UHERO
THE ECONOMIC RESEARCH ORGANIZATION
AT THE UNIVERSITY OF HAWAIʻI

Evaluating Protection Strategies for an Invasive Plant Species: *Miconia calvescens*

by

David Lewis, Christopher A. Wada, Kimberly M. Burnett,
James Leary, and Brooke Mahnken

Working Paper No. 2020-5

February 28, 2020

UNIVERSITY OF HAWAIʻI AT MANOA
2424 MAILE WAY, ROOM 540 • HONOLULU, HAWAIʻI 96822
WWW.UHERO.HAWAII.EDU

Evaluating Protection Strategies for an Invasive Plant Species: *Miconia calvescens*

David Lewis, Christopher A. Wada, Kimberly M. Burnett,

James Leary, and Brooke Mahnken

Abstract

The choice to shift among invasive species management strategies depends on ecological, biological, and economic conditions that vary by species, location, and stage of invasion. Typically, as time and area invaded increases, economic returns to management shift away from prevention and eradication, and towards species containment and/or asset protection. This is the case for Miconia calvescens (M. Calvescens) in the East Maui Watershed (EMW), Hawai'i where the species was introduced to a private nursery and botanical gardens 50 years ago, and subsequently escaped and spread throughout the forests of East Maui. While ground management efforts have been continuous since the early 1990s, this research focuses exclusively on the efficacy and impact of aerial herbicide ballistic technology (HBT) management efforts. We use a 25-yr management data set identifying the location and time of each M. calvescens individual eliminated to develop a spatiotemporal spread model, and use information on treatment costs and potential avoided damages to assess the relative benefit-cost ratio of a management strategies such as inaction, containment, and asset protection, under a number of EMW-informed biological and economic parameters. The primary goal of the research presented is to develop an operational methodology for evaluating biological and economic outcomes of containment and asset protection management strategies for M. calvescens in East Maui.

Keywords: Miconia calvescens, invasive species management, Hawai'i, containment, asset protection, herbicide ballistic technology, benefit-cost ratio, stage-matrix population model, spatial spread model

David Lewis

Dept. of Natural Resources & Environmental Management, University of Hawai'i at Mānoa, HI, USA.

e-mail: ddlewis@hawaii.edu

Christopher A. Wada

University of Hawai'i Economic Research Organization, University of Hawai'i at Mānoa, HI, USA.

e-mail: cawada@hawaii.edu

Kimberly M. Burnett

University of Hawai'i Economic Research Organization, University of Hawai'i at Mānoa and Dept. of Natural Resources & Environmental Management, University of Hawai'i at Mānoa, HI, USA.

e-mail: kburnett@hawaii.edu

James Leary

Agronomy Department, Center for Aquatic and Invasive Plants, University of Florida and Dept. of Natural Resources & Environmental Management, University of Hawai'i at Mānoa, HI, USA.

e-mail: learyj@ufl.edu

Brooke Mahnken

Maui Invasive Species Committee (MISC)

Makawao, HI, USA

e-mail: mahnken@hawaii.edu

Contents

1. Introduction

The choice to shift among invasive species management strategies will depend on ecological, biological, and economic conditions that will vary by species, location, and stage of invasion. A generalized invasion curve has been described as a sigmoidal curve that moves between prevention, eradication, containment, and asset protection as a function of time and area invaded (Department of Environment and Primary Industries Victoria, 2017; Braysher, 2017). Typically, as time and area invaded increase, economic returns to management shift away from prevention and eradication, and towards species containment and/or asset protection. This is the case for Miconia calvescens (M. calvescens) in the East Maui Watershed, (EMW), where the species was introduced to a private nursery and botanical gardens 50 years ago, and subsequently escaped and spread throughout the forests of East Maui.

While prevention and elimination of invasions before establishment are typically associated with the lowest economic burden, there are many cases around the world where this is no longer an option. Consequently, a better understanding of the relative merits of, for example, containment versus asset protection, are warranted.

M. calvescens is an invasive tree species currently distributed unevenly across the state of Hawaiʻi, with known populations on Kauaʻi, Oʻahu, Maui, and Hawaiʻi Island. While management goals on the islands of Kauaʻi and Oʻahu remain focused on eradication, efforts of Maui and Hawai'i Island have shifted to containment and in some cases asset protection. Prevention remains the objective for the islands of Molokaʻi, Lanaʻi, and Kahoʻolawe.

M. calvescens is a shade tolerant, large-leaved, midstory canopy species native to South and Central America, classified among the "100 of the world's worst invasive alien species" by the IUCN (Lowe et al., 2000). M. calvescens is able to displace native plant communities, transforming diverse forests into dense monospecific canopies, which can impoverish understory vegetation and expose the soil surface below the canopy (Meyer and Florence, 1996). The tree has large leaves which create large water drops with high-impact throughfall, accelerating localized soil erosion (Giambelluca et al., 2009; Nanko et al., 2013, 2015). This species has been observed with a disproportionately large canopy supported by a shallow root system, which, along with its propensity to colonize steep slopes, may increase landslides, as observed in Tahiti (Gagné et al., 1992).

M. calvescens is a major threat to the EMW, an ~50,000-ha forested landscape on the windward slope of Haleakalā Volcano, with an elevation gradient from sea level to 3,055 m above sea level. The EMW provides critical habitat to more than 100 threatened and endangered species and annually recharges more than 1.1 trillion liters of fresh groundwater (Shade, 1999). Much of the landscape is inaccessible to ground operations, with 72 separate drainage basins, all having slopes > 30°, relegating much of the current M. calvescens management strategy to aerial operations.

M. calvescens was introduced to Hana, Maui, as an ornamental specimen in the early 1970s and not identified as a major invader of the EMW until two decades later, when active management commenced (see Medeiros et al., 1997). In 1991, the first volunteer effort removed over 9,000 plants around the original point of introduction (Gagné et al. 1992). With plant maturity achieved in as little as 4 yrs. (Meyer and Malet, 1997), several generations were likely reproduced within that 20-yr period leading up to the first removal campaign. Over the next decade, over 1 million plants were eliminated. In 2012, herbicide ballistic technology (HBT) was introduced to eliminate satellite M. calvescens more efficiently, with long-range precision and accuracy (Leary et al., 2014). While management efforts have been continuous since the early 1990s, this research focuses exclusively on the efficacy and impact of aerial HBT management efforts. From 2012 to 2016, more than 116 missions (with 377 h of operational flight time) resulted in the elimination of over 21,000 miconia trees occupying more than 30% of the EMW. Despite efforts to manage the invasion, fruiting trees in the core infestation area (~2,000 ha) surrounding the point of introduction are coalescing into monotypic stands "saturating" the landscape. As economic support for these operations declines, continued effective containment of such a large area may not be possible.

Cacho et al. (2008) presented a decision model determining when it is optimal to switch from eradication to comprehensive containment and, further, when it is optimal to terminate management. Hester et al. (2010) applied a stage matrix simulation model to the eradication of a miconia (Miconia calvescens DC.) infestation in Queensland, Australia. Leary et al. (2018) explored some of the critical life-history traits of M. calvescens by using management data in the EMW from 1991 to 2016 and developed bioeconomic comparisons of management options. Since eradication and comprehensive containment of M. calvescens in the EMW may no longer be viable strategies, conservation of native flora in this small, but highly productive ecosystem is a high priority for local stakeholders, particularly the mitigation of invasive plant species (Loope and Mederios 1994; Mederios et al., 1995). M. calvescens is therefore an interesting case study of potential benefits of switching from containment to asset protection management approaches. We use a 25-yr management data set identifying the location and time of each M. calvescens individual eliminated, develop a spread model based on this data, and use information on treatment costs and potential avoided damages to assess the relative benefit-cost ratio of a variety of management strategies including inaction, containment, and asset protection, under a number of EMW-informed biological and economic parameters.

