Control of invasive species: lessons from miconia in Hawaii

Brooks Kaiser[1], Kimberly Burnett[2], and James Roumasset[2]
[1] Department of Economics, Gettysburg College, 300 N. Washington Street, Gettysburg PA 17325, USA
[2] Department of Economics, 2424 Maile Way, Saunders Hall 542, Honolulu HI 96822, USA

Summary Invasive plants have the potential to change ecosystems and the services they provide, causing direct and indirect economic damages. Optimal policy weighs the cost of any removal or prevention action against the damages of inaction, and will minimise the total expected costs and damages of management of the population. Miconia (*Miconia calvescens* DC.) is a weedy tree that has invaded tropical Pacific Islands. It creates monotypic stands of broad-leaved single layer canopy without a healthy understorey. This combination is expected to change watershed characteristics, reducing fresh groundwater supplies and increasing sedimentation to near-shore resources, and reduce biodiversity. Using optimal control methodology, we calculate optimal policy responses for five Hawaiian Islands. The islands currently vary in the level of invasion from not yet present (Molokai) to having a significant presence, though not yet at carrying capacity (Maui, Hawaii). Under the most likely growth, cost and damage scenario, we find eradication of existing populations prohibitively expensive; instead, populations should be maintained at relatively low levels. Significant prevention in not yet invaded locations is optimal. We examine other cost and damage parameters to determine conditions under which accommodation (no active removal activities) is preferred and for which eradication is preferred. Damages must be over two orders of magnitude lower than expected for accommodation to be preferred. Cost and growth functions are calibrated using data on existing conditions in Hawaii and Tahiti. Damage functions use models of hydrological change to determine the impact on water supply and reef quality as well as estimates of biodiversity losses.

Keywords *Miconia calvescens*, optimal control, Hawaii, economics of invasive species.

INTRODUCTION

The case of miconia is used to illustrate dynamic policy options for invasive forest species that are already present in an ecosystem. Hawaii's forest ecosystems provide direct and indirect ecosystem services, with high expected value generated from the preservation of existing ecosystem conditions stemming from unique biodiversity assets. Miconia generates concerns that extend from biodiversity to infrastructure for water supply as it threatens moist tropical island watersheds and forest ecosystems.

In this work, we seek to explain how biology and economics work together to determine policy. To improve outcomes and avoid costly mistakes, ranging from denying beneficial introductions to spending good money on ecologically impossible control or eradication efforts, these policies must be seen as a continuous effort to manage ecosystems rather than as separate decisions handled as emergencies as they arrive.

MATERIALS AND METHODS

Case overview A member of the Melastomataceae family from Central America, miconia was purposefully introduced to Hawaii. Starting in a handful of backyards and arboretums four decades ago, it has been spreading with increasing rapidity on the islands of Maui and Hawaii. It is also present on Kauai and Oahu, though it has not yet claimed significant acreage in either location. Miconia is not thought to be present on the island of Molokai.

A model of its potential expansion and damages is available through comparison with Tahiti, where dense, monotypic stands of the tree now cover 65% or more of the main island after a single specimen was introduced to the Papeari Botanical Garden in 1937 (Medeiros *et al*. 1997). Miconia has earned itself descriptors like the 'green cancer' of Tahiti and the 'purple plague' of Hawaii. Vast tracts of miconia have wiped out native forest and reduced forest cover, increasing the potential for soil erosion, landslides, and damages to near-shore resources.

The damages in Tahiti and the potential threats to Hawaiian biodiversity and forested watersheds have rendered miconia a priority weed in Hawaii. Since the early 1990s, millions of dollars have been spent in the battle against its spread, though success at spatial containment on Hawaii and Maui and eradication on Oahu and Kauai remains elusive. We explore quantitatively the policy options and their economic consequences for the continued treatment of the invasion in the modelling and discussion sections below.

