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Invasive Species Control over Space and Time: *Miconia calvescens* on Oahu, Hawaii

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The optimal size and location of an invasive species population depend upon spatially differentiated biological growth, economic costs, and damages. Although largely absent from most economic models, spatial considerations matter because the likelihood and magnitude of the invasion vary spatially and the threatened assets may be unevenly distributed across space. We map the current and future populations of an invasive species, *Miconia calvescens*, on Oahu, Hawaii, and the potential damages to water quantity, quality, and endangered-species habitat, and weigh these against treatment costs. We find that optimal densities vary from approximately 1% to 18% cover throughout the island.

Key Words: Geographical Information Systems, Hawaii, invasive species, *Miconia calvescens*, Oahu, spatial analysis, watershed

JEL Classifications: Q23, Q25, Q28, Q51, Q57

Invasive species have the potential to change natural capital stock and the flow of ecosystem services derived from that stock. The expected costs and damages of managing an invasive species will thus be dependent on the spatial distribution of these ecosystem services. Two spatial considerations matter. First, the likelihood and magnitude of the invasion (as measured by population growth over time) will vary spatially according to the current population and dynamics of growth. Second, the natural capital assets may be unevenly distributed across space.

We use Geographical Information Systems (GIS) to map the current and future populations of an invasive species, *Miconia calvescens*, on the island of Oahu, Hawaii, and the potential damages to water quantity, water quality, endangered bird habitat, and native habitat that houses endangered plants, snails, and insects. Although the tree has not gained as significant acreage as it has on the islands of Maui and Hawaii, the island of Oahu is of interest for several reasons. First, careful GIS data collection of discovered and treated trees has facilitated parameterization of our control cost and initial population estimates. Second, because Oahu is home to the majority of the state's human population and because the hydrological properties of Oahu generate greater reliance on groundwater recharge than Maui or Hawaii, potential damages from lost water recharge are highest on this island. Finally, because the *Miconia* population is still limited and somewhat isolated, chances for optimal management of this invader are better than on Maui or Hawaii. Current management of the tree on Oahu consists of

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monitoring and response when trees are discovered, while status quo management on Maui and Hawaii has turned almost exclusively toward containment of the large core populations. Thus, understanding the optimal treatment path for the lightly invaded Oahu case will further illuminate the paths Maui and Hawaii should take in treating new satellite populations as they appear. Using optimal control theory, we find the spatially dependent optimal population levels of *Miconia* and the paths to these populations over time.

Methodology

Optimal control theory provides an excellent methodology for considering economic policy toward invasive species (Burnett et al.; Olson and Roy; Pitafi and Roumasset). Using optimal control, we define our problem so that we minimize the expected costs and damages from the presence of and control activities undertaken against the invading species. In an improvement over the current literature, we allow costs and damages to vary spatially as well as temporally. Thus, the objective function is:

$$\text{(1)} \quad \underset{x_{it}}{\text{Max}} \int_0^{\infty} -e^{-rt} \sum_i (c(n_{it})x_{it} + D(n_{it}))dt,$$

subject to:

$$\text{(2)} \quad \dot{n}_{it} = g(n_t, n_{it}) - x_{it},$$

$$\text{(3)} \quad 0 \leq x_{it} \leq n_{it},$$

$$\text{(4)} \quad n_0 = n(0),$$

where i denotes the spatial location (grid cell), t represents the time period, r represents the discount rate, n_{it} and $\dot{n}_{it}$ are the population of the invasive species in a given location and its associated time derivative, $g(n_{it})$ is the growth function of the invasive species, x_{it} represents the number of removals, $c(n_{it})$ is the marginal cost function for removals, which varies with population level, and $D(n_{it})$ is the damages incurred at population n_{it}. In the following, we drop the time subscripts for ease of notation.