2. Methods

In order to analyze shifts in management strategies a spatiotemporal model was created to simulate a miconia invasion. Harnessing the life history traits and dispersal kernel profiled in Leary et al. (2018), the model projects the growth and diffusion of miconia from a single mature tree in an illustrative, uninvaded environment. Additionally, three different management strategies were applied to the model to assess the management costs, benefits (avoided damages) and the net present value and benefit-cost-ratio between them. The growth, diffusion, and the results of the management strategies are tabulated in one-year time steps over a 20-year time horizon.

a. Population model

The population model projects individual population demographics of miconia over a 20-year time period from one initial mature tree. A simplified three-stage stage-matrix model was adapted from Hester et al. (2010), Cacho et al. (2007), and Leary et al. (2018). The matrix was calibrated to reflect an intrinsic growth rate between 35% to 45% with plants reaching maturity at four years. Maturity is defined as the age where the plant achieves reproductive capabilities. Under these conditions, a population of 1,696 miconia trees reaches maturity in 20 years from one initial mature tree (Figure 1).

Each tree that reaches maturity in the model will have the individual population model applied to it to simulate the compounding effects of growth and diffusion. There is a four year "lag" period where miconia reaches maturity at four years in the simulation. As a result, four generations of plants reach reproductive age with the second, third, and fourth generations beginning in year 8, 12, and 16, respectively (Figure 1). This reflects the earliest possible timeline where we can see miconia reach maturity and begin to disperse seeds. As shown in Figure 1 the

Table 1. Population projections over 20 years starting with 1 initial mature tree at Year 0 (t0) with the total number of new trees that reach maturity in each year.

Year	Mature trees
Year 0	1
Year 1	0
Year 2	0
Year 3	0
Year 4	2
Year 5	3
Year 6	4
Year 7	6
Year 8	8
Year 9	11
Year 10	16
Year 11	22
Year 12	31
Year 13	44
Year 14	62
Year 15	88
Year 16	124
Year 17	176
Year 18	248
Year 19	351
Year 20	496

initial population (generation 1) has trees at a reproducible age from years 4 to 16, generation 2 begins four years later with trees producing offspring from years 8 to 20.

b. Spread Model

With the individual population model and timeline demonstrating growth over time, the spatial spread of miconia can be simulated. This was accomplished by creating a model that generates polar (x, y) coordinates for every new mature tree in the population model at the corresponding time step. By assigning coordinates to each tree, the dispersal kernel is transformed from a one-dimensional statistic that measures distance x from the maternal source to the site of progeny establishment, into a two-dimensional attribute that enables us to simulate and plot the spread of miconia. Each tree location, age it reached maturity, and generation are tabulated at each time step. This was accomplished by creating the following 'spread' function in R:

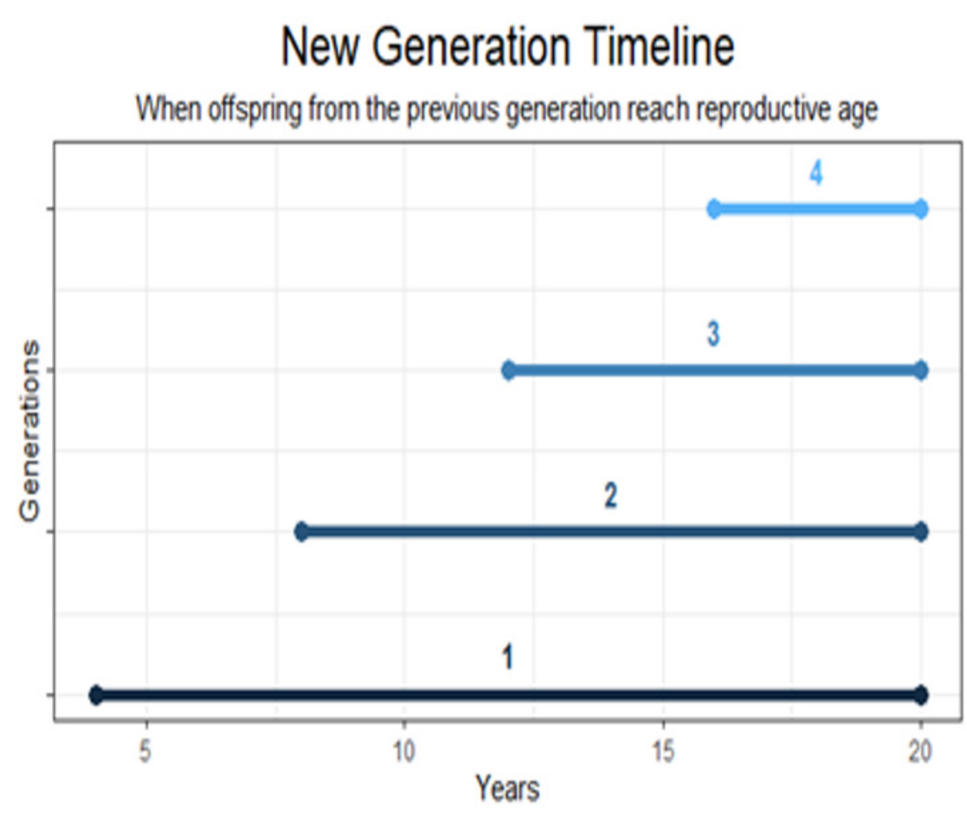


Figure 1. Miconia trees can reach maturity in as few as 4 years and begin reproducing. As a result, every four years the offspring from mature trees can be formed into generations.

i. Set the number of time steps to correspond to the year. For example, new mature trees in year 8 will only have 12-time steps to reproduce until the 20-year time horizon is reached.

ii. Draw a sample of random distances (x) from the data driven dispersal kernel (Leary et al., 2018) at each time step. The sample size is equivalent to the number of mature trees in the individual population model at that time step (Table 1). For example, year 5 in Generation 1 has 2 mature trees, therefore 2 random distances will be sampled from the dispersal kernel.

iii. A randomly generated Y coordinate between 0 and 2□ is assigned to each distance (x) to create polar (x, y) coordinates where each new tree establishes. Since habitat suitability is unknown, uniform distribution around each maternal source is assumed.

iv. Create a for loop that runs the 'spread' function at each time step to assign polar coordinates to each tree.

The 'spread' function only applied to one new mature tree and the population that it produces over the remaining time steps. The function is then applied to new mature trees at each time step (Table 1) to generate the miconia's growth and diffusion over time, which enables us to simulate management actions as the invasion occurs or in "real" time. For example, there will be six trees reaching maturity in generation 2, year 11, therefore the 'spread' function applied six times. This is accomplished by replicating the 'spread' function based on the number of trees reaching maturity four years prior in the previous generation. Applying the replicate function at each time step creates a dynamic model of the compounding growth effect that has the ability to track populations over time and adapt to changes through management.

c. Management Strategies

Three management strategies are applied to the model to reflect different invasion and economic outcomes. We define them as:

i. Inaction: No management actions or control effort to mitigate the invasion are taken and damages are accepted.

ii. Containment: A boundary that is established to prevent an invasion spreading into an uninvaded area beyond it. Management efforts are focused on eradicating any trees that occur beyond the containment boundary.

iii. Asset Protection: An uninvaded high value area that is protected from invaders. Management efforts are focused on eradicating any trees that occur within the high value area.

