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BY

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Abstract

Biocontrol, the introduction of organisms to control an unwanted species, has been cited as a powerful method to manage the invasive species *Miconia calvescens* in Hawaii. In addition to ecological advantages, biocontrol is often regarded as less costly than traditional methods despite the large initial investment. Currently, miconia in Hawaii is treated through aerial and manual operations, which cost over $1 million annually. Biocontrol for miconia in Hawaii began in 1997 and the search for more agents continues today. Although biocontrol for miconia has already begun, prior to this study no assessment of its economic justifiability had been done. This research evaluates the present value of net benefits of miconia biocontrol in Hawaii. Cost data were gathered from scientists in charge of biocontrol programs. Benefits were defined as the cost-savings of current control methods. Two different biocontrol programs were modeled: control achieved by a single agent, and control achieved by a suite of agents. In addition, different dispersal rates and efficacies of biocontrol and two release dates were modeled. Because most costs of biocontrol are incurred before the release of a successful agent and the benefits are only realized post-release, each scenario was evaluated over a 50-year time horizon. The results indicate a positive present value of net benefits in all scenarios, ranging from $12.8 million to $36.1 million. Thus, biocontrol for miconia in Hawaii appears to be economically justifiable. This research should enable scientists, economists and policy makers to make informed decisions about the optimal management of *Miconia calvescens* in Hawaii.

Introduction

The objective of this project is to determine whether or not the biological control of *Miconia calvescens* is economically justified for the state of Hawaii. If biocontrol is to be instituted, its benefits should outweigh its costs. The net benefit of controlling *Miconia calvescens* in Hawaii has already been shown to be positive and an optimal level of control[1] has already been suggested (refer to Burnett et al. 2007). However, a comprehensive assessment of the net benefit of biocontrol for miconia had not been done prior to this research. This economic assessment establishes the costs and benefits of biological control programs for *Miconia calvescens* in Hawaii. Economists worked with scientists at the HDOA and USDA Forest Service in order to ensure that the estimation of costs, benefits, and efficacy made in the assessment accurately reflect what is considered by agencies when implementing biocontrol.

Materials and Methods

Project design: Conceptual overview

The economic assessment reflects biological benefits and costs, or those that scientists consider when exploring possible biocontrol agents; for example, which structures on miconia the agent attacks (i.e. reproductive, stems, leaves), which affects the efficacy of the agent and thus the benefits of biocontrol, or if the agent can easily become established in the miconia populations, which reduces the cost of implementing biocontrol and increases the rate of accumulated potential benefits.

[1] The optimal level of control does not indicate that miconia should be eradicated. Best management dictates that populations of the weed should be contained to the point until the cost of an additional unit of control is equal to the benefit of that extra unit of control. The very last miconia individuals may occur on a steep precipice and thus their removal would be exceedingly dangerous and costly. The benefit of removing the last few trees, on the other hand, might not be very high because a few miconia trees could not completely take over the ecosystem. Thus, the optimal level of control does not mean that every individual of miconia is removed.

In this assessment, the benefits of biocontrol are defined as cost-savings in comparison with current control methods (aerial and ground crew treatment with herbicides and manual control). For example, if current control costs $1 million annually and biocontrol achieves the same efficacy as this control, then the benefit of biocontrol would be $1 million per year[2]. These cost-savings represent a lower-bound estimate of the benefits of biocontrol, because they do not take into account the benefits associated from removing miconia from Hawaii, such as the value of native ecosystems and biodiversity (see Burnett et al. 2007 for a more detailed discussion of these aspects)[3]. This assessment assumes that miconia should be managed and examines the benefits of using biocontrol in comparison with current control methods. Several different benefit scenarios are evaluated, representing various levels of biocontrol efficacy based upon what structures the biocontrol agents attack.

There are two main classes of costs: fixed costs and variable costs. Fixed costs are incurred as lump-sum amounts and do not change with the amount of output produced. Fixed costs of biocontrol include all of the expenses incurred prior to the release of the agent: foreign exploration, quarantine and testing, and initial release. These costs are paid once for every agent and are independent of the amount of agent released or how much the agent is used in the future. The high up-front fixed costs reflect risk associated with introducing new species into native environments; the large investments in host-range testing reduce the risk that an introduced agent will have unintended deleterious effects[4]. Variable costs change with the amount of output

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[2] If biocontrol is not 100% effective: Again assuming that current control costing $1 million: if, biocontrol is 80% as effective as chemical and manual control, then the benefits of biocontrol will be $80,000 (0.80 * $1 million). An alternate way to express this 80% efficacy: implementing biocontrol would reduce the level of current control by 80% (only need to do 20% as much chemical and aerial treatment).

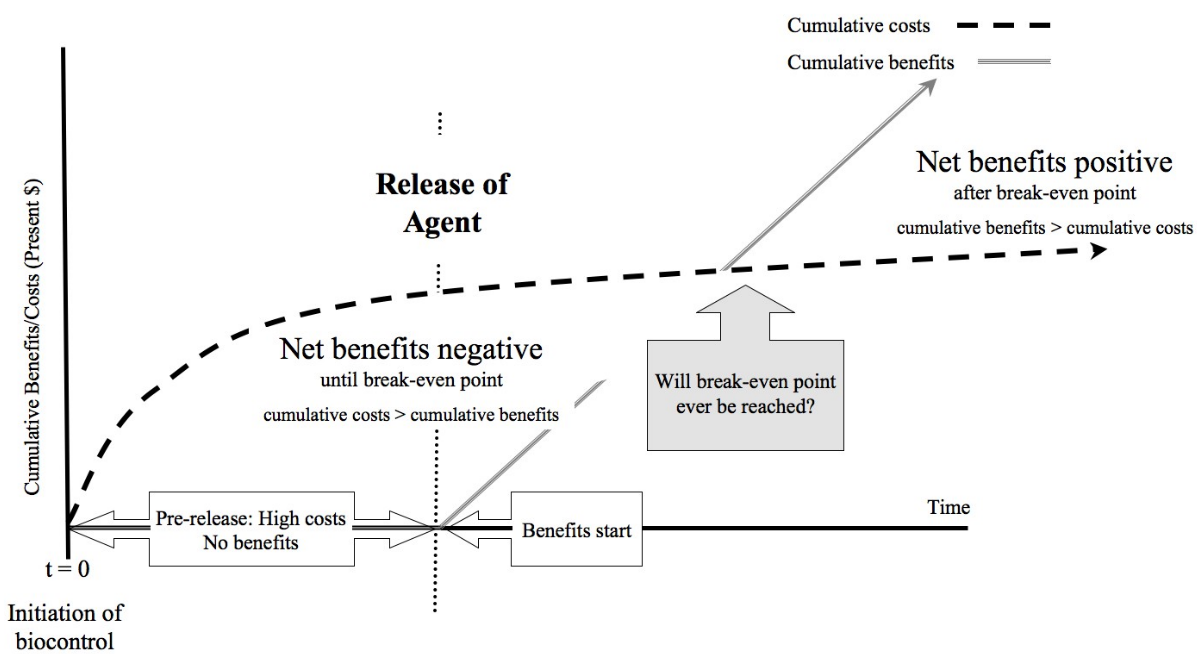
[3] In addition, these cost-savings do not include the potential damages of herbicides that are avoided by using biocontrol, such as the potential threat to native forests when chemical control is used at high elevations.