The Hamiltonian current value for each location is defined as:

$$\text{(5)} \quad H_i = -c(n_{it})x_{it} - D(n_{it}) + \lambda_i[g(n, n_i) - x_i].$$

Application of the maximum principle (assuming an interior solution for x) generates first-order conditions:

$$\text{(6)} \quad \frac{\partial H_i}{\partial x_i} = -c(n_i) - \lambda_i = 0,$$

$$\text{(7)} \quad \frac{\partial H_i}{\partial n_i} = -c'(n_i)x_i - D'(n_i) + \lambda_i g'(n, n_i) = r\lambda_i - \dot{\lambda}_i,$$

and

$$\text{(8)} \quad \frac{\partial H_i}{\partial \lambda_i} = g(n, n_i) - x_i = \dot{n}_i.$$

Taking time derivatives of Equation (6) yields

$$\text{(9)} \quad \dot{\lambda}_i = -c'(n_i)\dot{n}_i.$$

Substituting Equations (6) and (9) into Equation (7) yields

$$\text{(10)} \quad -c'(n_i)x_i - D'(n_i) - c(n_i)g'(n, n_i) = -rc(n_i) + c'(n_i)\dot{n}_i.$$

Replacing x_i in Equation (10) using the equation of motion (2) gives

$$\text{(11)} \quad -c'(n_i)[g(n_i) - \dot{n}_i] - D'(n_i) - c(n_i)g'(n, n_i) = -rc(n_i) + c'(n_i)\dot{n}_i,$$

or

$$\text{(12)} \quad rc(n_i) = D'(n_i) + \frac{d}{dn_i}[c(n_i)g(n, n_i)].$$

Equation (12) is the condition describing optimal management of *Miconia*. The Left hand side (LHS) is the opportunity cost (foregone interest) of removing the marginal unit in a location today instead of one period later. The Right hand side (RHS) is the net benefit of removing said unit. This includes the decrease in current-period damages and the decrease in the costs of harvesting current-period growth, both of which result from a marginal decrease in invasive population. Growth is a function of internal growth for the location (increasing density) and spread from the whole population for the area (n).

Equation (12) can be rewritten as:

$$D'(n_i) = rc(n_i) - c(n_i)g'(n, n_i) - c'(n_i)g(n, n_i). \quad (13)$$

In this way, we see that at an optimal population, the marginal damages should be equated with the costs of maintaining that population for the location. Were marginal damages to be higher (lower), additional (fewer) trees could be removed, reducing the overall losses. Areas with higher marginal damages, then, will have more trees removed.

Model Components

We divide Oahu into 16 ha plots, or cells, to analyze the optimal management of *Miconia* for the island over space and time. Each cell contains information on habitat quality and the current presence of the invading plant. We assume that the current invasion has already been underway for 37 yrs. and was initiated by purposeful individual plantings.

Population

Invasive species managers on the heavily invaded island of Hawaii estimate that the densest areas contain ~100 trees per acre. Our spatial cells are 16 hectares each. Carrying capacity per cell is thus 3,952 trees.

In theory, we can calculate the spread of the current population using a GIS-determined[1] estimated diffusion rate of 0.208 km²/yr and the distance from the current population, based on Fisher and Skellam (in Shigesada and Kawasaki), to determine the expected *Miconia* population in a given cell at a given time period. We assume the population changes as a function of both diffusion and internal growth:

$$\dot{n}_i = d\left(\frac{\partial^2 n_i}{\partial x_i^2} + \frac{\partial^2 n_i}{\partial y_i^2}\right) + (b - \mu n_i)n_i, \quad (14)$$

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, $\mu > 0$ captures intraspecific competition, 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, and the second term captures population growth within the given coordinates. We estimate that the maximum carrying capacity in any habitat compatible cell (K) is 3,952 trees, while it is zero in any noncompatible cells.

This simplifying assumption is still insufficient to realize an explicit solution to the nonlinear problem of Equation (14). In order to create a tractable model that incorporates both spread and internal growth, we use the explicitly solvable Skellam model for spread with exponential growth until the population of the cell reaches the point where it diverges significantly from a logistic growth function, which occurs at ~20 trees. From that point, we use a logistic growth function to determine population in an area. Thus, the population in any given cell will be driven first by arrivals through the Skellam expansion model and then by internal growth from the logistic function. 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

$$n(r, t) = \frac{n_0}{4\pi dt}\exp\left(bt - \frac{r^2}{4dt}\right) \quad (15)$$

until $n(r, t) \geq 20$. After this point,

$$n(r, t) = n_r\left(\frac{Ke^{bt}}{K + n_r(e^{bt} - 1)}\right), \quad (16)$$

where n_r is the population of the cell (here, 20) when the growth function changes.

