Title:

Spatial Economic Analysis of Early Detection and Rapid Response Strategies for an Invasive Species

Authors:

Brooks A. Kaiser, Gettysburg College, Department of Economics, 300 N. Washington St. Gettysburg, PA 17325 USA

Kimberly M. Burnett, University of Puget Sound, Department of Economics, 1500 North Warner St. CMB 1057 Tacoma, WA 98416 USA

Corresponding author:

Kimberly M. Burnett, University of Puget Sound, Department of Economics, 1500 North Warner St. CMB 1057 Tacoma, WA 98416 USA
Phone: 808-779-1884
Fax: 808-956-4347
kburnett@hawaii.edu, kburnett@ups.edu

Word Count: 7,684

Summary

Economic impacts from invasive species, conveyed as expected damages to assets from invasion and expected costs of successful prevention and/or removal, may vary significantly across spatially differentiated landscapes.

1. In this work, we consider the effect of these spatial differences on early detection and rapid response (EDRR) policies, commonly exploited in the management of potential invaders around the world, for the Brown treesnake (Boiga irregularis) in Oahu, Hawaii. EDRR consists of search activities beyond the ports of entry, where search (and potentially removal) efforts are targeted toward areas where credible evidence suggests the presence of an invader. EDRR costs are a spatially dependent variable related to the ease or difficulty of searching an area, while still assuming damages to be a population dependent variable.
2. Optimal EDRR search targets limited areas of high expected net damages. Only 8% of the island needs treatment in a thirty year period, if it is applied efficiently. Inefficient search can be extremely costly, if it is random or incomplete. However comprehensive island-wide searches can reduce social welfare damages and may have additional external benefits, especially if prevention at entry points is highly effective at reducing the hazard rate.
3. Optimally applied EDRR that integrates the costs, damages, and biological parameters of the snakes' potential presence can save the island $270m in present value losses to social welfare over 30 years.
4. **Synthesis and applications:** Our results have the following implications for invasive species management and policy. First, treating EDRR as a separate but

vital link between prevention at points of entry and control of known populations allows for insights into the costs of delay at low or uncertain invasion population levels. Second, in spite of the fact that eradication through concerted island-wide sweeps can be profitable, it is not optimal. Finally, search should not be limited to the incoming points of entry. EDRR should be applied to high population density areas as well as areas that serve both as conduits to new territory (roads) and areas that would experience particularly high damages from high snake populations in them.

Keywords: brown tree snake, early detection, invasive species, Oahu, rapid response, spatial analysis

1. Introduction

Management of invasive species presents spatial and temporal analytical challenges that require integrated biological and economic parameterization. Hitherto, applied research on optimal prevention and control of the Brown treesnake (Boiga irregularis) in Hawaii has not accounted for either early detection and rapid response (EDRR) or spatial variation in an effort to focus clearly on the intertemporal tradeoffs in invasive species management. In this paper, we exploit the significant biological and economic research to date on the potential ecological and economic damages and costs of the Brown treesnake's imminent arrival in Hawaii (Rodda *et al*. 1992; Rodda *et al*. 1999; Burnett *et al*. 2006; Shwiff *et al*. 2006) as a case study to develop a spatially explicit, comprehensive intertemporal EDRR management strategy to minimize the expected impacts of a potential invader.

We advance the current literature in several respects. First, we consider EDRR, a real-world policy instrument commonly exploited in the management of potential invaders around the world, although not explicitly analyzed as a policy option in the literature to date. EDRR consists of search activities beyond the ports of entry, where search (and potentially removal) efforts are targeted toward areas where credible evidence suggests the presence of an invader. While some previous work has optimized management decisions over space and time (Livingston *et al*. 2004; McKee *et al*. 2006), our model focuses on these important EDRR costs, which are a spatially dependent variable related to the ease or difficulty of searching an area, while still assuming damages to be a population dependent variable. EDRR should not be simply considered either ex-post prevention or low-population control and deserves much greater analytical attention. Prevention differs from EDRR particularly as the opportunities for reaping high returns are foregone once a species has successfully passed any bottleneck entry conditions where intervention could occur. Control differs from EDRR particularly as control can be considered harvest of an unwanted species and planning can compare population-dependent harvest costs with population-dependent damages.

Second, we attempt to mimic real decisions facing managers with long run intertemporal consequences by examining decisions made across brief time horizons and assessing the impact of this myopia. Previous work focusing on long-run intertemporal tradeoffs has rightly been criticized for its lack of a spatial dimension. We also show here how spatial analysis without an appropriate intertemporal scale is likely to skew analysis and some implications of that distortion, even within a relatively short time horizon of thirty years.

2. Background and literature

Economic impacts from invasive species, conveyed as expected damages to assets from invasion and expected costs of successful prevention and/or removal, may vary significantly across spatially differentiated landscapes. Species often exhibit both positive and negative attributes or otherwise vary in the level of net damages (Kaiser 2006; Nicholson 2006; Paynter *et al*. 2006; Zivin *et al*. 2000). When these are spatially separable, i.e. when damages vary by landscape characteristics, policy decisions should incorporate this additional information to improve asset allocation in the search to minimize the total cost of the damages and management activities. All other conditions equal, we should target mitigation activities in areas where the return, in damages avoided, is highest, and these activities should continue as long as the present value returns to the endeavor are at least as high as the returns from other investment opportunities.

All other conditions for mitigation activities are rarely equal, however. Policy must also incorporate variations in the present value expected costs of these efforts. The magnitude of the effect of costs on optimal invasive species may be significant, given the findings of Ando *et al*. (1998) with regard to the impact of costs on optimal conservation of land for endangered species.

Management of invasive species is further complicated by the political expediency of ignoring the problem until it grows into a visible and expensive threat. This is in part because with typical discounting, pushing costs into the future reduces their present value, so that reducing prevention efforts may seem cost effective *a priori*. Additionally, in the presence of uncertainty about the need for such control activities, uncertain prevention efforts may similarly be inefficiently delayed in favor of certain, but more costly, control efforts (Finnoff *et al*. 2007).

Prevention and control, however, are distinguishable in many cases not just by the fact that prevention targets species that may or may not ultimately cause economic or ecological disruption, while control efforts target reductions in existing disruptors, but also by the fact that prevention activities target pathways of invasion that may be spatially limited by primarily economic considerations, while control activities' spatial limitations are a combination of biological and economic factors. For example, entry pathways for new invaders to remote islands are almost entirely human-assisted and will occur at sea or air ports of entry. Spread of an invasive species from that entry point, however, will be a species-dependent function of both local economic transport routes (e.g. Timmins, 2006) and biological growth (Christen and Matlack, 2006; Shigesada and Kawasaki 1997).

In this light, prevention of invasion and removal of successful entrant species may be viewed as both complementary and competing technologies for control of invasive species threats. The boundary between complementarity and competition is particularly clear in the case of EDRR efforts, where costly searches for possible invading populations must often extend far beyond the ports of entry targeted by prevention, yet may result in no captures. EDRR is a distinct management instrument and cannot be considered a typical prevention or control effort. The success or failure to adequately fund EDRR efforts is frequently cited as a major contributing factor to mitigating impacts of invasive species (e.g. New Zealand successfully intercepted *Solenopsis invicta* and *Lymantria dispar* at the border; while the lack of appropriate EDRR systems has been blamed for the spread of *Avian Influenza* globally) so the ability to more economically deploy these resources should have a significant effect on the success of invasive species policy.

In this paper, we address the effect of spatial variation in damages, costs, and biological growth on policy instrument choices over time using the case study of the Brown treesnake on the island of Oahu, Hawaii. The Brown treesnake has caused significant economic and ecological damages on Guam in the form of power outages, biodiversity losses, and medical costs related to snake bites (Savidge 1987; Fritts *et al.* 1987; 1990; 1994). There have been eight Brown treesnakes captured at the ports on the island of Oahu and hundreds of other sightings reported throughout the island. EDRR technology has been developed in the form of specially trained teams based throughout the Pacific who are immediately deployed following a credible sighting of a Brown treesnake on Oahu or on other at-risk islands. Two such deployments have occurred in Hawaii in the last two years, one on the island of Maui and the other on Oahu, although neither effort produced a snake.