[4] This risk is a serious concern and is capitalized in the high upfront research costs. Negative perceptions of biocontrol are often fueled by well-known failures, such as the introduction of mongooses to control rats, which has resulted in increased threats of predation to native birds. Biocontrol is often controversial because the long-term

produced. Variable costs of biocontrol include money spent on subsequent inoculations of the agent (if necessary), money spent to monitor the biological control programs, and costs to renew biological control permits. Variable costs are incurred over time.

Because biocontrol programs require such high initial costs and incur potential benefits over long periods of time, it is important to conduct an economic assessment over an appropriate time horizon. The high fixed costs will outweigh the benefits over the first years of a biocontrol program. Neglecting to evaluate the net benefits over time can inaccurately portray biocontrol as economically unjustifiable. Because these net benefits are considered over time, discounting must be used to find the present value of net benefit. If the present value of net benefits is positive, then biological control should be implemented.

Figure 1: Overview of analysis



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effects of introduced organisms are unpredictable and can possibly cause more harm than good. However, studies have shown that in cases where biocontrol is used on weed species that have no close relatives in the native flora, such as *Miconia calvescens*, the risk of non-target impacts is very low (Pemberton 2000).

The economic assessment of miconia biocontrol was conducted in two parts: estimating the costs of miconia biocontrol programs in Hawaii, and estimating the benefits of successful biocontrol on the Big Island and Maui. All costs and benefits were adjusted into constant 2008 dollars using the UHERO Consumer Price Index (CPI). The time horizon for the analysis was 50 years from the release of a successful agent.

Two types of scenarios: Single agent ("silver bullet") and suite of agents

Because of the uncertainty associated with the establishment, spread, and success of biocontrol, different scenarios were modeled. Biocontrol agents vary widely in their abilities to disperse throughout the target area, rates of efficacy, and interactions with the environment and other species. Pathogens such as fungi or nematodes potentially spread more rapidly than insects with longer generational times, and efficacy in laboratory tests does not always translate to the same level of control in the field. While the preferable scenario is to release a single, scientists in Hawaii are also looking at the possibility of using a suite of agents that attack various structures on miconia. Thus, two types of scenarios were modeled: one for the release of a single successful agent, the "silver bullet" scenario, and one for the release of three agents resulting in cumulative levels of control, hereafter referred to as a "suite" of agents[5]. In the following description, the general framework of cost and benefit calculation will be explained, and then the details of each scenario will be expounded.

Costs

Cost data was gathered from scientists at the USDA and HDOA through interviews regarding the research and release of the fungus *C. gloeosporioides* and the initial costs of

[5] These names are used in accordance with M. Tracy Johnson's reference to the different scenarios of biocontrol.

research for *C. melastomae*, D. *gallaeformis* and *C. miconiae*. After a conference call with M. Tracy Johnson of the USDA and an interview with Darcy Oishi at HDOA, a spreadsheet containing different cost categories associated with biocontrol was developed and sent to scientists at the HDOA and USDA via e-mail. Costs were roughly divided into two categories: costs incurred prior to release of a successful agent, and costs incurred during and after the release of a successful agent.

Table 1: Summary of biocontrol costs

Pre-Release Costs	Release/Post-Release Costs
Collection of potential control agents	One-time release costs
Facility and lab space	Subsequent release/monitoring costs
Research personnel (initial rearing and testing)	Additional costs
Costs of agents that failed to establish	

The costs of foreign exploration were gathered from Dr. Robert W. Barreto, an overseas collaborator in Brazil. Dr. Barreto provided data from Research Corporation of the University of Hawaii (RCUH) payments made to the Universidade Federal de Vicosa as part of a cooperative agreement "Foreign Exploration for Biocontrol Agents against Miconia" from 1997 to 2008.

For the single agent scenario, the anticipated costs of biocontrol for the release were modeled for two initial release dates, 2014 and 2019, based upon feedback from the HDOA's Darcy Oishi, who estimated that under optimal conditions a suitable agent for miconia could be found within two to three years. Under the current conditions of less-than adequate facility space and fewer staff members available for miconia projects, therefore, it was reasoned that within five to 10 years (2014 and 2019 releases, respectively) a successful agent would be released.

For the suite of agents scenario, it was assumed that the first agent would be released in 2014, the second successful agent in 2022, and the third agent in 2030. The eight-year interval between releases of the subsequent agents was based on McFadyen's (1998) findings. McFadyen (1998) reports, "On average, each agent tested and introduced requires three scientist-years, which, with technical support and facilities, cost about $460,000 in 1997." Expressed in $2008, therefore, on average the total cost of testing and introducing each agent is approximately $612,000. In Hawaii, eight years of testing and research of a potential agent cost approximately $650,000; this substantially longer pre-release time (eight years versus three years) may reflect the afore-mentioned inadequate facility and lab space and fewer staff members. It was assumed that each agent required an equal amount of resources, which corresponded to eight years of pre-release testing and research in Hawaii. Thus, it was assumed that releases of the agents in the suite would occur at eight-year intervals.

Benefits

Calculation of benefits

The benefits of biocontrol were calculated based on cost data provided by the Big Island Invasive Species Committee (BISC) and Teya Penniman of the Maui Invasive Species Committee (MISC). Benefits were calculated for the Big Island and Maui, the islands with the largest miconia infestations where biocontrol would most likely be used. The benefits of biocontrol were defined as cost savings of current miconia control. Because the costs of miconia control differ on the Big Island and Maui, the benefits for each island were calculated separately and then summed for the overall benefit of miconia biocontrol for Hawaii.

Benefits: Big Island

Establishment of the biocontrol agent was modeled using the following exponential function. The use of the exponential function to model dispersal was confirmed with HDOA and USDA scientists.

Equation 1: **B(y):** $B_y = f e^{gy}$

where B_y is the proportion of managed acreage on the Big Island where the biocontrol agent is established in year y after release, f is the intercept coefficient, g is a constant specific to the dispersal rate, and *e* is the base of the natural logarithm (≈2.718).

Establishment rates were defined by the time it took for the agent to establish within 100% of the managed area on the Big Island after an initial release over 1 hectare (2.47 acres).

