Spatial containment of invasive species: Insights from economics

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1. Introduction

Economics can clarify the discussion on invasive species in at least three ways[1]. First is through the use of incentives to change human behavior so as to enhance protection against the introduction, establishment, and spread of invasive species across the world. The second recognizes the public good characteristics of invasive species control, and develops institutions to support the weakest members of our global community (Perrings et al. 2002). The third component involves choosing optimal investment in invasive species management across space, species, and time. This paper is a first attempt at addressing the third component, optimal spatial containment of an invasive species.

This study has three objectives. First, to elucidate the confusing taxonomy related to the management of invasive species. Second, to take one level of this categorization, containment, and develop a bioeconomic model for determining how this strategy can be executed optimally. Finally, we will use the results of the model to suggest improvements to current invasive species policy.

The paper is organized as follows. Section 2 describes and illustrates the invasive species management taxonomy. Section 3 focuses on one component of this categorization, containment, and shows how policymakers could go about determining the optimal size in which to contain an invasive plant. Sections 4 and 5 define the biological and economic variables and set up the model, and Section 6 provides and interprets results. Implications for policy are discussed in Section 7, and Section 8 outlines directions for future research and concludes.

2. Invasives management taxonomy

Management of invasive species usually falls into one of three broad categories: prevention, control, or adaptation. We discuss each in turn below.

2.1 Prevention

Prevention entails investment in technologies to reduce the likelihood of a pest’s entry. Preventative measures include mechanisms such as inspections at incoming ports, irradiation, quarantine, restrictions on imports, etc. Even with the most stringent of policies, however, the probability of introduction remains above zero.

Instruments commonly used for prevention are highly regulatory in nature and include red (prohibited) listing, green (allowed) listing, inspection, quarantine, public education, and risk assessments. Species that are placed on a red list are banned from being imported

[1] Charles Perrings brought the first two to our attention in 2002, although they have not been fully attended to since.

into a particular region, due to a proven or postulated threat the species poses to the area. More often than not the lists are reactionary responses to species that have already established in the region and revealed their destructive nature. Green listing takes the alternative approach – only the species who make it on to this roster are allowed to enter the region, and no others. Green listing establishes a guilty until proven innocent system for species introductions, however this more cautious approach is seen far less often than its reactionary counterpart. Ports of entry inspection is another common instrument intended to catch invasive species before they enter a region. Agency personnel and dogs are trained to inspect cargo for the presence of potentially harmful species. While an effective means of prevention, a very small percentage of total cargo is generally searched, allowing any number of species to slip through border defenses. Import permits, letter of authorization, quarantine and health certificates are other instruments used to prevent unwanted organisms from entering a region. Permit requirements, length of quarantine, and ease of obtaining all of the above will determine the success of these types of tools.

2.2 Control

The control phase entails reducing or eliminating the likelihood that a species will become established, spread, and cause harm. This stage decreases or eliminates the population of an invader. Under the control strategy there are another three possibilities. These include eradication (complete elimination of population), suppression (reducing population levels to an acceptable threshold), or containment (keeping within some predetermined barriers). Manual, chemical, and biological control are the most commonly used mechanisms against invasive species.

While eradication is often the desired outcome, it is often the least realistic. Complete removal of a species is complicated by high search costs, seed bank longevity, and incomplete information regarding the full population. Most successful eradication projects occur when the population is very small or in the very early stages of an invasion.

Suppression seeks to draw the population down, without eliminating it entirely. The suppression strategy removes a proportion of the population in each time period. Often annual or biannual reconnaissance will be conducted, and removal will occur based on ease of access, proximity to valuable “at-risk” resources, or number of individuals.