Using Geographical Information Systems (GIS) software, we analyze spatially-explicit EDRR policies given the reality that prevention of the snake's entry may already have failed or will eventually fail at least one of the most likely entry points, regardless of budget (Olson and Roy 2005; Burnett *et al*. 2006). EDRR policies comprise of search and destroy activities that occur beyond incoming crafts at points of entry (prevention) to target removal of uncertain but likely specimens throughout the potential habitat range that have evaded detection. Intertemporal and spatial differences in policies are compared given varying assumptions about the manager's planning and management horizons and the arrival of the snake.

3. Methods

3.1 Overview

Spatial analysis using geographical information systems (GIS) software and integrating biological parameters with economic ones can assist in developing optimal prevention and EDRR policies for invasive species. Layers of information regarding four main factors affecting the Brown treesnake's expected impacts on Oahu are coalesced through GIS to assess the net expected benefits of policy action in EDRR. The four decisive factors that encompass the policy choices for any given set of spatial conditions are the probability of arrival, biological growth potential, resource assets at risk, and cost of management activities. We investigate across thirty years of potential snake presence to establish the initial benefits of EDRR.

Consider that Oahu's 1,500 square kilometers are divisible into a grid of approximately 38,000 cells measuring 4 ha each. Each cell is assigned initial properties that include currently existent data on likelihood of snake presence (distance from points of entry, proximity to roads[1]), resource assets at risk (bird habitat, presence of power transmission lines, human population density) and accessibility of treatment (proximity of roads and trails, slope, and land ownership).

From these initial conditions, we estimate expected snake populations for each cell across a thirty year period based on the likelihood of the presence of snakes, the expected marginal damages (per snake) as a function of the resources at risk and the marginal costs (per 4 ha area) as a function of accessibility and terrain. Figures 1-3 illustrate these parameters.

Using this information, we build a spatial-intertemporal model that minimizes the expected net damages from the Brown treesnake on Oahu. Since treatment decisions are EDRR search decisions, the unit of decision is the spatial cell rather than the snake population directly. Net expected damages are calculated for each cell by assuming that

[1] We have more specific information about habitat than distance from points of entry, but after extended discussions with several Brown treesnake scientists it has become clear that the main limiting factor in Hawaii will be the availability of prey, for which we do not have specific densities. Fortunately for our analysis though unfortunately for avoiding the spread of the snake, the one point of agreement between all of the scientists on this matter is that they believe there exists sufficient prey base for snake expansion in all habitats present on Oahu for a population explosion comparable to the one on Guam after its arrival. Thus, since there exists no scientific evidence or theoretical model to credibly believe that forest habitat is more amenable than urban, for example, we accept that there will be abundant prey in every habitat and that differences for the snake will be minimal.

treatment clears an area of snakes for that time period, so that population-based damages are avoided. The more cells that are treated in any time period, the smaller the remaining population. We try a series of treatment options meant to mimic real policy decisions and the uncertainty regarding the snake population. These include allowing treatment over each of thirty years and only allowing treatment planning over a five year period, a scenario which more realistically reflects the ability to commit politically determined funds.

3.2 Model

The theoretical model is formalized as:

$$\min_{x_{it}} \sum_i \sum_{t=0}^{T} \beta^t \left(d_i \left(n_{it} \left(x_{it}, \sum_i x_{it} \right) \right) + C_i(x_{it}) \right)$$
$$s.t.$$
$$n_{it} = n(r,t,x) = \left(\frac{\sum_i x_{i,t-1}}{I} \right) g(n_{t-1}, r) * (1 - x_{it})$$
$$\sum_i C_{it} \leq A_t$$

Where d_i is the expected damage for cell i, n_{it} is the population of the cell at time t as a function of own-cell (x_{it}) and other-cell (x_{jt}) EDRR treatments, C_i is the cost of EDRR for cell i, I is the total number of cells, g is the biological growth function which depends spatially on the distance from the expected start of the invasive population, β represents the discount factor, and A_t represents a temporally constrained appropriations budget for EDRR.

Spending C_i brings the population for period t to zero for an area, but invasion from other parts of the island, or anew from off-island, re-initiates growth in the next period. The larger the proportion of treated cells $\left(\frac{\sum_{i=1}^{I} x_{i,t-1}}{I}\right)$, the lower the rate of re-growth.

3.3 Model components

3.3.1 Population

Figure 1 shows expected expansion patterns of the snakes from an initial invasion at the Honolulu Airport (HNL) or the adjacent Hickam Air Force Base Airport, Schofield Barracks and Barber's Point Air Station. These are selected as the most likely points of entry because of the eight Brown treesnakes that have been intercepted on Oahu, five were at HNL, two were at Schofield (with one of these known to have been transported directly from HNL), and one was discovered at Barber's Point. The expansion path without intervention is based on the estimated expansion rate of 1.6 km/yr (Wiles *et al.* 2003) from the expected origins of the airport runways and Schofield facilities and the terrain through which the snakes must pass. Expected origins were weighted by capture experience on Oahu to date, with HNL being the most likely port of entry. Roads and trails are expected to provide the most rapid expansion paths (Timmins 2006); distance from roads and trails slows the radial spread.

<<Figure 1 here>>

Using the diffusion rate of 1.067 km^2/yr (Shigesada and Kawasaki 1997: 51), the average radii calculated from those illustrated in Figure 1, and the following expansion model, based on Fisher and Skellam (Shigesada and Kawasaki 1997), we determine the expected snake population in a given cell at a given time period. We assume the population changes as a function of both diffusion and internal growth:

$$\dot{n} = D\left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2}\right) + \left(b - \mu n\right)n \qquad (1)$$

Where *n(x,y,t)* is population at time *t* in spatial coordinate *(x,y)* as measured from the original specimen's location, *D* is the diffusion rate, *b* is the intrinsic growth rate, $\mu \geq 0$ captures intraspecific competition, and *x* and *y* are spatial coordinates, and the radial distance, *r*, is determined by $r^2 = x^2 + y^2$. The first term captures the rate of spread, the second captures population growth within the given coordinates. We estimate from maximum densities experienced on Guam that the maximum snake carrying capacity in any cell (*K*) is 200 snakes.

Because there is no explicit solution to this non-linear problem unless $\mu = 0$, in order to create a tractable model that incorporates both spread and internal growth, we use the solution to the Skellam model for exponential growth and spread (i.e. $\mu = 0$) until the population of the cell reaches the point where it diverges significantly from a logistic growth function with a capacity of 200 snakes, which occurs at approximately 40 snakes. From that point, we use a logistic growth function to determine population in an area. We do not simply use the logistic function because it does not allow for radial spread to and from other cells.

Assuming an initial distribution where n_0 individuals invade the origin at t=0, we have untreated populations

$$n(r,t) = \frac{n_0}{4\pi Dt}\exp\left(bt - \frac{r^2}{4Dt}\right), \tag{2}$$

until $n(r,t) \geq 40$. After this point,

$$n(r,t) = n_r\left(\frac{Ke^{bt}}{K + n_r(e^{bt} - 1)}\right), \tag{3}$$

where n_r is the population (e.g. 40) when the growth function changes.

3.3.2 Damages

Figure 2 illustrates the range of damages across Oahu. Damages are calculated using a per snake linear coefficient that varies from a minimum of \$0 and a maximum of \$2143 (Fig. 2a). Damages consist of three potential impacts: power outages (Fig. 2b), medical costs and human-snake interactions (Fig. 2c), and biodiversity losses (Fig. 2d).

<<Figure 2 here>>

3.3.2.1 Power Outages

First, Brown treesnakes are known to cause frequent power outages by damaging power transformers and power lines. Localized hour-long power outages on Guam occur on average every other day, with less frequent wide-scale power outages when snakes interact with main power lines or transformers. We anticipate that an average snake will cause 1.01×10^{-4} power outages per year, that per-person power outage damages are $1.50, and that an island-wide power outage causes $1.2 m in damages (Fritts 1998, personal communication; Burnett *et al*. 2006). Thus, cells where only localized power outages are expected will have expected damages equal to the population in the cell (determined from census 2000 census block population density figures) times per-person damages times the per-snake rate of outages, or $d_{pl} = popn * 1.5 * 1.01 \times 10^{-4}$. Cells where main power lines are located have expected damages of:

$$d_{ph} = 1.2 \times 10^{6} * 1.01 \times 10^{-4} * power = 121.2,$$

where power is an indicator variable for whether main power lines are present in the cell.