Damages

We estimate damages from *Miconia* as evolving from indirect ecosystem services as well as nonmarket goods like biodiversity. Particular-

[1] While Pysek and Hulme reported a long-term aerial spread estimate for Tahiti of 11.9 km²/yr, the data for the spread on Oahu to date does not support this level of spread for the island's conditions. Among other things, Oahu does not suffer the same frequency of hurricane disturbances that are partly responsible for the rate of spread of *Miconia* on Tahiti (Meyer).

ly significant threats are a reduction in habitat for endangered species and a shift in the hydrological cycle that may reduce freshwater recharge and increase runoff and sedimentation.

Hawaii is home to a great percentage of the United States' and the world's identified endangered species. Changes in forest composition as described may threaten endangered plant species, bird species, and invertebrate species in particular.

Birds

In the federal register listing materials for the endangered Elepaio (*Chasiempis sandwichensis*) bird on Oahu, the main justification for protection is based on the bird's reliance on the current forest structure (see U.S. Department of the Interior, for example). Since *Miconia* poses a significant threat to that structure, the plant is listed directly as one of the concerns for the bird's survival. A set of studies indicates that, on average, each household would be willing to pay \$31 (95% confidence interval of \$16.66–\$48.92) per bird species per year to keep a species from extinction (Loomis and White).

For 280,000 Oahu households, the value of preventing extinction of the Elepaio is then \$8.68 million annually. Since this omits any values for the species from individuals outside of Oahu, we consider this an extremely conservative estimate. Spatially, damages will be attributed to the bird depending whether or not *Miconia* is present in the Elepaio's current range or whether the tree moves into the Elepaio's federally designated critical habitat. Therefore, we derive two types of damages due to the threatened Elepaio.

There are ~6,000 hectares on Oahu in which Elepaio are currently established. There are therefore 1.4 million potential trees that could lead to the bird's extinction. We calculate per tree damages in this range as \$5.85 a tree, assuming that each *Miconia* tree is equally as likely to contribute to the bird's extinction. Of potential *Miconia* habitat, 7.6% is also current Elepaio range. Federally designated critical habitat, which is defined as habitat in which the Elepaio would be established and that it would need for population recovery, is also of concern. There are approximately 26,700 hectares of critical habitat on Oahu; therefore, we calculate per tree damages to be \$1.32 in these areas. Approximately 39% of potential *Miconia* habitat is also Elepaio critical habitat.

Water

Additionally, damages to watershed functions are expected from dense stands of *Miconia*. The hydrological properties of *Miconia* suggest that there may be a significant change in the water balance, including an increase in runoff and a potential reduction in groundwater recharge. Estimates of potential expected losses from an invasion of *Miconia* on Oahu in terms of groundwater recharge suggest that a loss of 41 million gallons per day (mgd) would generate economic losses of \$137 million per year (Kaiser and Roumasset 2002), or \$3.3 million per mgd. Additionally, increased surface water runoff is expected to increase damages by \$1.2 million per mgd because of reduction in groundwater due to increased sedimentation costs (Kaiser and Roumasset 2000). Therefore, total annual losses due to water impairment are estimated at \$4.5 million per mgd.

The potential loss to aquifers is calculated by determining the effect of the change in forest cover to the aquifer's yield. First, we sum the sustainable yield estimates from the Hawaii Department of Land and Natural Resources (DLNR) for linked aquifers that lie beneath potential *Miconia* habitat into five main aquifers. Sustainable yield as defined by DLNR is the estimated amount of water that can be removed from the aquifer without adversely affecting the quality or quantity of the resource.[2] This value is dependent on current recharge to the aquifers. Next, using estimates taken from survey data of forested watershed experts in Oahu regarding the expected increase in runoff that would occur

[2] See http://www.hawaii.gov/dbedt/czm/wec/html/mountain/water/ground.htm.

with a shift in forest structure to one dominated by *Miconia* (Kaiser and Roumasset 2005), we calculate the expected annual reduction in recharge for these areas. The surveys of experts indicate that a 0.85% to 1.04% annual decrease in runoff might occur. We determine a lower bound and an upper bound estimate for lost recharge damages by multiplying these decreases by the sustainable yield. A dollar value is attached by multiplying this groundwater loss by $4.5 million. The aquifers of concern on Oahu are (expected per tree damages to water quality and quantity in parentheses): Honolulu ($0.44), Pearl Harbor ($0.70), North ($0.65), Schofield ($0.22), and Windward ($0.56) aquifers.