The proportion of managed acreage was multiplied by the total managed area to yield the number of managed acres in which the biocontrol was established each year (infested acres[6]):

Equation 2: B_y *** total managed acreage = infested acres**

To determine the total cost savings in that year, the number of acres infested with biocontrol was multiplied by the annual control cost per acre.

Equation 3: Infested acres * Annual control cost per acre = Cost savings per year

Benefit scenarios were analyzed over 50 years following the release of the first successful agent. The cost savings per year were summed to determine the total benefit of biocontrol. The total number of managed acres and annual control cost per acre for the Big Island were calculated based on data from the BISC and can be seen in Table 3.

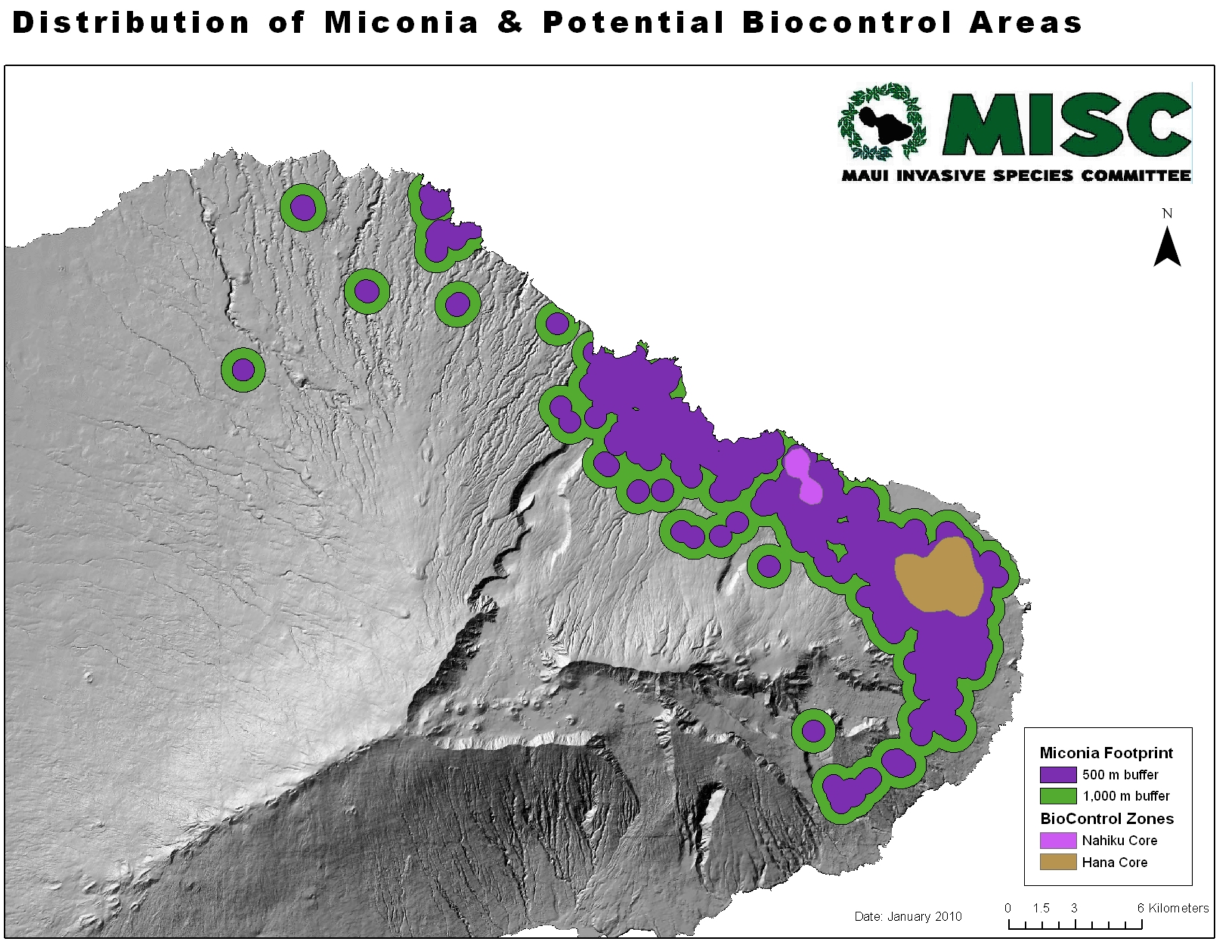
<u>Benefits: Maui</u>

The calculation of benefits on Maui followed the same methods as that for the Big Island, except that the total managed area was divided into two miconia populations, the "Maui core"

[6] Used here, "infested acres" means that biocontrol is established and achieving some level of control. In general, the spread of biocontrol can refer to 1) its dispersal throughout the area, indicated merely by the presence of the agent, 2) its establishment throughout the area, or when populations of the agent can be found in significant numbers, and 3) its presence and effect on the target species in the area.

and the "rest of Maui." These two areas differ in the level of miconia infestation and the control cost per acre.

Figure 2: Miconia infestation on Maui, 500 m and 1,000 m buffers



Source: T. Penniman, MISC, personal communication

The Maui core, which consists of two miconia infestations in Hana and Nahiku, has a population structure similar to that of the Big Island. Thus, it was assumed that biocontrol would establish in the Big Island and Maui core at the same rate.

Table 2: Size and age distribution of controlled plants in Big Island managed area and Maui core

	Big Island managed area	Maui core	
	% of miconia plants controlled	% of miconia plants controlled	
Age: 1.5 – 3 years	76.1%	71%	Height: 0 – 1 m
Age: 3 – 4.5 years	19%	20%	Height: 1 – 3 m
Age: 4.5 – 6 years	4.7%	8%	Height: 3 – 6 m
Age: 6+ years	0%	1%	Height: 6+ m

Sources: Big Island data from BISC, Maui core data from T. Penniman, MISC, personal communication[7]

Population age classes were not available for the other areas of Maui. From conversation with Teya Penniman, the MISC manager, it was determined that the miconia infestations throughout the rest of Maui were not as dense as those in the core. Thus, it was assumed that biocontrol would take twice as long to establish throughout these areas.

The data on managed acreage, miconia infestation and annual control costs on Maui were provided by Teya Penniman and were taken from GIS data and the MISC budget from FY 2008-2009. Only the annual costs of ground control were used in the calculation of cost savings for Maui; thus, these cost-savings represent a lower-bound estimate because they do not reflect the potential savings of aerial control. Only the cost savings from ground control were considered because Maui has traditionally exercised a much higher level of control than the Big Island, reflecting the different goals of miconia control on the two islands: Maui's goal is zero fruiting trees, while the Big Island is more focused on stopping the spread of the infestation. Even if biocontrol is introduced to Maui, it was assumed that MISC would continue some level of baseline management involving aerial sweeps. The annual cost savings for Maui were calculated

[7] Because of the different sources, the age class distribution was given in different units. It was assumed, after reviewing the literature about miconia growth, that these age and height classes were comparable across the two populations.

based on the average cost of control per acre in the Maui core; within a range based upon two different estimations of the cost of ground control in biocontrol areas. Teya Penniman, in her detailed report "Economics of Biocontrol Options for Miconia on Maui," which she prepared especially to enable this research, estimated that the cost of ground management per acre in the Maui core areas of Hana and Nahiku ranged from $188 to $235 per acre per three years. These estimations were averaged to produce the annual per acre values for Maui seen in Table 3, which summarizes the total managed acreage and annual control costs of the areas for which the benefits of biocontrol were calculated.