3.3.2.2 Medical Costs

Second, Brown treesnakes are venomous and Guam's infestation has generated an average of 170 bites per year with average costs of $264.35 per bite. This is an expected per-snake bite rate of 6.31×10^{-5} for Guam. We generate a bite rate for each Oahu cell by multiplying the Guam per-snake bite rate by the population density of the cell (again from the census block 2000 data) adjusted by the population density on Guam (United

Nations 2001). Using this bite rate, we then calculate the expected direct medical damages as the bite rate*average costs.

Additionally, Hawaii has no snakes at present; human-snake interactions are expected to reduce tourism and local quality of life significantly (Shwiff *et al*. 2006). Following conservative estimates for patterns of legal settlements of compensatory versus punitive damages for psychological suffering and other intangible losses (Eisenberg *et al.* 1997), and other evidence on the ratio of physical damages to psychic ones, including U.S. congressional recommendations for limiting punitive damages to no more than three times the physical damages (Kahneman *et al*. 1998), we use the anticipated physical medical damages as a minimum per-person estimate in the loss of well-being generated by the snakes to generate an indirect 'medical cost', so that total human-snake interaction damages for each location are estimated at $d_m = biterate * popn * \$264.35$.

3.3.2.3 Biodiversity Losses

Finally, adult Brown treesnakes prey upon birds, and Oahu's endangered birds, which have not co-evolved with snakes, are likely to fare as badly as Guam's indigenous birds have. On Guam, 11 of 18 indigenous species (Vice 2006, personal communication) have been extirpated. On Oahu, one native bird species occurs on island (Elepaio, *Chasiempis sandwichensis ibidis*) and its habitat covers only about 26,400 ha of the 1,500 square kilometers. Other birds at risk have habitat on other islands and are less likely to be rendered extinct through the presence of the snake, though the population losses will increase the probability of extirpation and extinction. Cells with habitat for the elepaio are estimated to have per snake damages of $6.52, based on willingness-to-pay estimates determined for households in Hawaii for the existence of bird species, and cells with other native bird habitat are estimated to have per snake damages of $1.13 (Loomis and White 1996; Burnett *et al*. 2006).[2] Biodiversity losses are thus

$$d_b = 6.52 * elepaio + 1.13 * otherbird,$$

where *elepaio* and *otherbird* are indicator variables for the presence of elepaio and other native bird habitats, respectively.

The overall damage function for each cell is therefore $d = d_{pl} + d_{ph} + d_m + d_b$.

3.3.3 Costs

As discussed, a particular distinction between EDRR and other discussions of invasive species control is that with EDRR it is not known with certainty that there exists a population, while with control one generally assumes one can "harvest" a known population of the invasive species. We describe EDRR treatment as consisting of preventative search, trapping and hand-removal (the only way to currently remove snakes too small to be trapped). Costs vary with terrain. Records on the costs of clearing an enclosed 5 ha plot on Guam (Rodda, personal communication) provide a least cost estimate of removing snakes from an area. Costs are scaled up from this base cost of $6,352 per 4 ha cell to account for slope of the terrain and distance from a road. The steeper the grade, the more energy required to search the area. Since the cost of

[2] The expected per snake damage level for other bird habitat is estimated by assuming that at carrying capacity, there is roughly a 98% chance of losing a single species and a 5% chance of losing a second bird species. With 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. The damage estimate for the elepaio is similarly calculated by assuming that the presence of the snake at capacity level in every habitat location will result in extinction, thus the per snake damages are $8.68 million/(6654 cells*200 snakes), or $6.52.

searching is a labor cost, we use a model of the American College of Sports Medicine to translate grade into energy expenditure, and then increase costs proportionally to the increase in effort. The energy expenditure rate (EER) is estimated to be:

$$EER = 0.1v + 1.8v \cdot a + 3.5 \qquad (4)$$

Where *v* is the speed of walking and *a* is the percent grade (Sabatini *et al*. 2004). We assume a constant slow rate of walking at 0.5 km/hour to accommodate searching (Rodda, personal communication, Lardner, personal communication). Average slope for each cell is calculated from hillshade projections of Oahu in ArcGIS 9.1. Figure 3 illustrates total costs.

<<Figure 3 here>>

For each cell, we first calculate the energy expenditure rate, EER. We then generate an energy expenditure ratio where we divide the cell's EER by the EER when the slope is zero, which provides an estimate of how much more difficult clearing the cell is than clearing the 5 ha test plot (which was on level ground) cost. This ratio is therefore multiplied by the base cost of $6352. The maximum cost for thoroughly searching a cell for EDRR purposes using this formula is approximately $27,500, while the average cost is $11,700.

Costs also increase with the distance of the cell needing treatment from accessible roads. We use analogous methodology to determine distance costs from roads by using

ArcView Spatial Analyst to calculate the least cost distance path. First, based on the EER from the nearest road to the cell, we determine the least cost EER path from the nearest road to the cell. Then we create a ratio of this distance cost to the linear distance from the road. We then multiply this ratio by the labor cost of reaching the cell, estimated at $60 per unit. The maximum access cost is approximately $3420, while the average is approximately $540. The total cell cost is then the sum of the in-cell treatment cost and the distance (access) cost.[3]

4 Application

We transfer the grid data from a GIS format to a spreadsheet format for intertemporal analysis and optimization. We use Palisade's Evolver Industrial Version, a genetic algorithm solver add-on to Microsoft Excel, for analysis.[4] For each spatial cell, the population is calculated using Equations 2 or 3 as appropriate for 30 years from an initial expected invasion and allowing for EDRR treatment of the cell so that population is reduced to zero for that period. Treatment of a cell returns the base population to $n(r,1)$, the expected re-infestation from diffused growth, at a cost of C.

In each new period, this base population is also mitigated by the overall treatment level on the island; if the entire island were to be searched then the population would fall

[3] Note this does not allow for treatment in multiple adjacent cells at discounted distance cost. However, since this method also assumes only one treatment time necessary (rather than repeated nights of search) the net effect is unclear. We leave this for later modeling. We also delay modeling of any external cost to accessing private land. One possibility is to assume that gaining access to private land and/or convincing private landowners to engage in search activities themselves is one of the main purposes of awareness campaigns, and that expenditures targeting awareness of a species can be considered additional costs of treating private land. In the case of the Brown treesnake in Oahu, this amounts to only about $3 per cell of private land, thus we have ignored this cost for now.

[4] As computing power increases, policy managers will be able to integrate even seemingly simple software like MS Excel into their decision-making tools. By using this program, we hope to provide a blueprint, in anticipation of the rapid pace of technological change, of how such analysis, using widely available data as in this case, can become a more standard management tool.

to zero and no damages would occur until another invasion. We model conservatively and assume that a new snake arrives in the next year (alternatively, that a snake is missed). If no treatment occurs, the population grows according to its biological limitations. For all other levels, the population of each cell is reduced by the percentage of treated cells on the island. Though this does not treat neighbors of treated cells differently, the Skellam growth model already incorporates the distance from the initial invasion and thus treatment will reduce growth proportionally. The simplification is necessary for computational feasibility. Expected damages are calculated for each cell as a function of whether it is treated or not and its population; net damages for a cell are equal to either untreated damages or the cost of treatment. The present value of net damages over all cells for thirty years is summed and forms the object of minimization.

Currently, no known snake populations exist on Oahu, but there is general agreement amongst the scientific community that there may be between 0 and 100. We begin our analysis with n_0=1. Mitochondrial DNA evidence suggests that the entire population of snakes on Guam may have originated from a single female. Thus, our initial application is for search only. Current search on Oahu occurs only after a suspected sighting, while all other funds are expended on Guam and are targeted at preventing snake arrival at defined points of entry. Previous research (Burnett *et al.* 2006) indicates that this may actually focus too much on the points of entry if snakes have already evaded detection there. Our results concur.

We calculate the spatial-temporal treatment schedule that minimizes the overall net damages and costs in present value terms for a thirty year period. Furthermore, given temporal and/or financial budgets, our method of analysis can identify where search should be currently occurring, across the landscape, for maximum benefit. We can determine whether overall spending is too little or too much – too little if the budget is spread too thin to do any permanent good; too much if we are searching for highly unlikely snakes now. This analysis should improve Hawaii's ability to minimize damages from this imminent threat and provide a methodology for other planners wishing to optimize limited invasive species budgets.