Native Habitat

Hawaii's evolutionary isolation has generated a number of endemic species that are threatened with extinction due to habitat loss. The economic value of non–"charismatic megafauna," such as plants, snails, and insects is not well studied or known. They are, however, important to the functioning of healthy ecosystems and contribute to the productivity of the islands' natural capital.

We represent damages to native habitat in general, including habitat for plants, rare snails, and insects, by the market value of the state's floriculture and nursery crops industry. We choose this measure as representative of the option value inherent in native habitat because it can be considered from the demand side as an approximation of willingness to pay for unique and attractive landscapes, and from the supply side, it represents the productivity of Hawaii's ecosystems.[3] In 2005, the total value of greenhouse and nursery crops to the residents of the island of Oahu was $65,674,070 (Jerardo). Although these commercial species are not necessarily the same species that are directly threatened by *Miconia*, this commercial industry estimate closely mirrors that of wildlife expenditures by Hawaii residents, which consist of expenditures for viewing nature and participating in ecosystem-dependent recreational activities (U.S. Department of the Interior). This gives us confidence that we can approach this value from the demand (willingness to pay for wildlife viewing) or supply (market value of plants) side and arrive at approximately the same value.

Threatened and endangered plants are present over 34% of potential *Miconia* habitat and 15% of Oahu. Based on these figures, we calculate native habitat damages of $12.02 per tree. Therefore, marginal damages for any given location will be calculated according to:

$$(17) \qquad d_{it} = d_{\text{bird habitat or range}} + d_{\text{water}} + d_{\text{native habitat}}.$$

Because not all locations will have all of these characteristics and because water damages will vary by aquifer, marginal damages will vary spatially. We find that in our analysis, marginal damages range from $0.22 per tree to $19.06 per tree.

Control Costs

Control begins with reconnaissance in helicopters to identify infestations and is followed by either herbicide treatment from the helicopters themselves or by operations on the ground to treat or manually pull the trees. In any case, there are two separate activities that must occur—the trees must first be found, then treated.

We therefore define a cost function consisting of two parts, the "search" component and the "treatment" component. While the unit cost of treating a tree with herbicide and/or cutting a tree may be constant across population levels, the cost of finding a tree rapidly decreases with population size.

We assume that the cost associated with finding *Miconia* will vary with population density, while treatment costs remain constant at $13.39 with respect to population. The Oahu Invasive Species Committee allocated $321,000

[3] A species-by-species approach for plants and insects may not be appropriate because the species share the same habitat, and attempts at preservation are not separable. Land values for such habitat are compromised by both zoning restrictions, which lower the price at which properties change hands, and by enforcement costs, which increase the cost of the land as habitat preserve.

to *Miconia* control in 2005 (Ryan Smith, personal communication). These status quo levels of expenditures, along with estimates of current populations, allow us to parameterize the control function appropriately.

We determine the two components for Oahu in the following manner. The search component involves a fixed cost that depends on the island's potential habitat acreage and that decreases with increased access to that habitat. Based on discussions with resource managers, we estimate that this fixed cost for searching one average acre for *Miconia* costs ~$1,000. The numerator of the search component for each spatial cell on Oahu is $1,000 per potential acre, or $39,520 per 16 ha cell.

The ability to search an island's habitat will also depend on several characteristics of the surrounding area, such as density of vegetation, the steepness of the terrain, etc. One major determinant is ease of access into the potential habitat. The costs per tree of searching will therefore vary with the ease of access. We use the combined length of roads and trails as a proxy for this variable. We create a ratio of the length of roads and trails as compared to Molokai, the most expensive island to search because it has the fewest roads and trails per acre of habitat, to generate the coefficient on population in the denominator of the search component (see Burnett, Kaiser, and Roumasset). Higher values of this coefficient imply greater ease of access, which translate into lower search costs for greater populations. Due to the number of well-maintained roads and trails throughout Oahu's forests, Oahu has the highest search coefficient (and therefore lowest marginal cost) of all islands, equal to 1.6258.