Damages incurred from the invasion are given two classifications of either low or high damage depending on where tree establishment occurs. They are defined as:

Low damage: Any tree reaching maturity outside of the asset protection area.

High damage: Any tree that reaches maturity within the asset protection area.

d. Management scenarios

Three different management scenarios (Baseline, Close, Aligned) were applied to each of the above management strategies to quantify the different ecological and economic outcomes. One key assumption in all management scenarios is that control efforts are assumed to be 100% effective. While unrealistic, this assumption "normalizes" the model to produce comparable outcomes.

In containment strategies, at each time-step, plants that reach maturity beyond the containment boundary are identified, tabulated, and removed from the model. For the asset protection approach, if the asset protection area is within (beyond) the containment boundary, trees reaching maturity are also identified, tabulated, and removed from the model. Additionally, at each time-step, plants that reach maturity inside the asset protection area are identified, tabulated, and removed from the model. An asset protection area was established 150 m from the initial mature miconia tree (invasion point) at t0 and remained unchanged in each simulation. The location of the containment boundary distinguished the key difference between each scenario.

i. Baseline management scenario (Figure 2)

In the baseline management scenario, the containment boundary is established 100 m from the initial invasion point and remains static throughout the entire simulation. The asset protection is a 150 sq. m subset of the containment area and lies 50 m past the containment boundary or 150 m from the initial invasion point. Low damages refer to any trees outside of the asset protection and high damages occur inside it.

ii. Close management scenario (Figure 3)

In the close management scenario, the containment boundary is established 10 m from the initial invasion point and remains static throughout the entire simulation. The asset protection is a 150 sq. m subset of the containment area and lies 140 m past the containment boundary or 150 m from the initial invasion point. Low damages refer to any trees outside of the asset protection and high damages occur inside it.

iii. Aligned management scenario (Figure 4)

In the aligned management scenario, the containment boundary is established 150 m from the initial invasion point and remains static throughout the entire simulation. The asset protection is a 150 sq. m subset of the containment area and is aligned with the containment boundary. Low damages refer to any trees outside of the asset protection and high damages occur inside it.

Statistics and simulations were done using R 3.5.2 (R Core Team, 2019), RStudio (RStudio Team, 2019), and the kdensity (v1.0.1; Moss and Tveten, 2019), popbio (v2.6; Stubben and Milligan, 2007), tidyverse (v1.3.0; Wickham et al., 2019) packages.

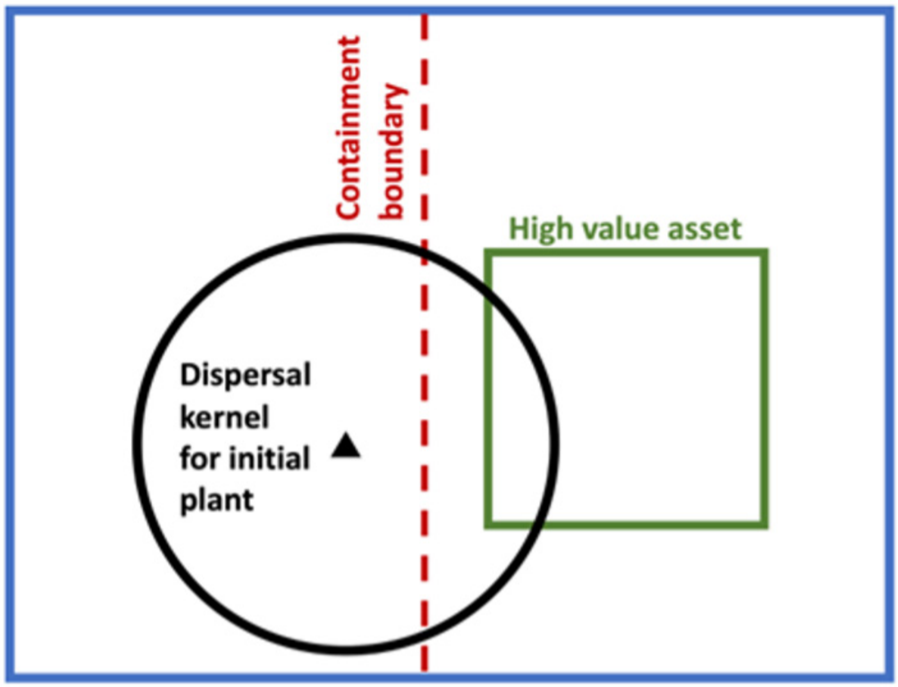


Figure 2. Baseline management scenario.

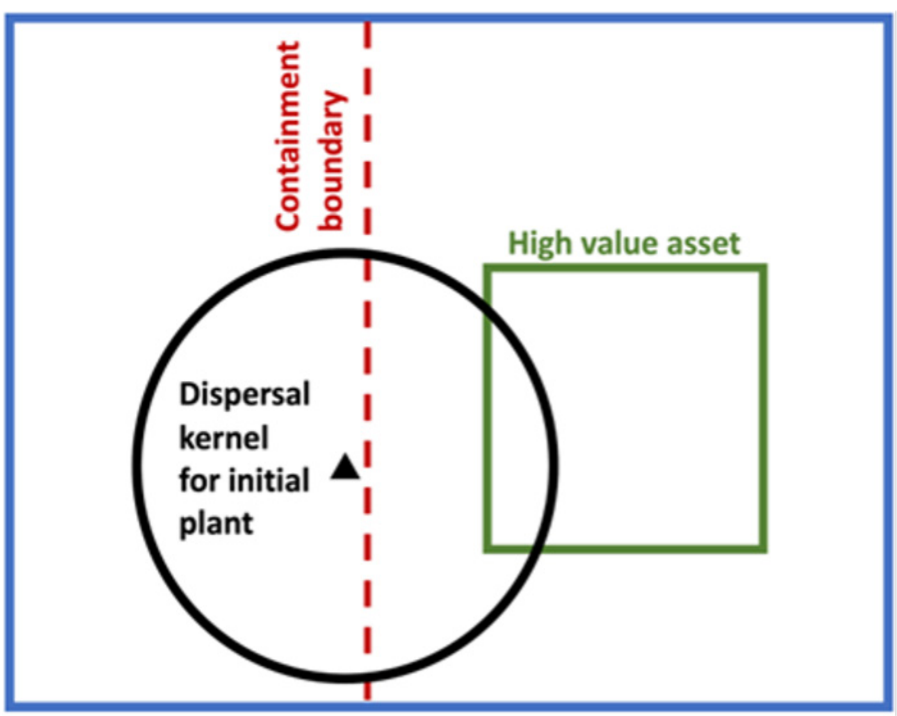


Figure 3. Close management scenario.