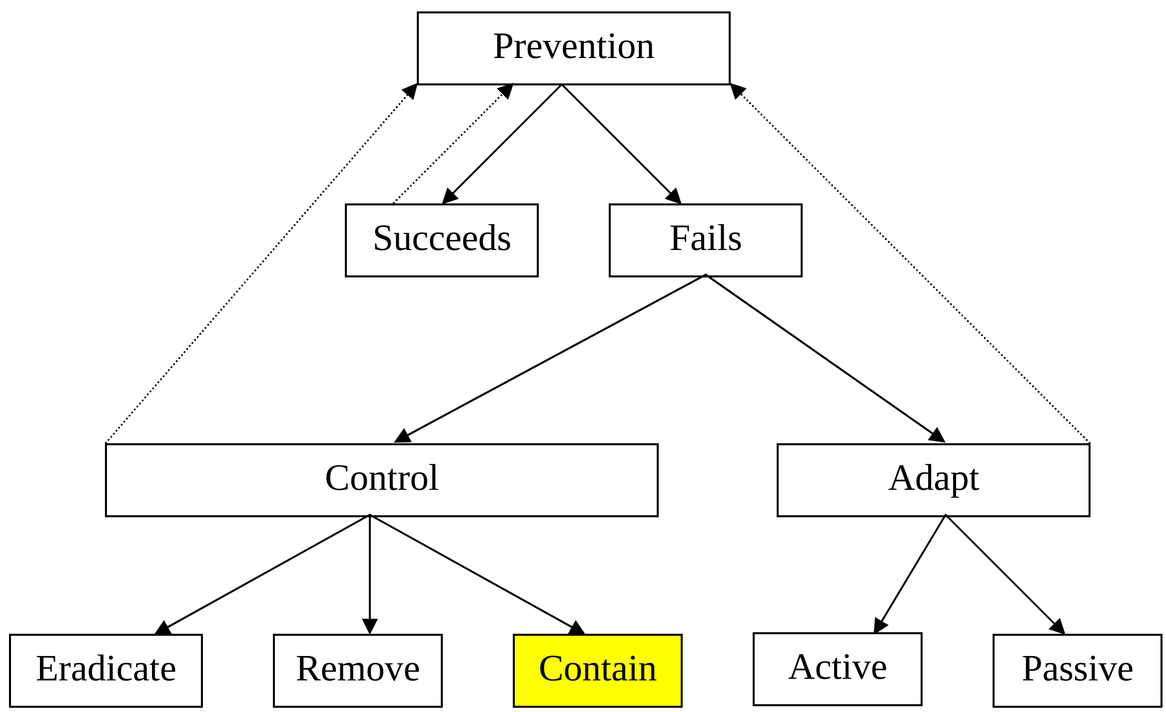
Finally, containment removes individuals around the boundary of an existing population. Rather than harvesting throughout the entire population, containment concentrates on containing the population within some specified barriers. Often these barriers will be natural boundaries, such as rainfall or elevation limits for the species.

2.3 Adaptation

Adaptation requires changes in behavior, be it publicly or privately, in order to lessen the impact of an invasive species. This strategy is meant to reduce the adverse consequences of an unwanted species becoming established. We further consider the adaptation stage as separable into actions that are passive, i.e. they accommodate the success of the new species by creating incentives for individuals to seek substitutes for the lost benefits, and actions that are active, i.e. intervention that invests directly in reducing the damages of the new species or in the creation of substitutes. Active adaptation includes planting native trees, water catchments, flood control, etc., while passive adaptation involves avoidance activities, such as creating incentives for individuals to seek substitutes for the lost benefits. Passive adaptation also includes the choice of doing nothing.

We illustrate the overall taxonomy in Figure 1.

Figure 1. Invasive species management taxonomy



3. Containment of an invasive plant

Containment focuses on controlling around the boundary of an existing population. We will use the Hawaiian example of the invasive tree, *Miconia calvescens,* as an example. Miconia, a beautiful purple and green tree from South America, was intentionally introduced to Hawaii in the 1960’s, and now threatens the economy with damages in the form of reduced quantity of groundwater, impaired quality of surfacewater, and biodiversity losses. The invasive tree has large populations on the islands of Hawaii and Maui, and smaller populations on the islands of Kauai and Oahu.