5 Results

The large number of choice cells that result from considering each 4 ha plot every year for thirty years (approximately 1.1 million cells) requires significant processing time to determine a globally optimal minimization solution without some assistance. We start from a present value of expected damages of $371 million accumulated over 30 years from an initial invasion of a single snake at one of three possible entry locations with no EDRR action. We start the optimization with treatments indicated for all cells when and where the current year damages exceed the current year costs, treatment of which will certainly reduce the social welfare losses. From there, evolver seeks to determine if treating the cell either earlier, or treating other cells, reduces overall damages. This could be the case as the more cells are treated, the lower the growth in the next period, as defined in n_{it}. Through iterative trials, EDRR treatment is applied to cells by the algorithm in an effort to reduce these net damages. For our parameters, it does not appear that there is sufficient long run benefit to treating cells in which the present value of net damages is negative in that time period, unless the cells will not, for some reason (such as budget), be treated at the first period in time where the damages exceed the costs.

We find that optimal treatment reduces social welfare losses to $101 million dollars. Over the thirty year period, we find the need to treat just over 3000 cells, or 8% of the island. The treatment plan also delays any search until the 12th year after an invasion. This result is driven by the interplay between the discount rate and the growth function; the chances of finding snakes when they are spreading out across the potential habitat and are at low densities, and causing low damages, mean that waiting discounts the costs more than the growth in the damages.

Nonetheless, there may be some benefit to periodic island-wide sweeps. We investigate the returns to island-wide sweeps at various stages to highlight these tradeoffs. The cost of a complete island search is estimated at just under $447 million. In the worst case scenario, if an island-wide search is conducted, and then another snake enters in the following year with no follow-up treatments, the total social welfare losses are $771 million, far more than never conducting the search.

However, if a single island-wide search is conducted between years 11 and 27, the net benefits of the search are positive, even with re-infestation the next year. Social savings range from $18 million to a peak of $120 million before they begin to fall again and become negative after year 27. This is due to the fact that the damages grow exponentially with the expansion of the snake, so that while the present value of the costs is constantly falling, the damages from the spread of the snake outpace the discounting of the future damages. Waiting until year 30, for example, will have total social losses of $523 million. Thus, the use of a lower discount rate might actually deter EDRR activities because the costs will appear higher for a longer period; using a 3% discount rate, the damages do not start to grow rather than decrease until year 16. At year 15, even with exponential growth, no cell has greater than 28 snakes, just over 10% of carrying capacity. This begins to change rapidly in years 15 to 30. Figure 4 illustrates.

<<Insert Figure 4 here>>

Another likely restriction for managers is the inability to plan for EDRR funds over a long period of time. We investigate what the optimal policy should be if funding can only be secured in 5 year increments. In this case, we find that at the end of the first 5 years, if there is uncertainty regarding future funding, one is best off treating a small number of cells with high net expected damages, reducing the overall expected cost by about $150 m to $227m. Treating a slightly larger group of high expected damage cells after another five years reduces damages to $142 m, while additional treatments at years 15 and 20 reduce the damages to $126 m. Compared to the periodic island-wide sweeps, this targeted EDRR activity is preferable, in spite of the fact there may still be snakes present. Furthermore, it suggests that taking decisive and targeted EDRR action, even though it may not be the optimal action, is more likely to reduce overall damages than to increase expenditures, especially when those expenditures are large.

Extensive but random search, however, is likely to raise costs more than reduce damages, unless it is comprehensive (island-wide) and occurs between the 11th and 27th year of a successful invasion. When search is random but incomplete, the present value of social costs regularly lie between $450 and $750 million. Successful damage-minimizing EDRR activities target areas that have high expected net damages, either because they have a combination of high expected populations, high asset values, and low search costs. Small changes in treatment allocations that explicitly weigh expected damages, population growth, and treatment costs can dramatically improve random solutions. Thus, random or incomplete efforts may not be better than doing nothing, but strategic action can dramatically improve outcomes.

The hazard rate (the interval between arrivals) should affect these results in two ways. We have used a thirty year time frame in part because this is the time, given the growth parameters, that it should take for the entire island to have snake populations. In this time frame, damages have just grown to exceed the present value of costs for an entire-island sweep (by year 28), which suggests that is the appropriate time to switch from an EDRR policy to a control policy, where removal of the snake population is undertaken directly.

We estimate elsewhere the hazard rate as a function of prevention expenditures (Burnett *et al*. 2006). As prevention cannot be expected to succeed with certainty as the time horizon extends (the cumulative probability will approach one), we consider the implications of a slower or faster hazard rate in terms of EDRR efforts. For explication, we focus on island-wide sweeps to clarify the effects. If the hazard rate is much slower than the current expected rate of one snake per ten years, given current prevention expenditures, then the expected damage calculation can be extended for additional years without becoming irrelevant due to a high likelihood of re-infestation. Our estimate of $371 million dollars without intervention will grow exponentially as the snake population does, so that island-wide sweeps are likely to become more profitable because their effects will last longer. On the other hand, if the duration between arrivals is considerably shorter, targeted searches are relatively more profitable.

Though delaying initial search until the 12th year after an invasion appears optimal, two caveats are offered that suggest additional benefits to earlier search. First, in an island-wide sweep, scientists may become confident that an early eradication is complete at a lower total cost than $447 million as they gain evidence from the search experience. Second, our damage function is not currently applicable to extension beyond thirty years because of the expected irreversible loss of the elepaio bird species. The 11 bird species extirpated on Guam were lost in fewer than 40 years, and a similar time frame for Hawaii can be expected. Thus if eradication efforts are deferred, the irreversible loss of the species imposes a dramatic threshold damage penalty and reduces the expected benefits of further action, which will then only serve to reduce human-snake interactions and electrical supply damages.

Some previous analyses have focused on the intertemporal progress of an invasion from inception until capacity and provided opportunities for intervention across time (Eiswerth and Johnson 2002; Burnett *et al*. 2006; Kaiser *et al*. 2006, 2007), while others have looked at spatial decisions to treat for invasive species over shorter time frames (Wainger 2006). Our analysis, however, stresses the importance of analyzing both spatially and intertemporally simultaneously.

Figure 5 shows a snapshot of the net current damages (i.e. only the damages in that year) that would occur if all cells were treated in the last year of invasion. In a significant majority of cells, the current damages are below the current EDRR costs (shown in grayscale), and intervention cannot be justified on the basis of current damages alone. The area for which damages do exceed costs (shown increasingly from orange to red), so that EDRR treatment is cost-effective in this single period, are obviously also the areas where optimal EDRR should be targeted. One can see that these cells integrate damages, costs, and the biological spread in such a way that EDRR treatment, when there is only funding for sporadic and incomplete treatment, should focus on not just the areas closest to the most likely point of entry (HNL airport) but also along roadways with major power lines adjacent and in locations where human-snake interactions would be high (the orange areas along the southeastern coast in the later snapshots are the densely populated Honolulu and Waikiki areas). In spite of the level of urbanization, scientists assure us there is plenty of prey available, and as the snake is nocturnal and reclusive snake, it is likely to do well in an urban environment with many places to hide.

<<Figure 5 here>>

6 Discussion

We find that optimal EDRR search targets limited areas of high expected net damages. Only 8% of the island needs treatment in a thirty year period, if it is applied efficiently. Inefficient search can be extremely costly, if it is random or incomplete. However comprehensive island-wide searchs can reduce social welfare damages and may have additional external benefits, especially if prevention at entry points is highly effective at reducing the hazard rate.

Our estimates are conservative in that, as there is no guarantee that there will not be another immediate snake arrival that starts another invasion, we assume that the population after a successful island-wide sweep is one. As discussed above, we investigate the effects of delay and the threat of re-invasion on eradication by asking what the 30-year present value of eradication is in each of the first 30 years of an invasion, assuming the worst case scenario that invasion is immediately followed by re-invasion in the next year. We discover that there is a non-linear relationship in which at first, eradication efforts are quite costly due to the re-invasion, but after just over a decade, deferring costs reduces their present value while damages from the low snake population are still low enough that the net effect reduces the overall present value of net damages. In the 24th year, this tradeoff reverses, the accumulated damages outweigh the deferred costs, and social costs begin to increase from the delay. By the 28th year, the net damages are greater than the damages of taking no action, indicating that the advantages of EDRR in avoiding growth and its associated damages have been lost and it is time to move into control of the invasive species. In short, treatment can wait, but it cannot wait long.