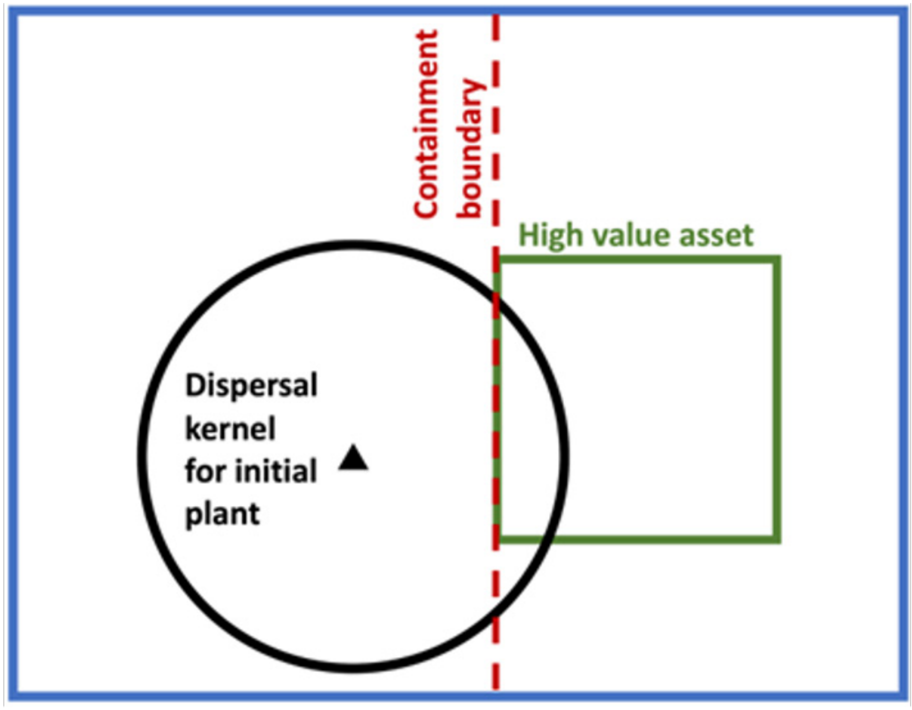


Figure 4. Aligned management scenario.

e. Management costs

The variable cost of herbicide ballistic technology (HBT) operations is driven by helicopter flight time and herbicide use rate. Following Leary et al. (2018), we assume that the mean flight time to engage a target M. calvescens plant is 39.6 seconds. At helicopter contracting costs of approximately $1,200 per hour on Maui, this translates to $13.07 per target. The mean herbicide dose required to effectively eliminate a target is estimated at 23.3 projectiles (Leary et al., 2018). Given a cost of $0.31 per projectile, the total herbicide cost per target is $7.22. After adjusting for inflation, this brings the total cost of eliminating a single M. calvescens plant to $21.07 in 2019 dollars. For comparison, Burnett et al. (2007) estimated a treatment cost of $13.39 per plant, or $17.37 in 2019 dollars after adjusting for inflation. The difference in costs is not unreasonable given that HBT had not yet been developed in 2007, and the treatment cost estimate at that time was based on ground crew operations, which are generally less costly on a per target basis but are more geographically limited. The management cost function is defined as Cit = 21.07xit, where xit is the number of plants treated in period t under management strategy i.

f. Management benefits (avoided damages)

Benefits of a candidate M. calvescens management strategy are estimated as the difference between the (lower) damages realized under management and the (higher) damages that would have been realized in a counterfactual "no management" future (the Inaction approach), where damages are measured in terms of reductions in ecosystem services. Following Burnett et al. (2007), we focus primarily on three services—native bird habitat, groundwater recharge, and protection against sedimentation—although we recognize that additional negative impacts could be realized in the absence of management. Consequently, our estimates should be viewed as conservative. For each of the three ecosystem services of interest, we first calculate the total potential damage at our study site as detailed in the remainder of this section. Assuming a linear damage function (Burnett et al., 2007), we then estimate a value for the damage coefficient (d) in the equation D(N) = d*N, using the maximum potential damage, D(Nmax), and the carrying capacity at the study site, (Nmax). Lastly, the damage equation is applied to the stock of M. calvescens plants (N) in both the management and "no management" futures, and the benefit is calculated in each year as the difference in damages, which represents the damages avoided by management activities.

Maui is home to 11 threatened or endangered bird species, many of which are reliant on the existing native forest structure for continued survival (US FWS, 2010). Because M. calvescens poses a major threat to that structure, failing to prevent its spread would result in the loss of critically important habitat. Following the approach taken in Burnett et al. (2007), we use Loomis and White's (1996) estimate that, on average, a typical household would be willing to pay $31 per bird species per year to prevent extinction. After adjusting for inflation and multiplying by the 455,502 households in the state (U.S. Census Bureau, 2019), the annual value for all Hawai'i residents of preserving each bird species is $24.2 million per year in 2019 dollars. If we further assume that half of the 11 bird species are at risk following Burnett et al. (2007), then the total potential damage due to habitat loss on Maui is approximately $132.9 million annually. Because our study site in East Maui is a subset of the island's total area, we adjust the potential losses in proportion to the site's estimated carrying capacity for M. calvescens, resulting in potential damages of $6.3 million per year at carrying capacity.

Changes to forest structure can have significant impacts on water balance in a watershed, including reductions in groundwater recharge. Although knowledge about the freshwater impacts of M. calvescens is currently limited, some studies have suggested that when compared to native canopy species in Hawai'i, invasive canopy trees tend to have higher evapotranspiration rates and lower fog interception rates, leaving less water to ultimately recharge underlying aquifers (Giambelluca et al., 2008; Takahashi et al., 2011; Cavaleri et al., 2014). Kaiser and Roumasset (2002) estimated that a 41 million gallon per day (mgd) loss in recharge on O'ahu due to invasion by non-native plant species would generate losses of $137 million per year, or roughly $3.3 million per mgd per year. Using results from Bremer et al. (2019), we conducted a similar exercise and found that annual losses on Maui likely range from $3.1 to $5.7 million per mgd depending on whether damages are estimated using average values in transition to full invasion by non-native forest or estimated using the full-invasion values.

In addition to altering groundwater recharge via evapotranspiration and fog capture, invasion by non-native forest can increase sedimentation if the changes to forest structure alter the runoff-to-recharge ratio in invaded areas (Kaiser and Roumasset, 2000). Following Burnett et al. (2007), we assume that every mgd of lost groundwater recharge generates $1.6 million per year in sedimentation damages after adjusting for inflation.

In summary, we estimate that the total damage from M. calvescens at full carrying capacity in our East Maui site is in the range of $11.0-14.7 million (Table 2).

Table 2. Estimated total damage from Miconia calvescens at full carrying capacity in East Maui, Hawai'i.

Bird Habitat Damage Estimate ($ million)	**Groundwater Recharge Damage Estimate ($ million)**	**Sedimentation Damage Estimate ($ million)**	**Total Combined Damage Estimate ($ million)**
6.3	3.1-5.7	1.6-2.7	11.0-14.7

Recalling our linear damage equation, $D(N) = d*N$, we can plug in the total damage estimates above and the carrying capacity Nmax to calculate the value of the damage coefficient (d). We assume that the average density of trees in an invaded area is 100 trees per acre. Then given the approximately 6,721 acres of potential M. calvescens habitat at our study site, Nmax = 672,100 trees. The resulting coefficient values of $16.39/tree and $21.89/tree are assigned to untreated M. calvescens outside and inside the high priority asset zone respectively. This results in a slight modification of our damage equation as follows: $D(N) = dh*Nh + dl*Nl$, where the h (high priority) and l (low priority) subscripts designate the damage coefficients and the number of M. calvescens plants inside and outside the high priority asset protection zone respectively.