Management strategies for miconia consist of a combination of the strategies discussed above. The major preventative measure is miconia’s inclusion in *Hawaii’s Noxious Weed* list, thereby banning the sale and/or distribution of the plant anywhere in the state. Other preventative mechanisms include public education on the possible implications of a large population of miconia, in order to reduce the likelihood of hikers or other outdoor enthusiasts moving the seeds around on their equipment or person.

Major control strategies for miconia have been in place since the early 1990’s, when the plant was identified as a major contributor to the demise of Tahiti’s native forests and biodiversity. Suppression is the main strategy utilized on all four islands. Reconnaissance surveys are routinely performed by helicopter or on foot, and County Invasive Species Committees make annual plans for removal. Containment is also pursued for the larger populations on Hawaii and Maui. Large populations exist in close proximity to the state’s two national parks, Hawaii Volcanoes National Park on Hawaii and Haleakala National Park on Maui. The idea is to keep the populations away from these highly unique areas, which are teeming with biodiversity.

Containment is an appealing strategy when the initial population is large, and there are natural boundaries available to exploit such as rainfall and elevation limits. Rather than continuously removing some quantity of trees from the inner infestation, containment tries to keep the infestation from spreading outside some specified limits. This can be achieved by removing trees from around the perimeter of the infestation, or by setting the boundaries such that the species is not able to grow beyond them due to natural habitat limitations.

There are both biological and economic advantages to considering the containment strategy. Biologically, there will be fewer disturbances inside the core infestation, since we only remove around, not within the infestation. When soil is disturbed, there exists an increased potential for more invasives to take hold. Containment also limits the chance to transfer seeds (by field crews, or equipment) to uninfested areas, since we would not be working directly in the center of the population.

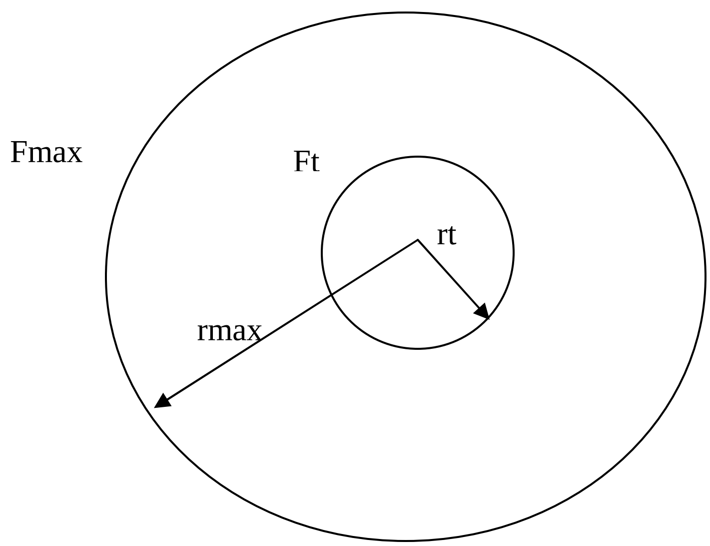
Containment also allows us to make more economic sense of cost and damage functions. It is hard to say exactly how cost will vary with population alone, as some removals will be located in harder to reach spots, so costs may not always decrease with population. Furthermore, if we can keep population isolated, we avoid high search costs. One of the most costly ventures in miconia control is that of reconnaissance, usually done in helicopters. Furthermore, containing where habitat is favorable and growth is voracious (in the center of the infestation) is harder than containing in less favorable areas (towards edges).

Even more ambiguous is how damage is related to population. For miconia, a single tree will not cause a great deal (if any) damage, and even thousands of trees, as long as they are spread out, may do little damage. What biologists are more certain about is that densely contained trees will result in considerable damage, namely in the form of reduced groundwater recharge and surface water quality, and a loss of biodiversity. Therefore, we are presented with a tradeoff: high damage costs vs. decreasing containment costs. The following attempts to address this tradeoff with optimal policy responses.