While the new evidence compiled for this study presents a myriad of opportunities for conclusions and controversy, we focus on three main findings we believe will stand the test of time.

First, treating EDRR as a separate but vital link between prevention at points of entry and control of known populations allows for insights into the costs of delay at low or uncertain invasion population levels. In particular, in the (almost certain) absence of sufficient funding to assure eradication, within 5 years of an invasion it becomes preferable to pursue limited EDRR, in most cases even if it is not optimally allocated, as compared to doing nothing. The benefits of imperfectly administering EDRR increase for the first 20-25 years, and then begin to decrease as damages accumulate. Given the handful of captures and the large number of credible snake sightings on Oahu, these results inform us that if the snake did in fact arrive on island even as far back as the 1980's, it is not too late to prevent significant losses in the future by acting today, though the window of opportunity is rapidly shrinking.

Second, in spite of the fact that eradication through concerted island-wide sweeps can be profitable, it is not optimal in our model. Thus, though managers often tout eradication as the best management policy, few economic studies to date, including this one, have been able to verify this. While economic models have proposed eradication as a possible corner solution (Olson and Roy 2005; Burnett *et al*. 2007), few case studies have found that it is preferred over some sort of interior solution. With budget constraints and myopic decision-making opportunities, it is beneficial to know that positive and significant returns can be generated by sporadic and incomplete treatments, especially if they are targeted to areas of high net expected damages. The threat of re-invasion reduces the advantages of eradication, but still eradication could be preferred to unmitigated growth.

Finally, incomplete treatments should not be simple extensions of prevention that focus efforts solely on areas adjacent to points of entry. The simple analytical tools and widely available data used here can be tuned to reduce search costs and increase the reduction in damages. In the case of the Brown treesnake, EDRR should be applied to high population density areas as well as areas that serve both as conduits to new territory (roads) and areas that would experience particularly high damages from high snake populations in them. Certainly areas closer to points of entry are likely to have higher invasion populations, however optimal search efforts will also weigh the net expected damages to locate the most efficient search locations and times.

Acknowledgements: We are grateful to Gordon Rodda, Diane Vice, Daniel Vice, Earl Campbell, Bjorn Lardner, Nate Hawley, Tom Fritts, Stephanie Shwiff, the USDA Wildlife Services staff on Guam and the CNMI-DLNR-DFW staff on Saipan for their insight into this problem.

References

Ando, A., Camm, J., Polasky, S., & Solow, A. (1998) Species distributions, land values, and efficient conservation. Science **279** (5359), 2126-2129.

Burnett, K., Kaiser, B. & Roumasset, J. (2007) Economic lessons from control efforts for an invasive species: *Miconia calvescens* in Hawaii. *Journal of Forest Economics*, in press.

Burnett, K., Kaiser, B. Pitafi, B., & Roumasset, J. (2006) Prevention, eradication, and containment of invasive species: Illustrations from Hawaii. *Agricultural and Resource Economics Review* **35**(1), 63-77.

Christen, D. & Matlack, G. (2006) The role of roadsides in plant invasions: a demographic approach. *Conservation Biology* **20**(2), 385-91.

Eisenberg, T., Goerdt, J., Ostrom, B., Rottman, D., & Wells, M. (1997) The predictability of punitive damages. *Journal of Legal Studies* **26**(2), 623-661.

Eiswerth, M., & Johnson, W. (2002) Managing nonindigenous invasive species: Insights from dynamic analysis. *Environmental and Resource Economics*. **23**, 319-342.

Finnoff, D., Shogren, J., Leung B., & Lodge, D. (2007) Take a risk: Preferring prevention over control of biological invaders *Ecological Economics*, **62**(2), 216-222.

Fritts, T.H., Scott, N.J. & Savidge, J.A. (1987) Activity of the arboreal browntree snake (*Boiga irregularis*) on Guam as determined by electrical outages. *The Snake* **19**, 51–8.

Fritts, T.H., McCoid, M.J. & Haddock, R.L. (1990) Risks to infants on Guam from bites of the brown tree snake (*Boiga irregularis*). A*merican Journal of Tropical Medicine and Hygiene* **42**, 607–11.

Fritts, T.H., McCoid, M.J. & Haddock, R.L. (1994) Symptoms and circumstances associated with bites by the browntree snake (Colubridae: *Boiga irregularis*) on Guam. *Journal of Herpetology* **28**, 27–33.

Kaiser, B. (2006) Economic impacts of non-indigenous species: Miconia and the Hawaiian economy. *Euphytica* **148**(1-2), 135-150.

Kaiser, B., Burnett, K. & Roumasset, J. (2006) Control of invasive species: Lessons from Miconia in Hawaii. *15th Australian Weeds Conference: Papers and Proceedings, Adelaide*, *South Australia* Council of Australian Weed Societies, C. Preston, J.H. Watts, and N.D. Crossman, eds. pp. 663-667.

Kahneman, D. Schkade, D.A., & Sunstein, C.R. (1998) Assessing punitive damages. *Yale Law Journal* **107**, 2071-2153.

Livingston, M., Johansson, R., Daberkow, S., Roberts, M., Ash, M. & Breneman, V. (2004) Economic and policy implications of wind-borne entry of Asian soybean rust into the United States. USDA/ERS Outlook Report No. (OCS04D02).

Loomis, J.B. & White, D.S. (1996) Economic benefits of rare and endangered species: Summary and meta-analysis. *Ecological Economics* **18**(3), 197-206.

McKee, G., Goodhue, R., Chalfant, J., & Carter, C. (2006) Modeling the effect of spatial externalities on invasive species management. Presented at the 2006 AAEA Annual Meetings, Long Beach, CA.

Nicholson, H. (2006) Conflicting values of topped lavender *Lavandula stoechas L.*: the essential oil on a complex issue, pp. 191-194, in C. Preston, J.H. Watts, and N.D. Crossman, eds., *15th Australian Weeds Conference: Papers and Proceedings*, *Adelaide, South Australia* (Adelaide: Council of Australasian Weed Societies).

Olson, L.J, & Roy, S. (2005) On prevention and control of an uncertain biological invasion. *Review of Agricultural Economics* **27**(3), 491-497.

Paynter, Q., Gourlay, H., Peterson, P., Wilson-Davey, J., & Fowler, S. (2006) Predicting the economic benefits and costs of introducing new biological control agents for Scotch broom Cytisus scoparius into New Zealand: how much will biological control of broom harm the New Zealand beekeeping industry? pp. 659-662, in C. Preston, J.H. Watts, and N.D. Crossman, eds., *15th Australian Weeds Conference: Papers and Proceedings*, *Adelaide, South Australia* (Adelaide: Council of Australasian Weed Societies).

Sabatini, A.M., Martelloni, C., Scapellato, S., & Cavallo, F. (2004) Energy expenditure rate in level and uphill treadmill walking determined from empirical models and foot inertial sensing data. *Electronics Letters* **40**(2).

Savidge, J. A. (1987) Extinction of an island forest avifauna by an introduced snake. Ecology **68**, 660–8.

Shigesada, Nanako & Kawasaki, Kohkichi (1997) *Biological Invasions: Theory and*

Practice. Robert M. May and Paul H. Harvey, eds., Oxford Series in Ecology and Evolution. Oxford University Press, Oxford.

Shwiff, S., Kirkpatrick, K., & Gebhardt, K. (2006) The potential economic impacts to Hawaii from the introduction of the Brown Tree Snake. Unpublished report to the Office of Insular Affairs and USDA T-Star Invasive Species Group.

Timmins, S. et al. (2006) Environmental weeds along New Zealand roadsides: An initial assessment in C. Preston, J.H. Watts, and N.D. Crossman, eds., 15th Australian Weeds Conference: Papers and Proceedings, Adelaide, South Australia (Adelaide: Council of Australasian Weed Societies).