Table 3: Managed acres and annual control cost of miconia on the Big Island and Maui

	Big Island	**Maui core (Hana and Nahiku)**	**Rest of Maui**
Managed acres	13,325 acres	1,817 acres	26,242 acres
Annual control cost	$25.34 per acre	$70.50 per acre	$15.73 per acre
Total control cost	$337,655 per year	$138,099 per year	$413,092 per year

Source: BISC and T. Penniman, MISC, personal communication

Benefits: Single agent "silver bullet"

Different single agent scenarios were modeled to reflect differences in establishment rates and efficacy of potential agents. After literature review and consultation with scientists who worked on biocontrol in Hawaii, establishment rates of three, five, and seven years were modeled.[8] These rates were based upon a rough average worldwide establishment rate of five years (Andy Sheppard, CSIRO, personal communication) that was confirmed with scientists at the HDOA and USDA.

[8] In other words, the fastest-establishing agent modeled would take three years to establish within all 13,325 acres on the Big Island, while the slowest-establishing agent modeled would take seven years.

Table 4: Establishment rates for biocontrol agents

Dispersal rate	Dispersal time y	Dispersal function parameters	
	Years	*f*	*g*
Fast	3	2.52 E-06	4.30
Average	5	2.16 E-05	2.15
Slow	7	4.43 E-05	1.43

In addition to these three different establishment rates, four different rates of efficacy were also modeled to yield a total of 12 different scenarios.

Table 5: Rates of efficacy[9]

Efficacy Rate	Characteristics of agent	Impact on miconia management
100%	Severely impedes miconia reproduction	No further control required once all mature trees removed
92.5%	Significantly effective at slowing miconia reproduction	May still have to conventionally treat fruiting and mature trees and their seedlings
77.5%	Very effective against immature survival of miconia plants	Discontinue treatment of juvenile and immature plants (ground control), focus effort on fruiting and mature trees (aerial control)
50%	Causes vegetative disturbance, weakens immature plants, delays miconia reproduction	Reduce treatment of juvenile and immature plants, continue to manage fruiting and mature trees

In the non-core populations of Maui, the establishment of the silver bullet agent was modified to reflect MISC's strategy for miconia control and the different population structure of this area. On Maui, biocontrol would be introduced in the core areas of Hana and Nahiku first and then spread to the rest of the infestation; thus it was assumed that the benefits of biocontrol in the non-core areas of Maui would begin to accrue only after biocontrol became established

[9] Refer to Lee et al. (2010) for a more detailed discussion based on population models and transformation matrices for the population structure after these four types of agents are established.

throughout the entire core area. It was assumed that the agent would establish twice as slowly in non-core areas of Maui due to the less-dense populations of miconia. Although the concept of efficacy was simple to apply to the calculation of net benefits, and only involved multiplying the calculated benefits by the efficacy rate, it is important to realize that these efficacy rates are tied to particular characteristics of the agents themselves. Different agents will attack different parts of the plant, and not all agents or their targets on miconia are equal. For example, an agent that causes vegetative disturbance by chewing holes in miconia leaves will weaken the plant and make it look unhealthy but might not greatly decrease the plant's reproductive ability[10]. This agent would therefore be less effective than another agent that attacks miconia's reproductive structures. The efficacy of biocontrol could also be affected by the presence of natural enemies of the biocontrol agents, such as parasites or predators. Thus, the simple percentages used to model efficacy belie more complex biological factors.

Benefits: Suite of agents

The suite was comprised of three different agents that achieved a cumulative efficacy of 95%. This cumulative efficacy rate was used based upon the reasoning that an ideal suite of agents would achieve almost complete control, although some follow-up treatment might be required. The estimated 95% efficacy rate was used because there was no detailed literature found about biocontrol programs in which a number of agents were involved in success of controlling the weed, as efficacy is difficult to evaluate and varies on a case-by-case basis. The number of agents was based upon the findings of Denoth et al. (2002) who analyzed 59

[10] As mentioned earlier, recent results from Tahiti indicate that the partial defoliation may produce benefits as well. The increased light reaching the floor allows more native species to come back and increases biodiversity, as J.Y. Meyer and R. Taputuarai reported in their presentation at the 2009 International Miconia Conference. This is a positive externality that is not encapsulated by a reduction in the costs of managing the area, and is another reason that just evaluating cost savings is a lower-bound estimate.

biocontrol projects against weeds worldwide and found that an average of 2.9 agents were involved in projects where control was achieved by multiple agents[11].

The three agents were assumed to have increasing marginal efficacy rates. It was assumed that the first agent would achieve a 20% reduction in current control, the combination of the first and second agents would result in a 50% reduction, and with the entire suite of agents 95% of current control efforts could be saved. These rates were estimated based on the reasoning that subsequent agents would attack different structures on the plant, progressively weakening miconia's ability to reproduce; for example, the first agent might attack the leaves of miconia, reducing its ability to photosynthesize; the second agent might damage the stems of miconia, reducing its ability to uptake nutrients and water from the soil, and the third might attack reproductive structures of the plant. The combined effects of these three agents would be almost complete miconia control. This follows the cumulative stress model, which postulates that increasing the number of biocontrol agents improves success of the program (Harris 1985). Again, these estimates were developed after a thorough literature search did not reveal any studies about biocontrol programs in which success was achieved by multiple agents.

As detailed in the "Costs" section, it was assumed that one agent would be released every eight years. It was assumed that each agent would take five years to establish in the Big Island, with the same establishment rate throughout the core of Maui and twice as slowly in the non-core areas. Given these assumptions, it would take the entire suite of agents 20 years to become completely established within the entire managed acreage of the Big Island.

[11] McFadyen (1998) presents data from 39 biocontrol programs, which on average had 4.2 agents introduced with 1.8 agents resulting in success. Funasaki et al. (1988) report an establishment rate of one agent every 2.8 releases. The Denoth et al. (2002) data were used because their analysis examined more programs and was more recent.