4. Variable definition

In this section we describe the variables involved in the containment model, and illustrate the spatial dimensions to the issue in Figure 2 below.

Figure 2. Spatial dimensions of the infestation



4.1 Biological variables

F_{max} maximum circumference of infestation, created by natural boundaries (rainfall, elevation, edges of island/ledges)

F_t circumference of infestation at time t

r_t radius of infestation at time t. Here, we model the radius rather than the population to capture spatial considerations. One can think of the radius as a representative measure of population. For simplicity, we assume the population grows symmetrically from the center of the island. The size of the radius thus follows the size of the total population.

r_{max} — maximum radius

x_t — containment, removal of trees around the edges at time t

$g(r_t)$ — biological growth function of radius of infestation. Ideally, we would like to be able to describe this growth function as follows. In the center of the infestation, growth is vigorous because the species is in its prime habitat (since this is where the infestation began). The rate of growth increases as the infestation expands, up to some level, at which the invasive runs into less favorable habitat (strawberry guava infestation, less rainfall, etc.). At this point, the growth rate begins to decline, until finally it reaches zero at the maximum perimeter, F_{max}.

The reason it is important to model the invasive this way is that cost of containment will depend on where the species is in the above growth cycle. Because getting the exact biological description for the species' growth is not easy, we choose to model growth as logistic, which still can account for the increase then decrease in growth rate. We will use the specification of the cost function to capture the spatial dynamics discussed above.

4.2 Economic variables

$C(r_t)$ — containment cost function, initially $C'(r_t) > 0$ (when invasive still in favorable habitat, the more trees the harder to contain), eventually $C'(r_t) < 0$. Costs will decrease as we approach F_{max}, as natural boundaries make it harder for the infestation to continue expanding. This specification of the cost function reflects the growth cycle of the species discussed above. We assume our initial r_0 is such that eradication of the entire radius is not economically feasible (this is the case on Maui and Hawaii).

$D(r_t)$ — damage function, everywhere $D'(r_t) > 0$, and $D''(r_t) < 0$. We assume constant density, therefore the bigger the circumference of the infestation, the more damage. Note the second derivative – the increase in damage decreases as the radius grows. These specifications are possible with the containment model, and are less realistic if we were considering simply harvesting rather than containment.

5. The bioeconomic model

Dynamic optimal control is used to minimize the sum of control costs and damages at each point in time through containment.

The social planner wants to minimize the sum of containment costs plus damages over time:

Minimize $W = \int_0^\infty e^{-rt} [C(r_t)\, x_t + D(r_t)]\, dt$

Or,

$$\underset{x_t}{Max} \{-W\}$$

subject to $\dot{r} = g(r_t) - x_t$, r_o given

Current value Hamiltonian:

$$H = -C(r_t)\, x_t - D(r_t) + \lambda_t [g(r_t) - x_t]$$

Necessary conditions:

$$\dot{r}_t = \frac{\partial H}{\partial \lambda_t} = g(r_t) - x_t \qquad (1)$$

$$\begin{aligned} \dot{\lambda}_t = r\,\lambda_t - \frac{\partial H}{\partial r_t} &= r\,\lambda_t - [-C'(r_t)\, x_t - D'(r_t) + \lambda_t\, g'(r_t)] \\ &= r\,\lambda_t + C'(r_t)\, x_t + D'(r_t) - \lambda_t\, g'(r_t)] \end{aligned} \qquad (2)$$

$$\frac{\partial H}{\partial x_t} = -C(r_t) - \lambda_t \leq 0 \qquad \text{(if <0 then } x_t = 0) \qquad (3)$$

From this problem, we can derive an optimal containment policy path for the case where it is uneconomic to eradicate the new population.