United Nations, Population Division. (2001) Population, environment and development. Report at http://www.un.org/esa/population/publications/pdewallchart/popenvdev.pdf , Accessed November 1 2006.

Wainger, L. & King, D. (2006) Choosing efficient treatment options by assessing costs and benefits in a spatial risk-based optimization framework. Presented at PREISM invasive species workshop, October 20, 2006.

Wiles, G.J., Bart, J., Beck, R.E., Jr., & Aguon, C.F., 2003. Impacts of the Brown treesnake: Patterns of decline and species persistence in Guam's avifauna. *Conservation Biology* **17**(5), 1350-1360.

Zivin, J., Hueth, B., & Zilberman, D. (2000) Managing a multiple use resource: The case of feral pig management in California rangeland. *Journal of Environmental Economics and Management* **39**(2), 189-204.

Appendix: Geographical Information System Data Sources

Spatial variable	**Layer**	**Source**
Oahu coastline	Coastline	USGS Digital Line Graphs, 1983 version.
Slope	100 Foot Contours	USGS Digital Elevation Models (DEMs), 1:24,000, 10 meter.
Population density	2000 Census Blocks	US Census Bureau, accessed from www.geographynetwork.com (May, 2001)
Distance from roads	DLG Other Roads	USGS Digital Line Graphs, 1983 version
Distance from trails	Na Ala Hele State Trails and Access System	State Department of Land and Natural Resources, DOFAW, 2000.
Bird habitat	Bird Habitat Ranges (Version 1)	Forest bird boundaries were digitized from maps found within J. Michael Scott's book, 'Forest Bird Communities of the Hawaiian Islands: Their Dynamics, Ecology and Conservation.' Water bird boundaries were digitized from USGS paper maps These maps were provided by DLNR's Division of Forestry and Wildlife (DOFAW).
Critical bird habitat (elepaio)	Critical Habitat Layers	U.S. Fish and Wildlife Service, Pacific Islands Office, 2004
Government land ownership	Government Landownership	C&C of Honolulu, Kauai County, Maui County, Hawaii County (2006)
Power lines	DLG Pipes and Transmission Lines	USGS Digital Line Graphs, 1983 version

*All datum NAD 83, with Projection UTM, Zone 4 (Meters).

Figures

Figure 1: Expected annual snake expansion, entry at HNL (3/4 weight), Barber's Point (1/8 weight) or Schofield (1/8 weight)