Table 6: Characteristics of the suite of agents

	Cumulative efficacy	Year introduced
Agent 1	20%	2014
Agent 2	50%	2022
Agent 3	95%	2030

The total benefit of the suite of agents in a given year was calculated as follows:

Equation 4:

Annual control cost per acre * # of acres infested by **Agents 1, 2, and 3** * 0.95 +

Annual control cost per acre * # of acres infested by **Agents 1 and 2 only** * 0.50 +

Annual control cost per acre * # of acres infested by **Agent 1 only** * 0.20

Benefits were evaluated for 50 years after the 2014 release of the first agent of the suite.

Results

Costs

Table 7: Annual cost estimations of costs obtained (US $2008)[12]

Pre-release Costs	Average Annual Cost	Details
Collection of potential control agents	$7, 000	Two international trips/collaboration agreements costing $7,000 each; made every other year up to the release date
Facility and lab space	$19,000	$10,000 for maintenance costs (electricity, $400 monthly repair costs) $9,000 for upgrade costs (purchases of new equipment, upgrade of facilities i.e. sewer tanks) **$10,000 + $9,000 = $19,000 total**
Research personnel (initial rearing and testing)	$32,000	Two personnel for rearing of agents: $80,000 annual salary, 10% time dedicated to miconia projects = $16,000 total Two personnel for agent testing: $80,000 annual salary, 10% time dedicated to miconia projects = $16,000 total **$16,000 x 2 = $32,000 total**
Costs of agents that failed to establish	$20,000	Encompasses costs of research, testing, release and monitoring of agents that failed to establish or achieve substantial control; assumed to begin in 1997 when the first biocontrol agent, *C. gloeosporioides* was released

[12] These costs were assumed to be the same for all scenarios and did not differ between the single agent and suite of agents. Although the suite would require the release of three independent agents, it was assumed that any release costs incurred after the initial release would be encapsulated in the $20,000 annual "Subsequent release/monitoring costs." This assumption is elaborated in the "Discussion" section of this thesis.

Table 7: Annual cost estimations of costs obtained (US $2008) [continued]

Pre-release Costs	Average Annual Cost	Details
Biocontrol release costs	One-time release cost: $8,200	$8,000 for Class IIA BiosafetyCabinet required for *Miconia calvescens* biocontrol permit $200 fee for maintenance of cabinet **$8,000 + $200 = $8,200 total**
Release personnel	Incurred each release: $20,000	Two personnel required to facilitate release of biocontrol, $50,000 annual salary, 10% of time spent on miconia = $10,000 per site $10,000 per site x two sites of release (Maui and Big Island) **$10,000 x 2 = $20,000 total**
Post-release costs		
Subsequent release/monitoring costs	$20,000	Four personnel, $50,000 annual salary, 10% of time spent on miconia = $20,000 total
Additional costs	$200	Maintenance fee for Class IIA Biosafety Cabinet

Table 8: Total cost of biocontrol (US $2008)
Costs and benefits evaluated from 1992 to 50 years post-release; dates in parenthesis indicate duration of biocontrol programs

Single Agent, 2014 Release (1992 – 2064)	Single Agent, 2019 Release (1992 – 2069)	Suite of Agents (1992 – 2064)
$3,863,900	$4,246,900	$4,487,900

Benefits

Table 9: Single agent: Benefits (millions US $2008)

Benefits accrued over 50 years post-release

		Big Island	Maui	Total
Fast (3 years)	100%	$16.2	$23.8	$40.0
	92.50%	$15.0	$22.0	$37.0
	77.50%	$12.6	$18.4	$31.0
	50%	$8.1	$11.9	$20.0
Average (5 years)	100%	$15.6	$21.2	$36.8
	92.50%	$14.4	$19.6	$34.0
	77.50%	$12.1	$16.5	$28.5
	50%	$7.8	$10.6	$18.4
Slow (7 years)	100%	$15.0	$19.1	$34.0
	92.50%	$13.8	$17.6	$31.5
	77.50%	$11.6	$14.8	$26.4
	50%	$7.5	$9.5	$17.0

Table 10: Suite: Benefits (millions US $2008)

Benefits accrued over 50 years following release of the first agent in 2014

Big Island	Maui	Total
$11.81	$16.94	$28.75

Net Benefits (Benefits – Costs)

Table 11: Total Net Benefits (millions US $2008)
Total net benefits accrued over 50 years post-release

		Net Benefits	
		2014 Release	**2019 Release**
Fast (3 years)	100%	$36.10	$35.70
	92.50%	$33.10	$32.70
	77.50%	$27.10	$26.70
	50%	$16.10	$15.70
Average (5 years)	100%	$32.90	$32.60
	92.50%	$30.20	$29.80
	77.50%	$24.70	$24.30
	50%	$14.50	$14.20
Slow (7 years)	100%	$30.20	$29.80
	92.50%	$27.60	$27.20
	77.50%	$22.50	$22.10
	50%	$13.20	$12.80
Suite		$24.30	