Optimal control of an existing invader Optimal control theory provides an excellent methodology for

considering economic policy toward invasive species. Using optimal control, we define our problem so that we minimise the expected costs and damages from the presence of, and control activities undertaken against, the invading species. Thus the objective function is:

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

subject to:

$$\dot{n} = g(n) - x \quad (1)$$

$$0 \le x \le n \quad (2)$$

$$n_0 \text{ given} \quad (3)$$

where n and $\dot{n}$ are the population of the invasive species and its associated time derivative, $g()$ the growth function of the invasive, x represents the number of removals, $c()$ the marginal cost function for removals, which varies with population level, and $D()$ the damages incurred at population n.

We first seek an internal solution for the choice of control level x in the standard manner (e.g. Clark 1990), defining the current value Hamiltonian as:

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

Application of the Maximum Principle (assuming an interior solution for x) generates the following condition:

$$-c'(n)x - D'(n) = c(n)[g'(n) - r] \quad (4)$$

In other words, the marginal costs and damages of the steady state population (LHS) must be just equal to the marginal opportunity costs of maintaining that population (RHS). If the LHS is greater than the RHS, we should be increasing the harvest rate, while if the LHS is less than the RHS, we should be decreasing the harvest rate.

The internal solution must be compared to alternative policy options of eradication ($x^*=n$) or accommodation ($x^*=0$). Thus, we compare the present value of eradication and accommodation policies to the present value of the internal solution to determine if the internal solution is dominated by either alternative.

The optimal policy for an existing invader can then be summarised by considering first where the population is in relation to an optimal steady state population, as determined by minimising the present value of damages and control costs across an infinite time horizon. If the population is currently at this steady state population, new growth should be continually harvested at the steady state, generating a stream of minimised economic costs and damages indefinitely, unless eradication or accommodation has a lower expected present value of costs and damages.

If the population is currently above the steady state population, control costs should be expended to reduce the population to its steady state and then maintain that population unless, again, a corner solution is preferable. If the population lies below the steady state population, damages should be accumulated as the population grows (which are lower than the costs of maintaining these lower populations) until at the steady state population maintenance is initiated as described above.

Empirical investigation We investigate empirically the case of miconia, discussed above. We determine growth, damage and cost function parameters with the help of scientists researching the species and resource managers actively pursuing miconia control. As potential habitat size, costs of control and damages vary widely across space we specify each by island. The parameters are discussed below, followed by results.

We utilise a standard logistic growth function to represent the spread of the invasive tree.
Thus:

$$g(n) = bn\left(1 - \frac{n}{N_{\max}}\right) \quad (5)$$

where b is the intrinsic growth rate, assumed here to be 0.3, N_{max} is the carrying capacity for each island, determined by the chief limiting factor for miconia in Hawaii; precipitation. The potential range indicates areas above the 1800 mm y^{-1} rainfall line as delineated in state GIS data (DBEDT, 2005). We report N_{max} for each island in Table 1 below.

We estimate damages from miconia as evolving from indirect ecosystem services as well as non-market goods like biodiversity. Particularly 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. In the federal register listing materials for the endangered elepaio (*Chasiempis sandwichensis* Gmelin, 1789) bird on Oahu, the main justification for protection is based on the bird's reliance on the current forest structure (see USAFW 2001 for example).

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, with an increase in runoff and a potential reduction in groundwater recharge. Estimates of potential expected losses from an invasion of miconia on Oahu to 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 reduction in groundwater due to increased sedimentation costs (Kaiser and Roumasset 2000). We have laid the groundwork for extending this estimate to the state with surveys of experts connecting miconia to watershed health and nearshore resources affected by sedimentation (Kaiser 2005a, 2005b). Total expected damages for any given population are described by the function:

$$D(n) = d_i n \qquad (6)$$

where d_i is the linearised per-unit medium damage estimate (D) as shown in Table 1.

Control efforts began on Maui in 1991 and continue on the four invaded islands. Control begins with reconnaissance in helicopters to identify infestations, followed by either herbicide treatment from the helicopters or ground operations 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 define a cost function consisting of two parts, the 'search' and '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 increases as population decreases. That is, it is extremely expensive to find the last tree, but much less so to find one tree out of 120 million trees. We use considerable data from invasive species committees working on miconia removal on every island to build our cost of control functions listed in Table 1.

Table 1. Summary of bio-economic parameters.