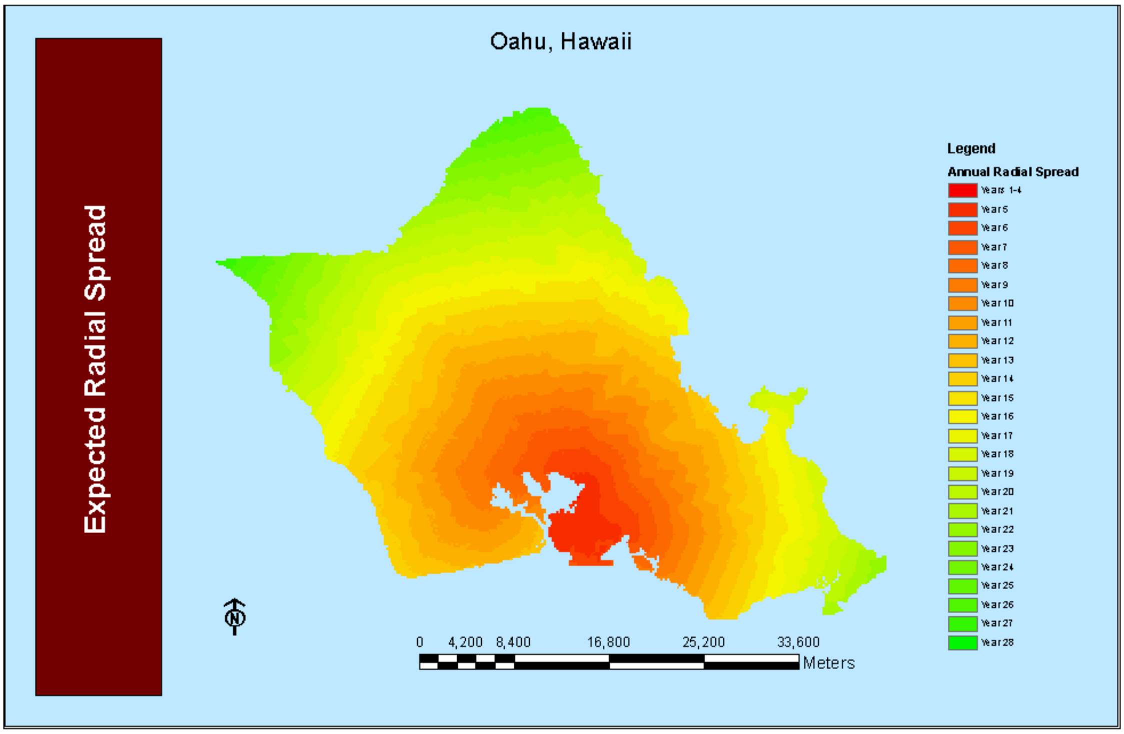


Figure 2: Damages

Figure 2a: Marginal Damages

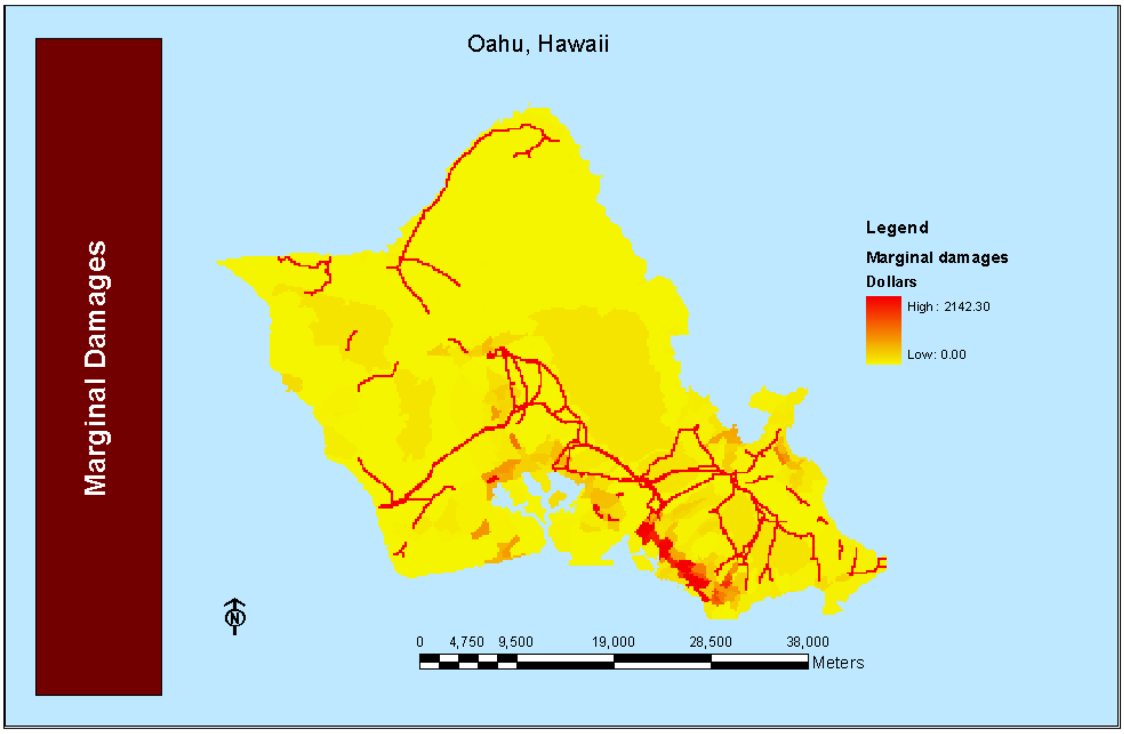


Figure 2b: Damages from Power Interruptions

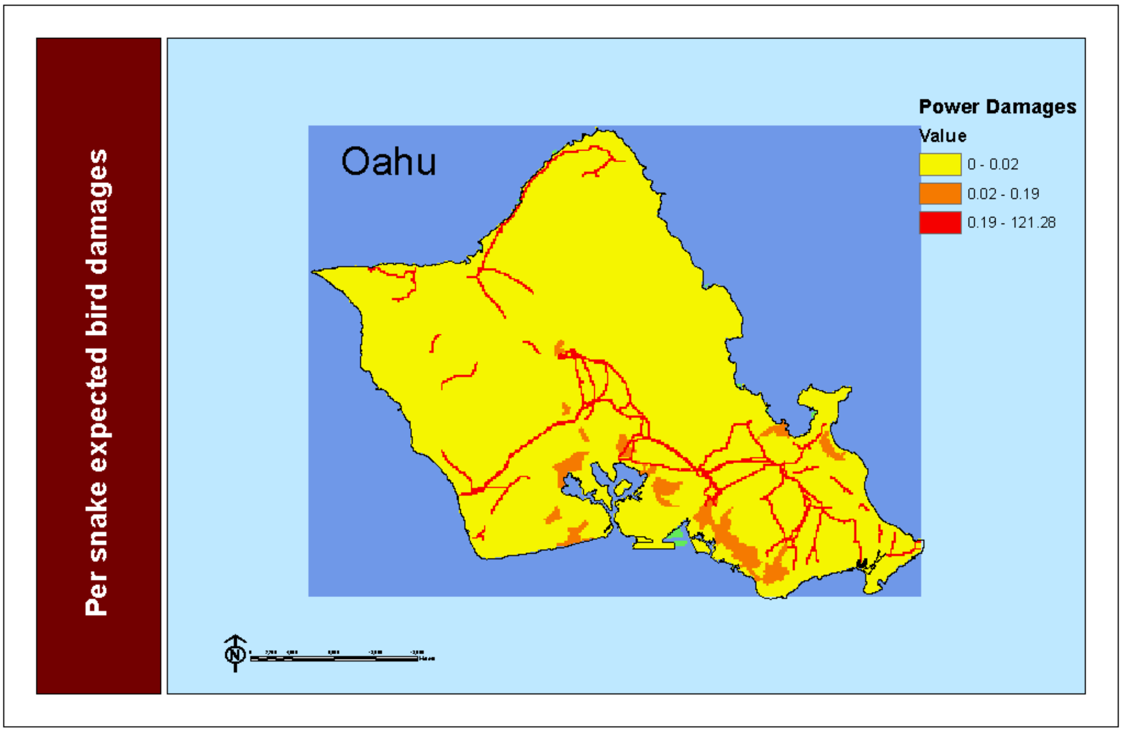


Figure 2c: Direct Medical Damages

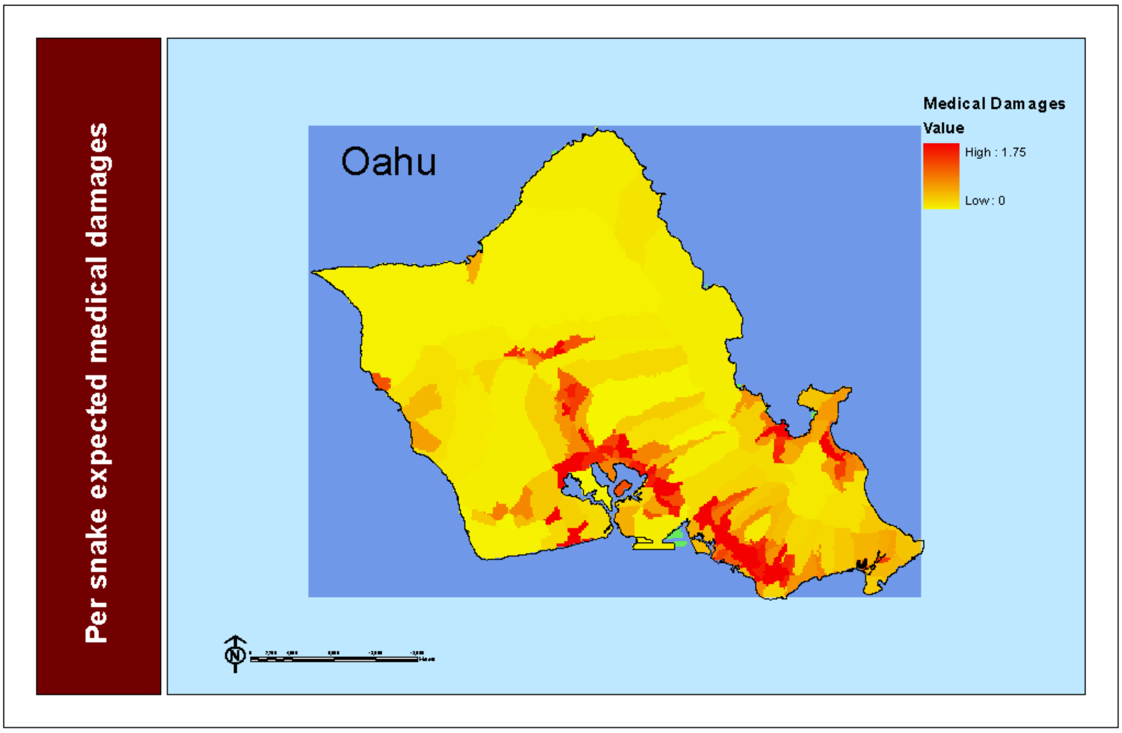


Figure 2d: Bird habitat damages

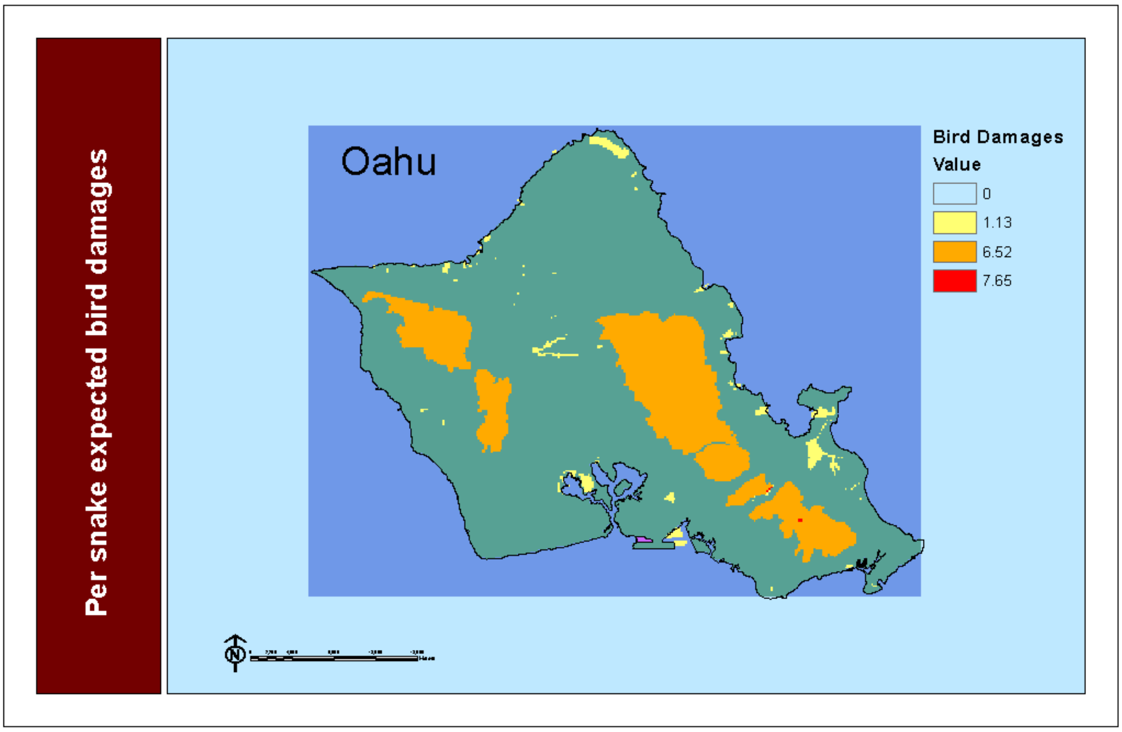


Figure 3: Costs