Figure 3: Cumulative benefits and costs, single agent

2014 release of average-spreading single agent with 100% efficacy

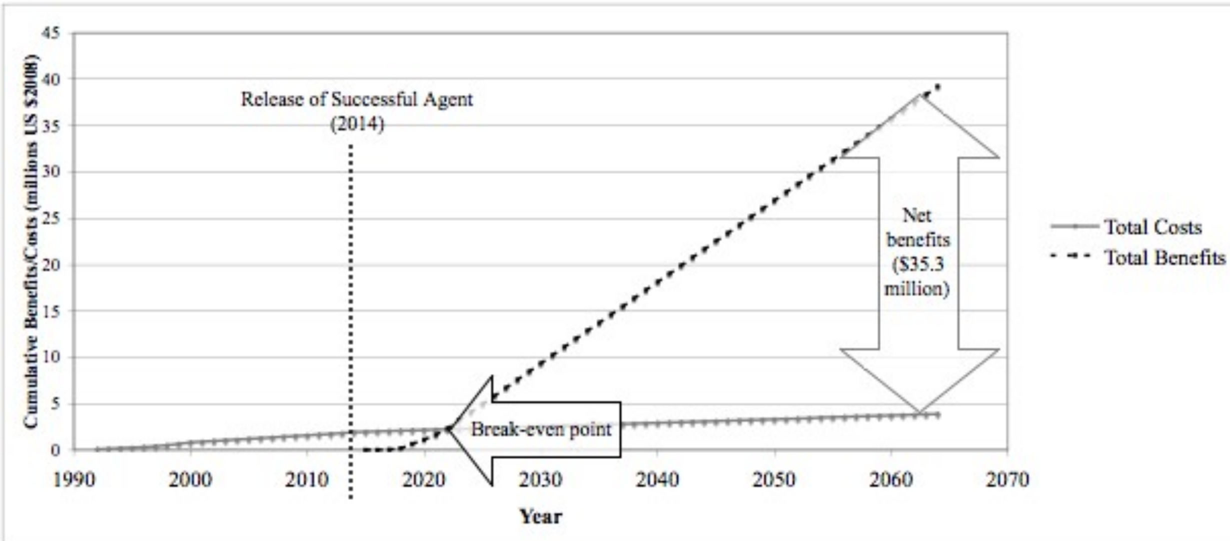
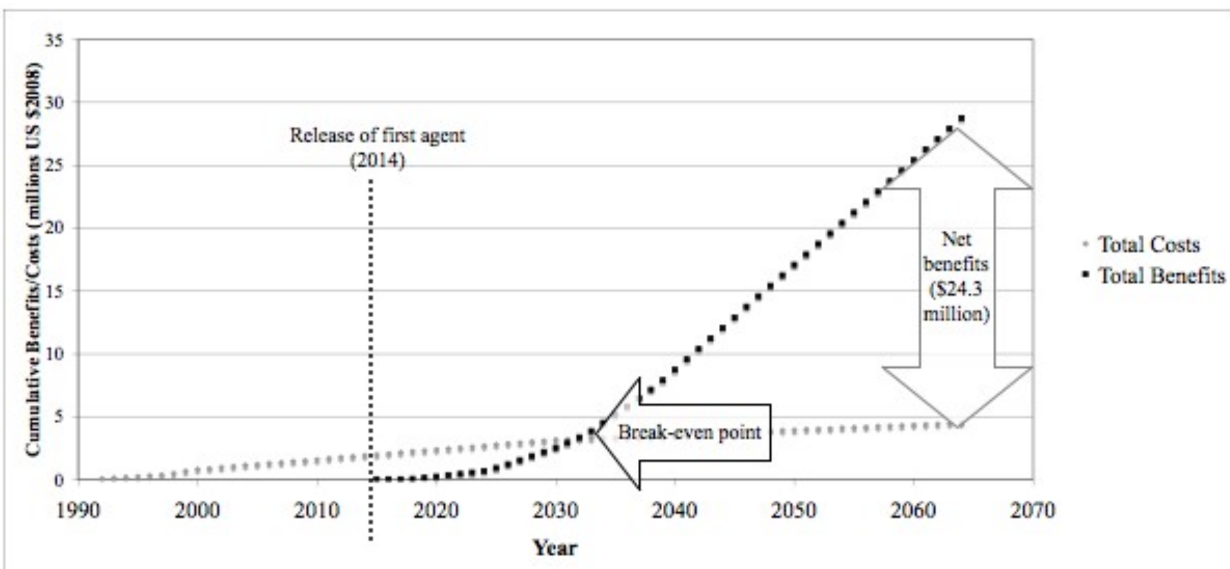


Figure 4: Cumulative benefits and costs, suite



Discussion

In all scenarios considered, the present value of net benefits is positive, indicating that investment in biocontrol programs for miconia in Hawaii is economically justifiable. The present value of net benefits of all scenarios considered ranged from \$12.80 million to \$36.10 million. The best-case scenario with the highest present value of net benefits would be to release a single agent (the "silver bullet" agent considered here) by 2014 that would establish rapidly and have 100% efficacy. However, even the worst-case scenario considered, a single agent released in 2019 that established slowly and had 50% efficacy, yielded positive net benefits of \$12.80 million.

These findings are comparable to studies that have evaluated the net benefits of other biocontrol programs. van Wilgen et al. (2004) analyzed the costs and benefits of biocontrol programs that achieved substantial or complete control in South Africa. Their results are summarized in Table 12 below.

Table 12: Benefits and costs of biocontrol programs achieving substantial or complete control in South Africa in millions US $2008 [a]

Species controlled	Total Benefits [b]	Cost of biocontrol research [c]	Net Benefits
Jointed cactus (*Opuntia aurantiaca*)	$1142.3	$1.6	$1140.7
Red sesbania (*Sesbania punicia*)	$4.2	$0.6	$3.6
Lantana (*Lantana camara*)	$72.9	$3.2	$69.7
Long-leafed wattle (*Acacia longifolia*)	$45	$0.4	$44.6
Golden wattle (*Acacia pycnantha*)	$84.2	$0.1	$84.1
Silky hakea (*Hakea sericea*)	$430.8	$1.7	$429.1

[a] All values expressed in millions of US $2008, converted from South African rand2000 using the 2000 yearlong average from the currency calculator on http://www.x-rates.com/d/ZAR/USD/hist2000.html and inflated to US $2008 using the UHERO CPI.
[b] van Wilgen et al. (2004) estimated the benefits of biocontrol by estimating the rate of spread of each weed and then estimating the damages that would be avoided by preventing the weed's spread. The three categories of damages avoided were economic losses from reduced streamflow, the impact of the invasive species on land values, and the benefit due to biodiversity. These values were summed to yield the total benefits.
[c] The costs of each program were obtained using historical records, personal communication and estimation based upon average salaries. These figures represent the costs incurred from the initiation of biocontrol research to the year 2000 for each species.
[d] The Benefit : cost ratio allows a relative comparison of economic benefits and costs that does not depend on the currency used. A comparison table of the Benefit : cost ratios is given below.

Using the same methodology as van Wilgen et al. (2004), McConnachie et al. (2003) conducted an economic evaluation of biocontrol for the invasive water weed *Azolla filicoides*, also in South Africa. The authors compared the average benefits and costs of biocontrol per hectare and found that from 1995 onwards, the net present value of benefits was $267.4 million US $2008, inflated using the UHERO CPI. Other studies conducted by Pettey (1950), Chippendale (1992), Coombs et al. (1996) and the Cooperative Research Centre (CRC) (2001) and summarized in McConnachie et al. (2003) all yielded benefit : cost ratios greater than one.

The benefit : cost ratio of biocontrol for *Miconia calvescens* calculated in this assessment are comparable to these findings, as seen in Tables 13 and 14.

Table 13: Benefit : cost ratios of selected scenarios of miconia biocontrol programs

Scenario of miconia control		Benefit : cost ratio [a]
Spread of agent	Efficacy rate	
Immediate (3 years)	100%	9.9 : 1
Average (5 years)	92.5%	8.4 : 1
Slow (7 years)	50%	4.2 : 1
Suite of agents		6.4 : 1

[a] Benefit : cost ratio calculated using the average of "Low" and "High" benefits for given scenario (see Table 9) and the average cost of 2014 and 2019 release (see Table 8).