Finally, we estimate the benefit of management strategy i in year t as $Bit = Dot - Dit$, where Dot is the damage in year t for the “no management” case. That is, the benefit of management strategy i in year t is the difference between the damages realized with no management and the damages realized under strategy i. In simple terms, the benefit of management is measured as the damages avoided that would have otherwise occurred in the absence of management.

g. Net present value and benefit-cost ratio

With our management costs and benefits clearly defined, we can now calculate the net benefit (NB) of management strategy i in period t: $NBit = Bit - Cit$. However, because the timing of the benefits and costs will vary across management strategies, comparing the stream of net benefits over time can be difficult. To make the outputs more directly comparable, we compress those streams into net present values (NPV) using the following equation: $NPVi = \sum t[NBit(1+r)-t]$, where r is the discount rate. The net benefit in each period is discounted (weighted) according to $r = 0.03$, and each discounted NB is then summed over all of the time periods (t). We also calculate the benefit-cost ratio (BCR) of each strategy, where $BCRi = \sum t[Bit(1+r)-t]/\sum t[Cit(1+r)-t]$.

h. Damage function uncertainty and switching points

Given the high level of uncertainty surrounding the damage function coefficients, we also estimate NPV and BCR for each management strategy under the assumption that the damage coefficients are +/-25% of their initial values. For each hypothetical geographical scenario (containment boundary 100 m from maternal source, containment boundary 10 m from maternal source, containment and asset protection boundaries aligned at 150 m from maternal source), we compare the NPV and BCR of each management strategy under the assumption of low, medium, and high damage. We then determine the values of the damage coefficients for which the NPV of containment and asset protection become equal under each scenario, i.e. we identify the management switching points.

3. Results

Inaction (Figure 5) results in present value damages totaling $144,800 in present value terms under the assumption of moderate damages per tree. For the baseline geographic scenario (Figure 6), the containment strategy generates a higher NPV ($7300) than asset protection ($1100), although the BCRs are equal (2.2). For the close geographic scenario (Figure 8), the containment strategy generates a much higher NPV ($34,100) than asset protection ($1100), but the BCRs remain equal (2.2). When the geographic boundaries are aligned (Figure 7), the NPV for containment ($1500) remains higher than for asset protection ($1100). However, the BCR is higher for asset protection (2.2) than for containment (1.5), which suggests that the former is more cost-effective, in the sense that it generates more benefits per dollar invested. Results for the moderate damage case are summarized in Table 3.

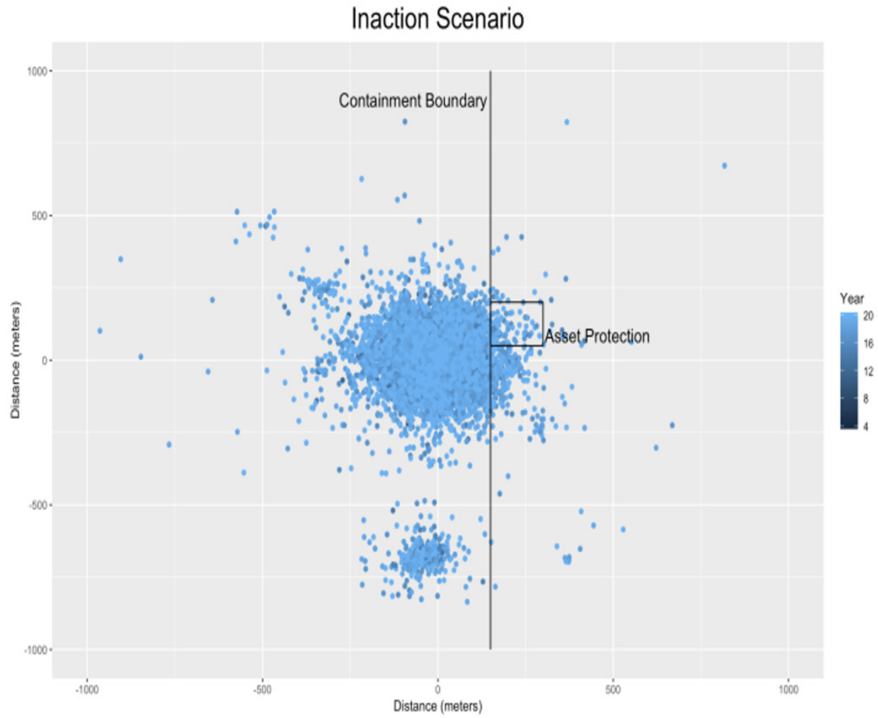
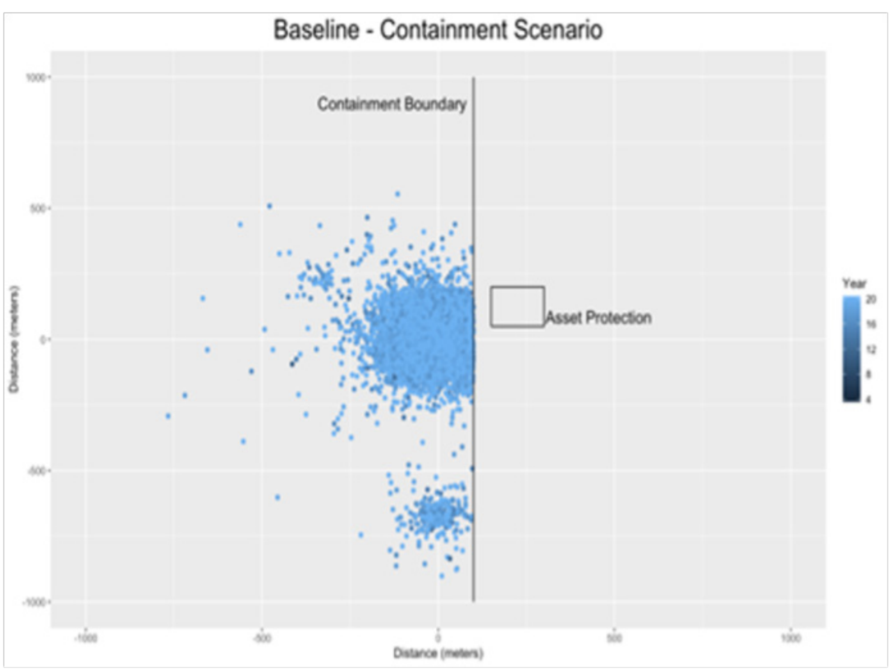


Figure 5. Inaction Scenario. No management actions are taken, and the invasion and resultant damages are accepted.

When damages per tree are lower, the consequences of inaction are correspondingly lower ($108,600). In the baseline geographic scenario, the NPV of containment ($3900) still exceeds asset protection ($600), although the gap is smaller than for the moderate damage case. Similarly, in the close geographic scenario, the NPV of containment ($18,400) is larger than asset protection ($600), but the difference is smaller than observed under the assumption of moderate damages.

For both geographic scenarios, the BCR is slightly higher for asset protection (1.7) than for containment (1.6). The most notable change occurs when the geographic boundaries are aligned. In that scenario, both NPV and BCR are higher for asset protection ($600 and 1.7) than for containment ($300 and 1.1). Table 3 summarizes results for the low damage case (numbers in round brackets).