Rearranging (2),

$$\dot{\lambda}_t - D'(r_t) - C'(r_t)\,x_t = \lambda_t[r - g'(r_t)] \tag{4}$$

The marginal net benefits of containment are composed of the reduction in damages from a more contained population, less the marginal cost of that containment

The marginal cost component includes the discounted shadow price of resource containment, adjusted by the marginal growth in radius

From (3),

$$\begin{aligned} \lambda_t &= -C(r_t) \\ \dot{\lambda}_t &= -C'(r_t)\,\dot{r}_t \end{aligned} \tag{5}$$

Equation 5 describes the shadow price of invasive species containment. The shadow price should be equal to the (negative) cost of containment at time t. This is the cost savings from containment. Furthermore, the change in the shadow price should be equal to the decrease in MC times the change in radius over time (bigger radius, MC decreases; smaller radius, MC increases).

Plugging these conditions into (4),

$$-C'(r_t)(\dot{r}_t) - D'(r_t) - C'(r_t)\,x_t = -C(r_t)[r - g'(r_t)]$$

Rearranging,

$$-C'(r_t)(\dot{r}_t + x_t) - D'(r_t) = -C(r_t)[r - g'(r_t)] \tag{6}$$

From our equation of motion $\dot{r} = g(r_t) - x_t$,

$$g(r_t) = \dot{r} + x_t \tag{7}$$

Plugging (7) into (6) and rearranging,

$$C(r_t) = \frac{C'(r_t)g(r_t) + D'(r_t)}{[r - g'(r_t)]} \tag{8}$$

The LHS describes the PV cost of containment. This must be set equal to the MB of containing a unit of invasives from spreading. This MB component consists of future damages avoided by containing the marginal unit and the saved MC of additional growth of this unit. Because we are describing the PV cost of containing the marginal unit now and forever, the RHS term must be divided by the own rate of interest, which is the interest rate minus the marginal growth.

6. Results

We can rearrange Equation 8 again for further insights,

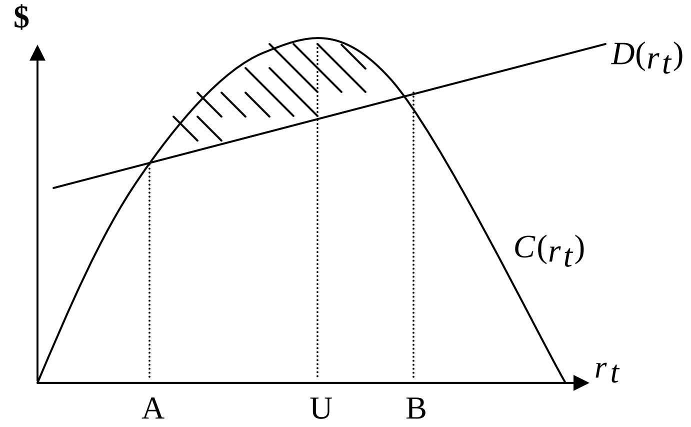
$$g'(r_t) = r - \frac{C'(r_t)g(r_t) + D'(r_t)}{C(r_t)} \tag{9}$$

Equation 9 informs us how the growth of the invasive should change optimally over time. This will depend on the magnitude of the second term on the RHS. Note all components are unambiguously positive, with the exception of $C'(r_t)$. The sign of MC will depend on where we are in relation to F_{max}[2]. Again, this is a feature of using the spatial model. Initially, we are far from F_{max}, so costs of containment are increasing, $C'(r_t) > 0$. However, as we approach F_{max}, the invasive enters less hospitable habitat, encounters greater resistance, so growth slows, making it easier to contain, and $C'(r_t) < 0$.

To more clearly understand the tradeoff created from the containment damage and costs, and to see why there are multiple steady states, it is useful to look at the interaction of the cost and damage functions. See Figure 3 below.