Table 14: Benefit : cost ratios of different biocontrol programs

Species controlled	Region	Benefit : cost ratio	Reference
Jointed cactus (*Opuntia aurantiaca*)	South Africa	709 : 1	van Wilgen et al. (2004)
Red sesbania (*Sesbania punicia*)	South Africa	8 : 1	van Wilgen et al. (2004)
Lantana (*Lantana camara*)	South Africa	22 : 1	van Wilgen et al. (2004)
Long-leafed wattle (*Acacia longifolia*)	South Africa	104 : 1	van Wilgen et al. (2004)
Golden wattle (*Acacia pycnantha*)	South Africa	665 : 1	van Wilgen et al. (2004)
Silky hakea (*Hakea sericea*)	South Africa	251 : 1	van Wilgen et al. (2004)
Azolla filiculoides	South Africa	15 : 1	McConnachie et al. (2003)
Prickly pear (*Opuntia megacantha*)	South Africa	5.6 : 1	Pettey (1950)
Noogura burr (*Xanthium occidentale*)	Australia	2.3 : 1	Chippendale (1992)
Tansy ragwort (*Senecio jacoba*)	Oregon	13 : 1	Coombs et al. (1996)
Bitou bush *(Chrysanthemoides monilifera* ssp. *rotundata*)	Australia	20.7 : 1	CRC (2001)
Alligatorweed (*Alternanthera philoxeroides*)	USA	8 : 1	Andres (1977)
Kariba weed (*Salvinia molesta*)	Sri Lanka	53 : 1	Doeleman (1989)
Paterson's Curse/ Salvation Jame (*Echium* sp.)	Australia	47 : 1	Nordblom et al. (2001)

A comparison of the benefit : cost ratios of this assessment and these other findings highlights some differences in the methodology used in this study and the others. The relatively low values of the benefit : cost ratios for the miconia scenarios is primarily due to the lower-bound estimate of the benefits of biocontrol used in this assessment.

The benefits used in this assessment, cost savings from reduced future chemical and manual control, are conservative estimates. Cost-savings do not even consider the benefits that would accrue from controlling miconia in Hawaii, such as the avoided damages to native forests, potential for increased runoff, and the loss of biodiversity. Furthermore, in the valuation of potential benefits on Maui, only the cost-savings due to reduction in ground control, not including aerial control, were used. The other studies estimated the benefit of biocontrol by using total damages avoided, not cost-savings. In a cost-benefit analysis of biocontrol of the bitou bush in Australia, CRC (2001) estimated four categories of benefits, only one of which was a reduction in control costs.[13] Likewise, Doeleman (1989) included averted damages in his analysis of biocontrol of the waterweed *Salvinia molesta* using the beetle *Cyrtobageous salviniae* in Sri Lanka. This economic analysis of biocontrol for *Miconia calvescens* in Hawaii use of cost-savings to estimate benefits allowed this analysis to compare the potential efficacy of biocontrol to chemical control to give miconia managers and policymakers information more relevant to their actual decision-making. Because miconia has already been declared a priority species for control in Hawaii, the relevant policy question is not whether to control, but how best to control the species.

The benefit : cost ratio of controlling miconia in Hawaii has already been accepted as highly positive; otherwise, control would not have been initiated in 1992. Now, however, managers must determine how to best achieve this control. Their options are the current ground and aerial operations or biocontrol. Defining benefits as cost-savings of current control allows this comparison because both of these costs are incorporated into the analysis. The positive net benefits in this study show that biocontrol is justifiable because it saves money in comparison

[13] The other three categories of benefits were: increase in biodiversity in currently infested areas, increased amenity values in currently infested areas, and improved outcomes (benefits from prevented potential infestation).

with the current control methods, not only because benefits of miconia control exceed the costs of biocontrol programs. This presents an even stronger argument for biocontrol specifically, not just miconia control in general. Including an estimate of damages avoided from removing miconia would only increase the magnitude of the positive net benefits found in this study.

As mentioned earlier, the benefits of biocontrol on Maui only reflect cost-savings of ground control and do not include potential cost-savings of aerial control. Ground control comprises the majority of costs in the Maui core area and is generally more expensive than aerial operations. Based on MISC's control strategy and goal of zero fruiting miconia trees, it was assumed that aerial operations to survey the miconia infestations and continue to treat mature trees would continue throughout the course of the biocontrol program. Thus, biocontrol was assumed not to result in any cost-savings associated with aerial operations. However, it is likely that after a few decades of well-established biocontrol, aerial operations would become less necessary and further cost-savings would result.

The total costs of biocontrol for miconia found using this assessment are relatively high; an average of $4.2 million versus an average of $1.27 million in the six programs evaluated by van Wilgen et al. (2004). The program for biological control for the bitou bush in Australia cost $2.2 million (CRC 2001). This economic assessment for miconia biocontrol also included $20,000 in annual monitoring costs for biocontrol, which the van Wilgen et al. (2004) study did not specifically consider.[14] These monitoring costs were included following the recommendations of scientists from the HDOA and USDA who work extensively with biocontrol in Hawaii, all of whom stressed the importance of a successful monitoring program to

[14] van Wilgen et al. (2004) and McConnachie et al. (2003) did consider future costs of the maintenance of biocontrol programs, which they defined as 20% of the mean annual historical costs of research. In comparison, the $20,000 annual monitoring cost plus the $200 annual cost for the biosafety cabinet in this assessment represent about 31% of the estimated average annual cost of research.

assess the impacts of biocontrol. In past efforts, no such program has really existed, which could account for the lack of concrete post-release data on the efficacy of biocontrol in the literature.

One of the biggest concerns associated with biocontrol is the potential non-target impact that an introduced species could have on the native environment. However, as Pemberton (2000) notes in his analysis of 117 introduced and established biocontrol agents in Hawaii, the continental United States and Caribbean since 1902, "only one of 117 established agents has come to use a native, non-target plant species unrelated to the target weeds." As discussed in the background, *Miconia calvescens* has no native relatives in Hawaii; it is part of the Melastomataceae family, which does not naturally occur here. To reinforce this point, Pemberton (2000) reports that 40 of the 41 non-target, native plant species that have been attacked (meaning that the agents have fed on these native plant species but do not use them as a major host) are within the same family as the weed that was targeted for control.

Pemberton (2000) found that in Hawaii, only one out of 18 projects against weeds has resulted in a non-target impacts on a native plant; a rate of just 5.6%. As of 2000, there was only one agent out of 49 total introductions that currently used a native Hawaiian plant as its host: the lacebug *Teleonemia scrupulosa* Stal, introduced to control *Lantana camara*, was reported to use the endemic shrub *naio* (*Myoporum sandwicense*). Pemberton (2000) concludes that "patterns of non-target, native plant use by introduced biological control insects indicate that the risk to native flora can be judged reliably before introduction," which is the reason for the extensive testing that occurs before the release of any agent. Mistakes made in the past have, at least, been translated into valuable lessons for the present and future. Funasaki et al. (1988) report that "Specificity of the released organisms… have improved over the years", citing an 88% specificity rate in the 20 years prior to the publication of their paper, and a 96% specificity rate in the 15 years prior to the publication of their paper. This trend towards greater specificity indicates that the current review system has been successful in reducing the non-target impacts of biocontrol in Hawaii.