(A)



(B)

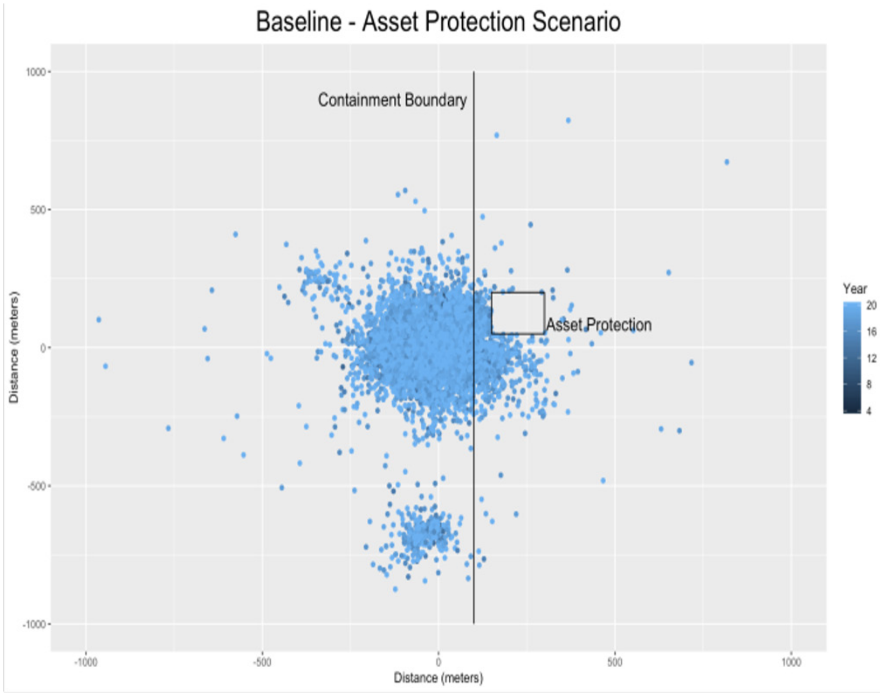
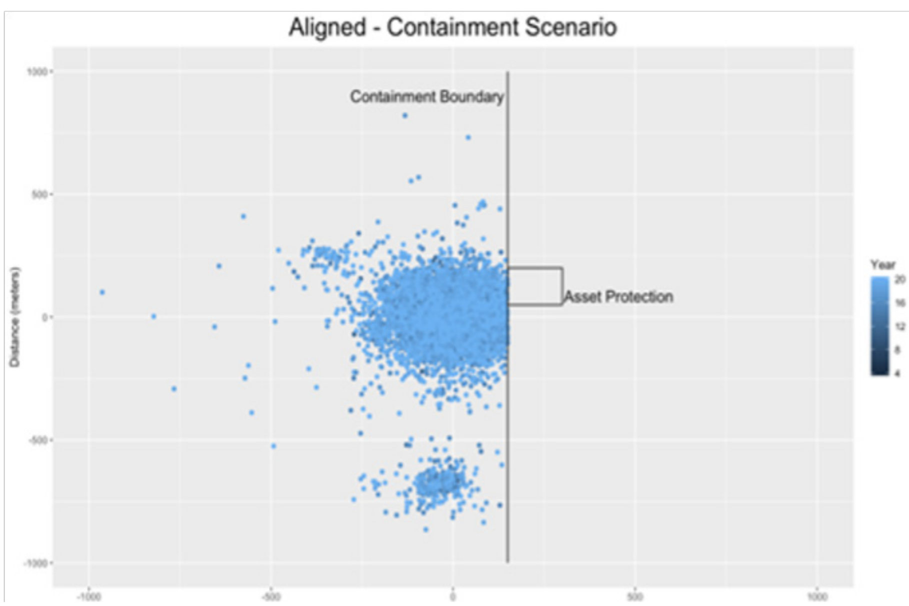


Figure 6. Baseline management scenario results. A) Invasion results after containment actions are taken by management. B) Invasion results after asset protection actions are taken by management.

(A)



(

(B)

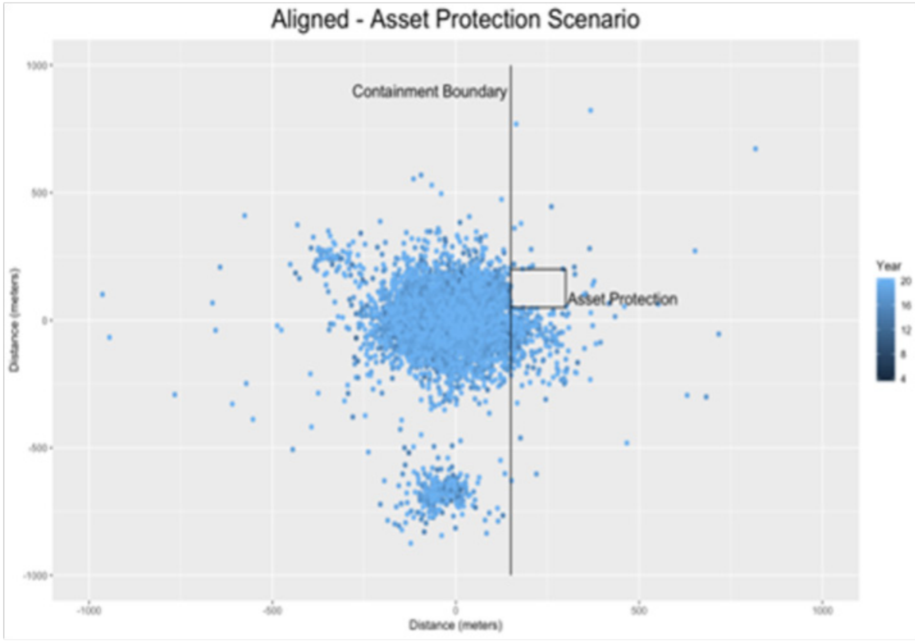
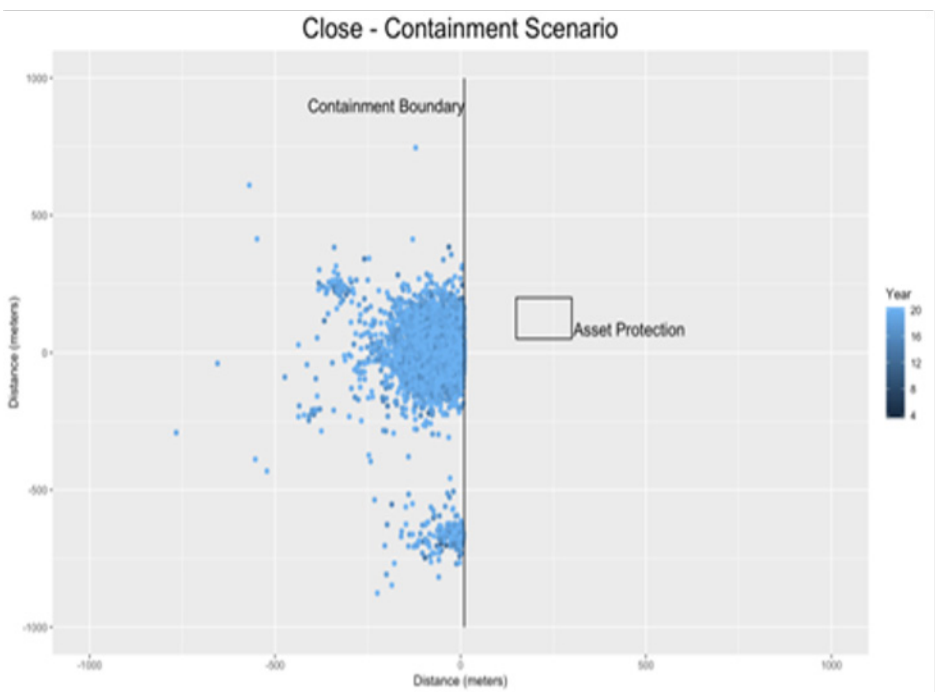


Figure 7. Aligned management scenario results. A) Invasion results after containment actions are taken by management. B) Invasion results after asset protection actions are taken by management.



