady state situation where larger snakes were continually trapped and removed, we estimated the distribution of a steady state population where trapping was frequent. From there we estimated that due to the rapid growth rate of the snakes, even when the larger snakes were killed off, we could still employ mostly trapping to catch the younger snakes as they grew. Thus our final cost function is based upon spending 1/6 of our time with visual searches and the other 5/6 removing the population through trapping.

Appendix 3. The Arrival Function

The Poisson Distribution

The Poisson distribution is the limiting distribution of a series of Bernoulli trials as the time over which those trials take place approach zero. In our particular case this allows us the ability to predict the expected number of snake arrivals over any given period of time so long as a few conditions are met:

a) At least one probability of arrival for some number of snakes over a given amount of time is known
b) Snake arrivals can take place on a continuous time basis with no one time more probable than any others
c) Each snake arrival is independent of any others (note: this does rule out a group of snakes arriving together)

Once we know that the probability of x snakes arriving over the course of y days (or years or seconds), then we can use this simple formula to determine the Poisson distribution’s primary parameter, λ, by means of the following formula:

$P(x) = \frac{e^{-\lambda}\lambda^{x}}{x!}$ over the given period of time. One interesting result of this is that λ is both the expected value of the trial as well as the standard deviation.

In our particular case, we know from conversations with snake managers and scientists that the probability that there are exactly no snake arrivals (under certain conditions) over the course of 10 years is roughly 0.1. From our formula above, we can determine that for any given 10 year period, P(0)=e^-L because x=0. Thus, λ would equal-ln (.1)= 2.30259. Thus we would expect to have 2.3 snakes arrive over a 10 year period with a standard deviation also of 2.3. If we wanted to calculate the probabilities of specific numbers of snakes arriving in the 10 year period we could then plug the appropriate numbers into x in the formula above.

Table A1. Calculating snake arrivals using the Poisson distribution

Avoidance expenditures (y)	Probability that at least 1 snake will arrive in 10 years	Probability that no snake will arrive in 10 years	Probability that no snake will arrive in a given year ($f(0)$)	Implied Poisson λ ($\lambda = -\ln[f(0)]$)
2.6 million	0.9	0.1	$0.1^{1/10} = 0.794328$	0.230259
4.7 million	0.45	0.55	$0.55^{1/10} = 0.941968$	0.059784
9 million	0.2	0.8	$0.8^{1/10} = 0.977933$	0.022314

The Weibull Distribution

The Weibull distribution takes the form $f(x) = e^{(a-bx^c)}$. The Weibull distribution was chosen primarily because it had several nice properties. First of all, we assume that the first dollar spent on prevention would be much more effective than the billionth dollar spent on control, but that every increase in spending would decrease the probability of arrival (and thus the expected value). A strictly decreasing convex function was thus desired. We also assume that as spending increased a perfectly impenetrable barrier with no BTS arrivals was approached. The Weibull also has the nice feature that the limit as prevention expenditures goes to 0, of marginal snakes prevented approaching infinity. This guarantees that we will spend on prevention in every period.