The biggest assumption that this assessment makes is that a successful biocontrol agent for miconia will eventually be found. As described earlier, research for potential biocontrol agents for miconia has been underway for almost 15 years, and although scientists have many promising candidates there still have been no successful releases. If no agent is able to establish and control miconia, then the benefits of biocontrol will be zero, the present value of net benefits is negative, and biocontrol is economically unjustifiable. There are two elements that must be considered when discussing biocontrol success: the percentage of agents released that become established and achieve control, and, more importantly, the percentage of biocontrol programs overall that achieve substantial or complete control of the target species.

Overall, about 60% of all agents introduced establish, and 33% of all established agents ultimately contribute to controlling the weed (Cruttwell McFadyen 2000). Denoth et al. (2002) reports similar findings of an establishment rate of 52% of agents in programs where a single agent was released, and a 32% establishment rate where multiple agents were released. Out of the 59 programs analyzed by Denoth et al. (2002), 19 involved the release of a single agent, 16 projects used two, eight projects used three, six used four and 10 used five or more agents. In a comprehensive but dated review of biocontrol releases in Hawaii from 1890 – 1985, Funasaki et al. (1988) reported that of 679 total released species, 243 became established (an establishment rate of 35.8%). However, these data include many releases that occurred before the current system of pre-release research was established and therefore may not provide an accurate estimate of a reasonable establishment rate in the current conditions.

The costs of releasing unsuccessful agents that either did not establish or achieve control were assumed to begin in 1997 with the release of the fungus *Colletotrichum gloeosporioides*. These costs were assumed to continue until the release of the first successful agent. It was assumed that these costs would average $20,000 a year, consistent with the costs of release of successful agent. The $8,000 fee for the BioOne Safety Cabinet required for a permit to release biocontrol for certain species, including miconia, was only incurred once, because the cabinet could be used for any subsequent miconia biocontrol releases (D. Oishi, HDOA, personal communication) The cost of a suite of agents was higher than the cost to release a single agent ($4.5 million vs. $3.9 million for a 2014 single release) because the suite required the research and release of three separate agents.

The “Subsequent release/monitoring costs” of $20,000 encompassed any subsequent inoculations of the agent (for example, to broaden the initial release area or to help an agent with a natural dispersal rate of, say, 20 years establish throughout the entire managed area in seven years). CRC (2001) notes that “The cost of spreading the biological agent is minimal compared to the research costs in selecting, evaluating and monitoring the control agent.” The reasoning for a simple $20,000 cost for subsequent release/monitoring seemed more consistent with the actual operation of the agencies involved with miconia control. Managers are acutely aware of the amount of resources they have available. In an ideal world with unlimited funds, costs could increase until the target release size had been achieved, but given the budgetary restraints and priorities to other projects that the HDOA, USDA and invasive species committees like MISC face and the track record of scarce resources and under funding of these agencies, it unfortunately seems unlikely that the size of the release may be dictated more by the availability of resources rather than the optimal release size. It therefore seemed unreasonable, in this current analysis, to consider a plethora of scenarios that would involve multiple releases and subsequently increasing costs. As more research regarding the optimal release size for biocontrol is conducted, the baseline cost estimate of $20,000 per year could be adjusted to reflect scenarios for multiple releases.

This economic analysis assumes that biocontrol for miconia will be effective and does not consider the possibility that biocontrol might not work. Modeling the uncertainty of whether or not biocontrol would be successful in Hawaii is outside the scope of this analysis. Uncertainty is complicated to model in any case, and given the current stage of biocontrol research in Hawaii, in which many potential agents are still currently being researched, it would have been even more difficult. This analysis assumes that biocontrol will eventually establish throughout the entire target areas, albeit at different rates, and considers different rates of efficacy that the biocontrol can achieve.

Although this economic assessment does not directly factor in the uncertainty of miconia biocontrol, history can provide an indication of the program's possibility to succeed. The biggest question is: how many biocontrol programs actually achieve substantial or complete control of their target species? Denoth et al. (2002) find that out of 109 projects worldwide, 66 of them successfully achieved control; in other words, approximately 60.6% of all programs were successful. A dated history of Hawaii's success with biocontrol of weeds reflects a 52% success rate, when 11 of 21biocontrol programs achieved at least partial success (results reported by Markin et al. 1992; data used from 1983). Given these rates, a conservative estimate would indicate that the chance that miconia biocontrol would succeed in Hawaii is about 50%.

This success rate may seem low to some, but given the potential of *Miconia calvescens* to severely harm Hawaii's ecosystems, the potential net benefit of at least $12.67 million in the most conservative scenario to pursue biocontrol should be seriously considered. Based on the findings of this economic assessment, biocontrol for *Miconia calvescens* in Hawaii is economically justifiable not only because miconia is one of Hawaii's highest priorities for weed control but also because biocontrol would result in significant cost-savings in comparison with chemical control in the long run. Even with the conservative 50% success rate overall of biocontrol, it serves well to remember that the potential damages of *Miconia calvescens* may be much greater than the approximately $4.2 million that would be invested in a potentially successful agent (Burnett et al. 2007). Even if no successful agent is ever released, and all pre-release costs continued for the next twenty years before the biocontrol research terminated, only $2.5 million would be spent in total. This investment seems a relatively small price to pay in light of the over $1 million currently spent annually on miconia control. However, miconia managers should be aware of the possibility that $2.5 million could be spent on a biocontrol program that does not result in any benefits, and consider to what extent spending an extra $2.5 million on current operations could potentially contribute to controlling miconia.

At present, the USDA Forest Service and HDOA are the only two agencies with the capacity for biocontrol. The Hawaii Invasive Species Committee (HISC) 2010 report to the Hawaii State Legislature states that "The building of a new state biocontrol containment and testing facility is needed, as the two current facilities are inadequate to combat widespread species for which chemical and mechanical control is not cost-effective" and estimates that a new facility would cost $10 million, with research and operating costs of over $3.1 million (DLNR/DOFAW 2009). It is important to recognize that the new facility and research and operating costs would cover all biocontrol programs in Hawaii, not just those for *Miconia calvescens*. The significant benefits of biocontrol that can be attributed to miconia alone enumerated in this economic analysis indicate these expenditures should be seen as economically justifiable. Unfortunately, in HISC's budget request and recommended funding for FY 2010, the line item for HDOA biocontrol was reduced to $0 (DLNR/DOFAW 2009). Without adequate investment in biocontrol, the benefits of biocontrol will not be realized.

The positive present value of net benefits found in this assessment indicates that biocontrol for *Miconia calvescens* in Hawaii is economically justifiable. It is important to remember, above all, that biocontrol is an investment; one must pay large up-front costs of research before accumulating significant benefits.

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