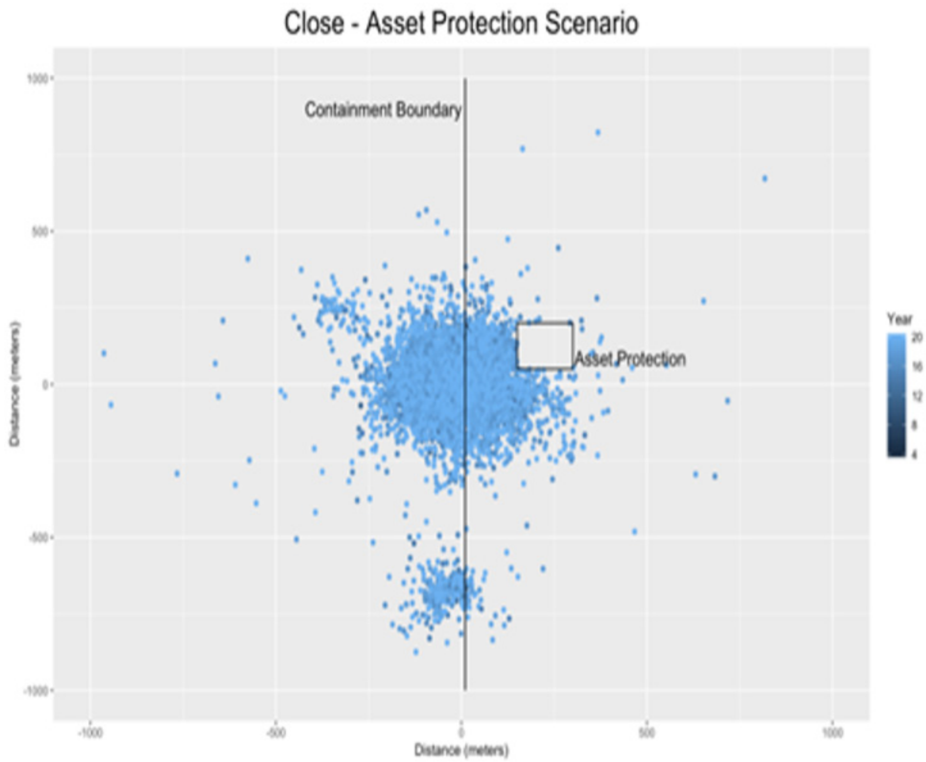


Figure 8. Close management scenario results. A) Invasion results after containment actions are taken by management. B) Invasion results after asset protection actions are taken by management.

In the case that damages per tree are higher, the consequences of inaction are also higher ($181,000). It follows that the benefits of management are also generally higher across the board. For the baseline geographic scenario, the NPV of containment ($10,600) exceeds the NPV of asset protection ($1600) by a larger margin than for the moderate and low damage cases. Similarly, for the close geographic scenario, the difference between the NPV of containment ($49,900) and asset protection ($1600) is larger than when damages are lower per tree. Like in the previous cases, the BCR remains roughly constant across management strategies for the baseline and close geographic scenarios. For the aligned geographic scenario, the NPV for containment ($2800) remains higher than asset protection ($1600), but asset protection generates a higher BCR (2.7 vs. 1.8). Results for the high damage case are presented in Table 3 (numbers in square brackets).

Lastly, we calculate the approximate switching point (in terms of the damage parameter values), beyond which the most efficient management strategy transitions from containment to asset protection. Here we classify a management strategy as "efficient" if it has both a higher NPV and BCR than alternative management strategies under consideration. The breakeven point occurs when the damage parameters are approximately 84% of their baseline values. When the values of the damage parameters are below this threshold, asset protection is more efficient than containment.

4. Discussion

The preferred miconia management strategy varies across geographic scenarios and in accordance with the assumed damage coefficient values. When the containment boundary is relatively close to the maternal source (baseline and close scenarios) and far from the asset protection zone, the containment strategy generates a higher NPV than asset protection and an equivalent BCR, regardless of the damage coefficient values. This type of spatial configuration results in more trees crossing the containment boundary and being treated, without necessarily falling into the asset protection zone. The effect of higher avoided damages (PV benefits) under the containment strategy outweigh the higher PV costs associated with the removal of more trees. In other words, containment is preferred when the containment boundary and invasion front are far from the high value asset.

Table 3. Present value damages, management costs, avoided costs (benefits), net present value, and benefit cost ratio for each management strategy and geographical scenario under the assumption of moderate damage. Results for low and high damage coefficient values reported in round and square brackets respectively.

Management strategy	PV damages (thousand dollars)	PV management costs (thousand dollars)	PV benefits (thousand dollars)	Net present value (thousand dollars)	Benefit cost ratio
No management	144.8 (108.6) [181.0]	- (-) [-]	- (-) [-]	- (-) [-]	- (-) [-]
Asset Protection					
Asset protection	142.9 (107.2) [178.6]	0.9 (0.9) [0.9]	2.0 (1.5) [2.5]	1.1 (0.6) [1.6]	2.2 (1.7) [2.8]
Scenario 1: baseline					
Containment	131.4 (98.5) [164.2]	6.2 (6.2) [6.2]	13.5 (10.1) [16.8]	7.3 (3.9) [10.6]	2.2 (1.6) [2.7]
Scenario 2: close					
Containment	82.0 (61.5) [102.4]	28.7 (28.7) [28.7]	62.9 (47.2) [78.6]	34.1 (18.4) [49.9]	2.2 (1.6) [2.7]
Scenario 3: aligned					
Containment	140.0 (105.0) [174.9]	3.3 (3.3) [3.3]	4.9 (3.7) [6.1]	1.5 (0.3) [2.8]	1.5 (1.1) [1.8]

However, when the containment and asset protection boundaries are relatively far from the maternal source but very close to each other (aligned scenario), asset protection may become the more desirable management strategy, especially when the damage coefficient values are low. In fact, when the damage coefficients are 84% or lower than their baseline values, asset protection is always preferred (higher NPV and BCR). In this particular spatial configuration, a high percentage of trees that cross the containment boundary also fall within the high value asset zone, and the cost of removing all of the trees that end up outside of the high value asset zone but beyond the containment boundary is not justified by the benefit (avoided damage) of doing so. That is to say, as the invasion front moves toward the high value asset, efficient management transitions from containment to asset protection.

The primary goal of the research presented in this chapter was to develop an operational methodology for evaluating biological and economic outcomes of containment and asset protection management strategies for M. calvescens in East Maui. Given the multiple dimensions of uncertainty in parameter values governing miconia dispersal, spread, and management, the results of our simulations should be viewed as illustrative. Nevertheless, we believe that our big picture conclusions are generally robust and provide a reliable method of assessing relative costs and associated benefits of the different management strategies. With our modeling framework as a foundation, future research can build on our findings and continue to reduce uncertainty by, for example, incorporating search costs, adjusting the biological model to allow for non-uniform miconia habitat suitability across the landscape, considering additional spatial configurations of management boundaries, and determining the optimal timing for switching from one management strategy to another.