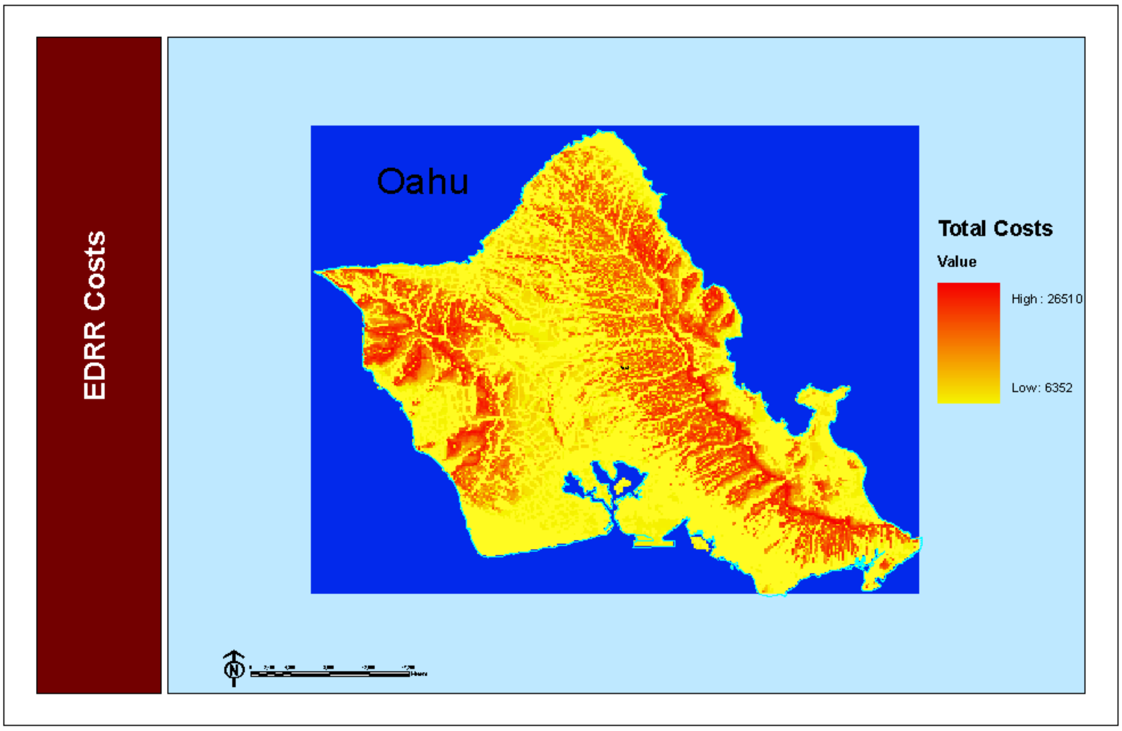


Figure 4: Returns to Eradication (Island-wide EDRR)

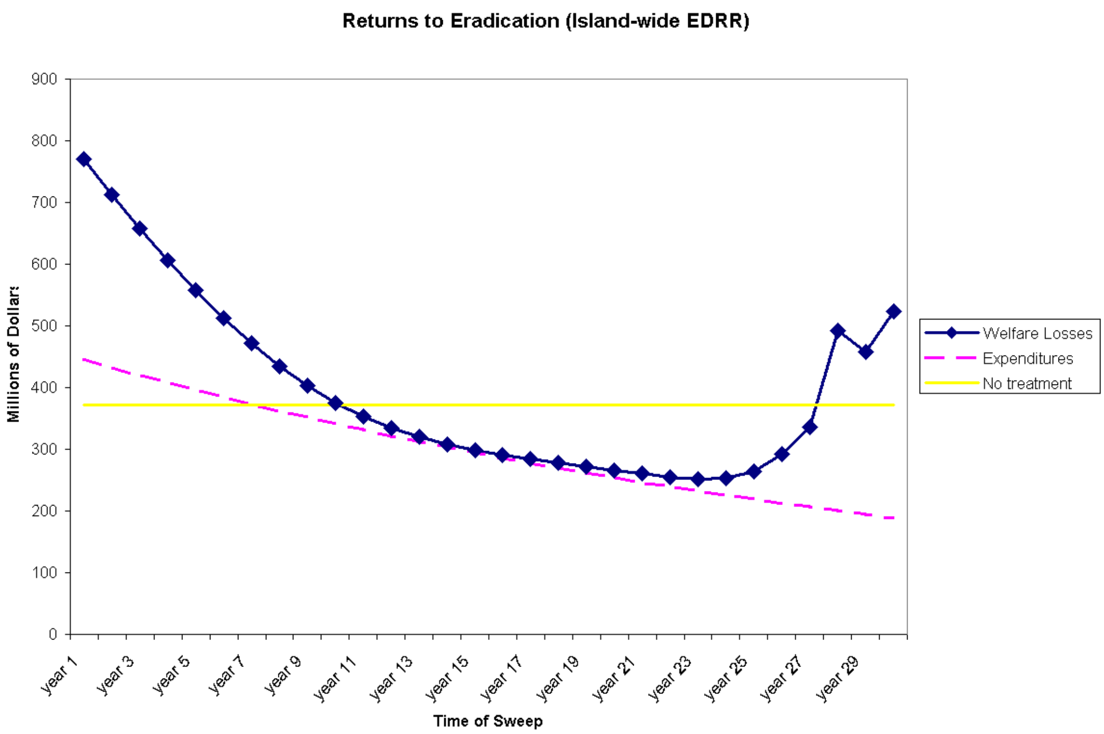
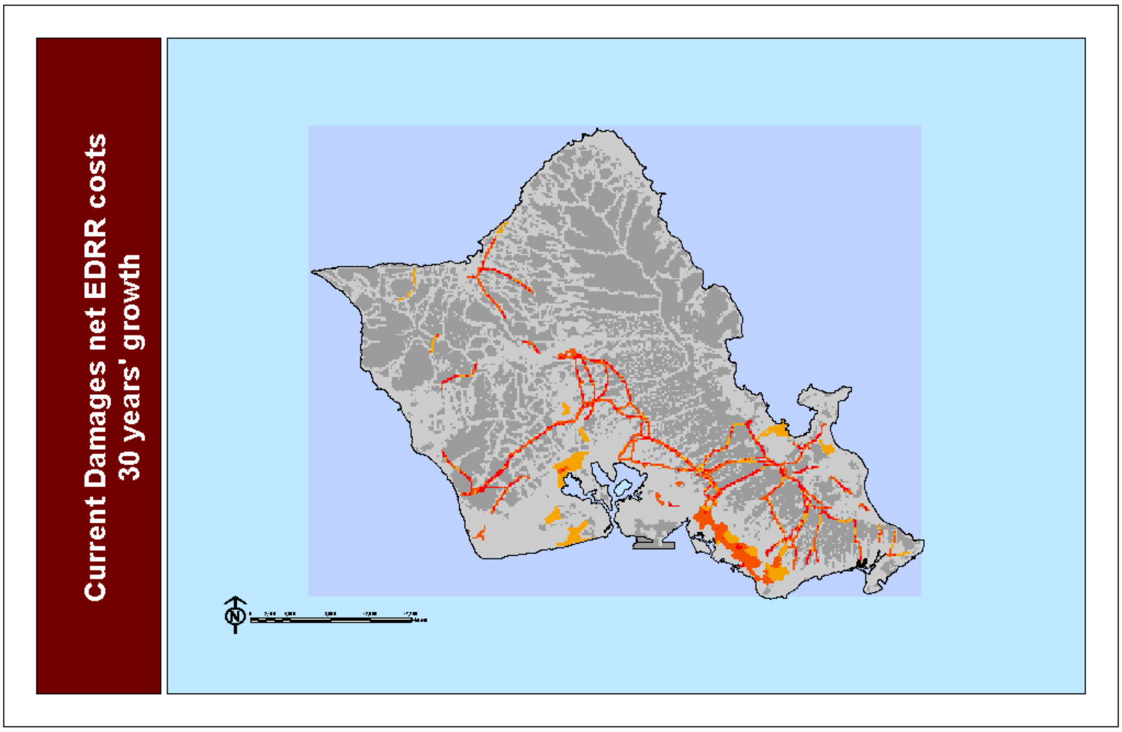


Figure 5: Current net damages across first 30 years of invasion



Notes: Orange and red cells have current damages increasingly higher than current costs. Light gray and dark gray have current costs increasingly higher than current damages.