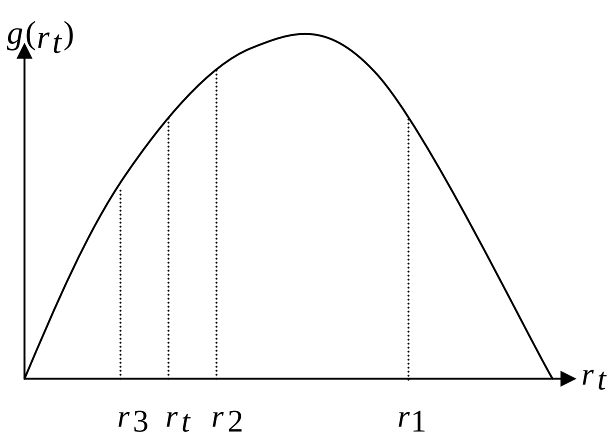
[2] Note that when $C'(r_t) = 0$, we are left with the expression $g'(r_t) = r - \frac{D'(r_t)}{C(r_t)}$. Since marginal damages are always positive, we have the case where $g'(r_t) < r$, which seems counterintuitive (the presence of damages leads to a policy of letting the radius grow). However, since the sign of the second derivative is negative, damages are increasing at a decreasing rate. And when we reach the point that $C'(r_t) = 0$, we can assume that the increase in damages have decreased sufficiently to justify allowing the radius to grow, until $C'(r_t) < 0$, at which point the optimal policy will again be to cut the radius back.

Figure 3. Cost vs. damages from spatial containment



The cost of containment increases until the species reaches unfavorable habitat (point U above), at which point cost begins to decline. However, our damage function is a strictly increasing function of radius. The functions intersect twice, creating thresholds by which we can determine policy. At the initial intersection, point A, costs are lower than damages, therefore it is optimal to take the action of removing trees. The shaded region between the two thresholds represents the area under which costs exceed damages, and where it is optimal to let the population grow. Finally, we reach a second threshold, point B, where again costs fall below damages and it is optimal to remove trees. These two threshold points represent two potential steady states. The reason our model produces three steady states is the existence of our discount rate. This simplistic figure cannot account for the importance of considering, or not considering, future generations. Figure 4 depicts the position of these three steady states, r_1, r_2, and r_3.

Figure 4. Potential steady states



To illustrate, imagine at time t we are at r_t. There are a total of 3 possible steady states, depending on the sign of $C'(r_t)$ and the magnitude of $\frac{C'(r_t)g(r_t)+D'(r_t)}{C(r_t)}$ in relation to r.

Let A = $\frac{C'(r_t)g(r_t)+D'(r_t)}{C(r_t)}$.

<u>Increasing MC</u>. $C'(r_t) > 0$. We assumed that the initial population, r_0, is large enough to make eradication infeasible, and that marginal costs are therefore initially increasing. The species is in favorable habitat, so it grows quickly and is difficult and expensive to contain. The first two cases we consider are under this range of increasing MC.

Case 1 – increasing MC and low relative discount rate. $C'(r_t) > 0$ and A > r. Then, $g'(r_t) < 0$. Since the slope of the growth function is negative in this case, it is optimal to move to the right hand side of the curve, allowing the radius to grow significantly, towards r_1. This case illustrates a technical difference between this and other renewable resource models (e.g., fisheries), as a potential steady state exists beyond MSY. The intuition behind this result is that since MC still in the increasing range, it would be beneficial to wait until it reaches the decreasing range of growth. The discount rate is low, so we put positive weight on future generations, and don't want to expend all resources today when it is too costly to do so. Waiting will drive the cost down for future generations.

Case 2 – increasing MC, high relative discount rate. $C'(r_t) > 0$ and A < r. Then, $g'(r_t) < r$. In this case, the slope has decreased, so it is optimal to move towards r_2 (with a smaller but still positive slope). We are allowing the radius to grow under this policy. This case is intuitive since we know that when the infestation is in its initial phases, growth is vigorous and it is hard to contain. Thus, allowing the radius to expand will lower the costs of containment. Furthermore, since the A term is less than r, marginal damages must not be significant. However, because the discount rate is relatively high, we care a lot about today, thus want to cut sooner than in case 1.