References

Braysher M (2017) 'Managing Australia's Pest Animals: A Guide to Strategic Planning and Effective Management.' (CSIRO Publishing: Melbourne.)

Bremer, L. L., Wada, C. A., Medoff, S., Page, J., Falinski, K., & Burnett, K. M. (2019). Contributions of native forest protection to local water supplies in East Maui. Science of The Total Environment, 688, 1422–1432. https://doi.org/10.1016/j.scitotenv.2019.06.220

Burnett K, Kaiser B, Roumasset J (2007). Economic lessons from control efforts for an invasive species: Miconia calvescens in Hawaii. Journal of Forest Economics 13:151-167. doi: 10.1016/j.jfe.2007.02.007.

Cacho, O.J., Hester, S. and Spring, D. (2007), Applying search theory to determine the feasibility of eradicating an invasive population in natural environments. Australian Journal of Agricultural and Resource Economics, 51: 425-443. doi:10.1111/j.1467-8489.2007.00389.x

Cacho OJ, Wise RM, Hester SM, Sinden JA (2008) Bioeconomic modeling for control of weeds in natural environments. Ecol Econ 65: 559–568.

Cavaleri MA, Ostertag R, Cordell S, Sack L (2014) Native trees show conservative water use relative to invasive trees: results from a removal experiment in a Hawaiian wet forest. Conservation Physiology 2:1-14. doi: 10.1093/conphys/cou16.

Department of Environment and Primary Industries Victoria (2017). 'Protecting Victoria from Pest Animals.' (The State of Victoria: Melbourne, Vic.)

Gagné BH, Loope LL, Medeiros AC, Anderson SJ (1992) Miconia calvescens: a threat to native forests of the Hawaiian Islands. Pac Sci 46:390–391.

Giambelluca TW, Delay JK, Asner GP, Martin RE, Nullet MA, Huang M, Mudd RG, Takahashi M (2008) Stand structural controls on evapotranspiration in native and invaded tropical montane cloud forest in Hawai'i. American Geophysical Union.

Giambelluca TW, Sutherland RA, Nanko K, Mudd RG, Ziegler AD (2009) Effects of Miconia on hydrology: a first approximation. In Loope LL, Meyer JY, Hardesty BY, Smith CW, eds. Proceedings of the International Miconia Conference, Keanae, Maui, Hawaii, USA, May 4–7 2009. Honolulu, HI: Maui Invasive Species Committee and Pacific Cooperative Studies Unit, University of Hawaii at Manoa. 7 p.

Hester, S.M., Brooks, S.J., Cacho, O.J. And Panetta, F.D. (2010), Applying a simulation model to the management of an infestation of Miconia calvescens in the wet tropics of Australia. Weed Research, 50: 269-279. doi:10.1111/j.1365-3180.2010.00778.x

Kaiser B, Roumasset J (2000) Water management and valuation of indirect environmental services. Interdisciplinary Environmental Review 2:102-122.

Kaiser B, Roumasset J (2002) Valuing indirect ecosystem services: the case of tropical watersheds. Environment and Development Economics 7:1-12. doi: 10.1017/S1355770X02000426.

Leary J, Mahnken BV, Cox LJ, Radford A, Yanagida J, Penniman T, Duffy DC, Gooding J (2014) Reducing nascent miconia (Miconia calvescens) patches with an accelerated intervention strategy utilizing herbicide ballistic technology. Invasive Plant Sci Manag

7:164–175.

Leary J, Mahnken B, Wada CA, Burnett K (2018) Interpreting life-history traits of miconia (Miconia calvescens) through management over space and time in the East Maui Watershed, Hawaii (USA). Invasive Plant Science and Management 11:191–200. doi: 10.1017/inp.2018.26.

Loomis JB, White DS (1996) Economic benefits of rare and endangered species: summary and meta-analysis. Ecological Economics 18:197-206.

Loope LL, Medeiros AC (1994) Impacts of biological invasions on the management and recovery of rare plants in Haleakala National Park, Maui, Hawaiian Islands. Pages 143–158 in Bowles M, Whelan CJ, eds. Restoration of Endangered Species. Cambridge: Cambridge University Press.

Lowe S, Browne M, Boudjelas S, De Poorter M (2000) 100 of the World's worst invasive alien species: A selection from the Global Invasive Species Database. Volume 12. Auckland: Invasive Species Specialist Group.

Medeiros AC, Loope LL, Conant P, McElvaney S (1997) Status, ecology, and management of the invasive plant, Miconia calvescens DC (Melastomataceae) in the Hawaiian islands. Bishop Museum Occasional Papers 48:23–36.

Medeiros AC, Loope LL, Hobdy RW (1995) Conservation of cloud forests in Maui County (Maui, Moloka 'i, and Lana 'i), Hawaiian Islands. Pages 223– 233 in Hamilton LS, Juvik JO, Scatena FN, eds. Tropical Montane Cloud Forests. New York: Springer.

Meyer JY, Florence J (1996) Tahiti's native flora endangered by the invasion of Miconia calvescens DC. (Melastomataceae). J Biogeogr 23:775–781.

Meyer JY, Malet JP (1997) Study and management of the alien invasive tree Miconia calvescens DC (Melastomataceae) in the islands of Raiatea and Tahaa (Society Islands, French Polynesia): 1992–1996. Honolulu, HI: University of Hawaii Cooperative National Park Resources Studies Unit Technical Report 111.

Moss J, Tveten M, (2019). kdensity: Kernel Density Estimation with Parametric Starts and Asymmetric Kernels. R package version 1.0.1. https://CRAN.R-project.org/package=kdensity

Nanko K, Giambelluca TW, Sutherland RA, Mudd RG, Nullet MA, Ziegler AD (2015) Erosion potential under Miconia calvescens stands on the Island of Hawaii. Land Degrad Dev 26:218–226.

Nanko K, Watanabe A, Hotta N, Suzuki M (2013) Physical interpretation of the difference in drop size distributions of leaf drips among tree species. Agric For Meteorol 169:74–84.

R Core Team (2019) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

R Studio Team (2019). RStudio: Integrated Development for R. RStudio, Inc., Boston, MA URL http://www.rstudio.com/.

Shade PJ (1999) Water Budget of East Maui, Hawaii. U.S. Geological Survey Investigations Report No. 98-4159.

Stubben CJ, Milligan BG (2007) Estimating and analyzing demographic models using the popbio package in R. Journal of Statistical Software 22:11.

Takahashi M, Giambelluca TW, Mudd RG, DeLay JK, Nullet MA, Asner GP (2011) Rainfall partitioning and cloud water interception in native forest and invaded forest in Hawai'i Volcanoes National Park. Hydrological Processes 25:448-464. doi: 10.1002/hyp.7797.

U.S. Census Bureau. (2019). QuickFacts Hawaii. https://www.census.gov/quickfacts/HI. Accessed on Dec 11, 2019.

U.S. Fish and Wildlife Service (USFWS). (2010). Hawaiian Island Animals: Updated April 13, 2010. Listed Species as Designated Under the U.S. Endangered Species Act. https://www.fws.gov/pacificislands/publications/listinganimals.pdf. Accessed on Dec 16, 2019.

Wickham et al., (2019). Welcome to the tidyverse. Journal of Open Source Software, 4(43), 1686, https://doi.org/10.21105/joss.01686