The marginal cost of searching and treating x trees is:

$$c(n_i) = \left(\frac{\$39{,}520}{n_i^{1.6258}} + 13.39\right). \tag{18}$$

Application

If left untreated, the damages from *Miconia* will grow at an increasing rate into the foreseeable future. Under our parameterization of the spread, it will take ~80 more years for *Miconia* to blanket its potential habitat on Oahu in the way that it now covers Tahiti. In part because planning horizons are short, and in part because new treatment technologies are likely to evolve in the long run that will change control costs, we focus on the more immediate future and investigate the benefits of management over a 40-year time horizon. In particular, remote-sensing technology already can identify large stands of *Miconia*, and improvement in this technology may allow for quick identification of smaller *Miconia* populations. Additionally, since the loss of an endangered species is irreversible, and the demand for groundwater is likely to change over time as well, damages may not be constant over the long-term either. Unchecked damages over the next 40 years have a present value of ~$627 million dollars using a 3% discount rate. This is the cost of doing nothing.

Using the parameterization described already, we solve for the optimal populations in each spatial location over time. We find the steady-state population for each cell by solving Equation 12 in Mathematica version 5.0. The growth equation is used to find the time it would take to reach the steady-state population in each cell. We find that 9,616 ha need immediate treatment at an expected cost of $5.21 million dollars. This should be followed by spending that keeps the population in each location cell somewhere between 43 and 705 trees per 16 ha plot. Over 40 years, this cost will increase from $1.12 million per year to $3.71 million per year. The total present value of control costs from now until 40 years into the future is $54.5 million, using a 3% discount rate.

The initial large immediate outlay of $5.21 million should be followed by continuous control expenditures. Note that while these expenditures increase in current dollars, after year 12, they decrease in present value. We emphasize that long-term planning is essential to optimal management. It will become increasingly difficult to find new funds for management; therefore, setting aside funds for future management so that they can keep pace with the discount rate will be helpful to achieving optimal management goals.

By comparing the outcome from no control, as measured by damages, to the outcome from optimal control, as measured by damages from untreated trees plus the control costs for treated trees, we find that the returns to control grow in present value over time. In the first year of management, current expenditures and damages ($9.0 million) are more than current untreated damages ($3.8 million) by $5.2 million. By the second year, however, optimal management costs $2.2 million less than untreated outcomes, and the benefit is that cost ratio increases to just over 10:1 by year 40, with annual present value net benefits between $14 million and $17 million beginning in year 12.

Conclusions and Extensions

We analyzed management of a current invasive species, *Miconia calvescens*, in Hawaii. Currently, the shrubby tree has a seed bank and small population spread across ~700 hectares of the island of Oahu. Using GIS, we mapped the current known locations of the tree and predicted its spread over time with growth functions that allow for dispersed spread to new areas (Skellam) and internal growth (logistic). We integrated this information with data on the aquifers and the associated water values that would be affected by hydrological change from the spread of the tree, as well as data on endangered species and native habitat, to calculate spatially differentiated damages. We found that without management, damages will conservatively accrue to a total of $627 million over the next 40 years and will still be increasing on an annual basis thereafter.

Using information from current expenditures on *Miconia* search and removal efforts in the islands, we estimated a marginal cost function for control that is a decreasing function of an area's population. Using optimal control theory, we find that depending on marginal damages, the optimal population in cells should range from about 40 to 700 trees per 16 ha cell. This translates to densities of about 1% to 18% cover. These control costs do not therefore eliminate all damages from *Miconia* and, in current dollars, will need to increase over time as the tree spreads. Long-range planning will minimize the impacts of these annual increases, however, as they are virtually constant in present-value terms. In the first year of management, the current expenditures are higher than current damages—$5.2 million should be spent to reduce the stock and slow the future spread considerably—but after the initial outlay, the present value of net costs from *Miconia* is lower, and the present value of the gap between damages and costs when optimally managed and when ignored increases over time.

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