Island	n_0	N_{max}	D	Cost of control
Kauai	1,540	15.8 m	9.7	$\left(\frac{158,490,570}{n^{1.6095}}+13.39\right)*x$
Oahu	6,890	8.7 m	11.3	$\left(\frac{87,135,510}{n^{1.6258}}+13.39\right)*x$
Maui	111,050	14.1 m	8.9	$\left(\frac{141,337,910}{n^{1.6089}}+13.39\right)*x$
Hawaii	315,000	78.2 m	2.9	$\left(\frac{782,161,240}{n^{1.6028}}+13.39\right)*x$
Molokai	0	3.1 m	22.1	$\left(\frac{30,874,790}{n^{1.6}}+13.39\right)*x$

RESULTS

Using the parameters calculated above, and the assumption that the current stock of miconia in Hawaii is given by the initial populations listed with the summary of parameters in Table 1, we find the following. Optimal policy calls for population reduction on the islands of Oahu, Maui, and Hawaii, population expansion on Kauai and continued prevention on Molokai.

Differences in steady state populations are mainly the result of variations in search costs and potential habitats. For example, the population on Kauai is currently 'too small', that is, the high search cost calls for waiting until the population is larger to invest in harvesting. Although the damage per tree is significant, it does not outweigh the magnitude of the search component of control.

On the island of Oahu, however, ease of access to miconia habitat is facilitated by the comparatively large amount of roads and trails on the island. Furthermore, the search cost on Oahu is almost half that of Kauai (due to fewer potential acres of habitat). Therefore, we find a reduction of approximately 1400 trees to be optimal.

Maui and Hawaii have lower per unit expected damages than Oahu, and higher search costs due to both greater amounts of habitat and more difficult access. While optimal populations are higher than Oahu and Kauai, significant reductions of the Maui and Hawaii populations are preferred to the current state.

Because there are currently no trees known to exist on the island of Molokai, the complete solution requires an integrated model of prevention and control (see e.g., Burnett *et al*. 2006). For illustrative purposes, we find that, if prevention fails and a population establishes on the island, we find the steady state population occurs at 2300 trees. At this level, annual costs of the invasion are minimised at $149,000, significantly higher than current monitoring expenditures of $13,500.

Current miconia policy in Hawaii entails spending different amounts on control efforts on each island. As a final exercise for this species, we compare the

Table 2. Initial versus optimal populations for the five major Hawaiian islands.

Island	n_0	n^*
Kauai	1,540	9,171
Oahu	6,890	5,495
Maui	111,050	8,901
Hawaii	315,000	39,937
Molokai	0	0

consequences of status quo spending to those associated with the optimal policy program for Oahu and Maui in order to investigate the extent to which status quo expenditures may be misaligned with optimal expenditures. We also highlight consequences of two other potential policies: doing nothing, or spending on control in order to remain at the same initial population forever. Comparisons are drawn in Table 3.

Table 3. Present value policy comparisons.

Island	Policy			
	Do nothing	Current n forever	Status quo	Optimal policy
Oahu	$3.08 b	$10.5 m	$16.9 m	$10.4 m
Maui	$4.6 b	$73.5 m	$51.7 m	$17.2 m

DISCUSSION

Using optimal control theory, we generate appropriate comparisons for policy options concerning an existing invasive species. For the islands analysed, we show that the status quo policy for miconia is inefficient. The removal expenditures on Oahu, Maui, and Hawaii are inadequate to remove annual growth and therefore simply postpone the growth of the pest population towards carrying capacity and high sustained damages. The optimal policy involves spending more now to reduce the population thus allowing lower removal expenditures in the future. Potential gains from switching to the optimal policy are large. On Maui, for example, continuing to spend one million dollars on removal each year results in a present value of $51.7 million in removal and damage costs. Switching to the status quo reduces those costs to $17.2 million. A stitch in time saves nine.

In contrast, optimal expenditures on Kauai are less than what is currently being spent. This is largely because of high search costs necessitated by the vast dense and rugged habitat. Optimal policy calls for spending nothing on removal until the population size makes removing growth more affordable.

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