<u>Decreasing MC</u>. $C'(r_t) < 0$. We assumed that at some point, cost of containment would start decreasing, as containment becomes easier as the invasive moves into unfavorable habitat. When this occurs, we have 2 sub-cases, depending on the magnitude of $C'(r_t)$. Will it dominate the marginal damages $D'(r_t)$ or not? Our final two cases are in this range of decreasing MC.

Case 3 – decreasing MC and high damage. If $|-C'(\cdot)| > D'(r_t)$, then $g'(r_t) > r$. The slope is more positive, so it is optimal to cut the radius back, containing a smaller area. Move towards r_3. The infestation has reached an area for which costs of containment are falling, so optimal policy calls for reduction in radius. Positive marginal damages are outweighing the very negative marginal costs, so containment of a smaller area is preferred. In this case, damages dominate costs by a lot.

Case 4 – decreasing MC and low damage. If $\left|-C'(\cdot)\right| < D'(r_t)$, then the positive marginal damages dominate, and we are back to the comparison between A and r, as in Cases 1 and 2 above. Marginal damages are larger than marginal costs as in 3 (but the difference is not as pronounced), but when this magnitude is not as large we have to consider the tradeoff between containing today (decreased damage) vs. containing tomorrow (decreased costs). In this case, damages dominate costs by less than above. Therefore, we need to again consider the discount rate. If it is small, we let the population grow beyond MSY (we wait longer to contain). If the discount rate is large, we care less about future generations and contain the population sooner, albeit at higher costs.

7. Implications

This exercise, while not meant for direct application to policy, illustrates important tradeoffs to consider when allocating funds towards invasive species initiatives. Because resources for mitigating threats from invasive species are limited, we need to spend wisely, and consider not only biological aspects of the problem, but economic implications as well. Below we describe how policy can be improved by consideration of some important economic consequences.

The model suggests the following to improve invasive species policy. First, it may be beneficial to allow the species to reach some positive level of stock before attempting to control it. This is due to the fact that when the species is in its favorite habitat, growth is vigorous and control is costly. Current policy calls for immediate reduction of a new population, disregarding any potential benefit from waiting.

The optimal population we choose to contain will also depend on how much damage the species generates. Current policy occasionally makes mention of some potential qualitative damages, but rarely computes and compares benefits (damages reduced) to costs of control. Rather, quantity controlled is determined by where the species in question falls on a "prioritization list," which does not account for damages reduced, instead it is based on how likely the species is to be eradicated or how easy the related control is[3].

[3] A possible exception is *Miconia calvescens* in Hawaii. While eradication is largely infeasible (especially on Hawaii or Maui), control is extremely difficult and costly. One explanation for the large investment in miconia control is this plant's reputation as the "Green Cancer" or "Purple Plague" that has caused a significant loss of biodiversity in Tahiti. However, scientists are unsure of the extent to which miconia would have similar effects in Hawaii.

On the other hand, our model suggests that if the damage is much larger than the costs, optimal policy improvement calls for reducing the size of the population. If the damage is only a bit larger than the costs, optimal policy improvement calls for consideration of future generations. Putting significant weight on the future (represented by a small discount rate) will call for more growth as the optimal policy, as this significantly lowers the cost of containment, while less concern for the future will contain growth of the invasive species sooner, although at a much higher cost.

8. Directions for further research

No theoretical model of invasive species control is complete without some type of numerical illustration. The utility of this research would be increased greatly by simulating the model, perhaps parameterizing based on biological and economic data from the miconia experience on either Hawaii or Maui. Another avenue to consider would be to see how the model performs, for a given infestation or island, compared to a more straightforward suppression model, as developed by Kaiser and Roumasset (2004).

References

Kaiser, BA and JA Roumasset (2004) *Integrating Prevention and Control of Invasive Species: Lessons from Hawaii*. Presented at the Western Agricultural Economics Meetings, Honolulu, HI (June, 2004) and the Western Economic Association Meetings, Vancouver, BC (July, 2004).