Invasive Plant Science and Management 2013 6:292–303

Calibration of an Herbicide Ballistic Technology (HBT) Helicopter Platform Targeting *Miconia calvescens* in Hawaii

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Miconia (*Miconia calvescens* DC.) is a tropical tree species from South and Central America that is a highly invasive colonizer of Hawaii's forested watersheds. Elimination of satellite populations is critical to an effective containment strategy, but extreme topography limits accessibility to remote populations by helicopter operations only. Herbicide Ballistic Technology (HBT) is a novel weed control tool designed to pneumatically deliver encapsulated herbicide projectiles. It is capable of accurately treating miconia satellites within a 30 m range in either horizontal or vertical trajectories. Efficacy was examined for the encapsulated herbicide projectiles, each containing 199.4 mg ae triclopyr, when applied to miconia in 5-unit increments. Experimental calibrations of the HBT platform were recorded on a Hughes 500-D helicopter while conducting surveillance operations from November 2010 through October 2011 on the islands of Maui and Kauai. Search efficiency (min ha^{-1}; n = 13, $R^2 = 0.933$, $P < 0.001$) and target acquisition rate (plants hr^{-1}, n = 13, $R^2 = 0.926$, $P < 0.001$) displayed positive linear and logarithmic relationships, respectively, to plant target density. The search efficiency equation estimated target acquisition time at 25.1 sec and a minimum surveillance rate of 67.8 s ha^{-1} when no targets were detected. The maximum target acquisition rate for the HBT platform was estimated at 143 targets hr^{-1}. An average mortality factor of 0.542 was derived from the product of detection efficacy (0.560) and operational treatment efficacy (0.972) in overlapping buffer areas generated from repeated flight segments (n = 5). This population reduction value was used in simulation models to estimate the expected costs for one- and multi-year satellite population control strategies for qualifying options in cost optimization and risk aversion. This is a first report on the performance of an HBT helicopter platform demonstrating the capability for immediate, rapid-response control of new satellite plant detections, while conducting aerial surveillance of incipient miconia populations.

Nomenclature: Miconia, *Miconia calvescens* DC. MICA20.

Key words: Hawaii, Herbicide Ballistic Technology.

The loss of endemic biological diversity due to exotic plant invasions is particularly detrimental on isolated islands (Denslow 2003; Mack et al. 2000; Reaser et al. 2007). Either eradication or containment of the invasive species can serve as viable mitigation strategies depending on which option has the greatest potential for success (Panetta 2009; Panetta and Cacho 2012; Taylor and Hastings 2004; Wittenberg and Cock 2001). Regardless of the approach, detection and control must be effectively applied to the entire population, particularly with the most isolated satellites (Brooks et al. 2009; Cacho et al. 2006; Hulme 2006; Myers et al. 2000; Panetta 2009; Panetta and Lawes 2005). Archiving knowledge of the target species is also critical to determine the management approach and would include studies on the biology (e.g. growth and fecundity), ecology (i.e. propagule dispersal) and physiography (i.e. suitable habitat) of the target species (Chimera et al. 2000; Florence 1993; Hardesty et al. 2011; Kuefer et al. 2010; Pouteau et al. 2011). An effective species mitigation strategy combines (1) practical knowledge, (2) sustained resources and (3) proven actions that progress towards a measurable reduction of target density and contraction of the delimited invasion perimeter.

DOI: 10.1614/IPSM-D-12-00026.1

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Management Implications

Herbicide Ballistic Technology (HBT) is a novel application technique designed to deliver encapsulated herbicide projectiles with long-range accuracy and precision. We report on the performance of an HBT platform providing immediate control of miconia (*Miconia calvescens* DC.) satellite plants, detected while conducting helicopter surveillance calibrations in Hawaii's remote watersheds. Flight calibrations (n = 13) generated efficiency parameters related to the functionality of the platform. Plant target density was a significant variable for determining search efficiency (min ha^{-1}), target acquisition rate (plants hr^{-1}) and herbicide use (g ae ha^{-1}). The product of detection efficacy and treatment efficacy estimated population mortality (i.e. reduction) as another operational parameter used in simulation models to project feasibility and expected cost of different population reduction strategies based on cost optimization and risk aversion. This research is critical to our technology transfer program that includes development of the standard operating procedure for safe use of the HBT platform, which has been approved by the Pacific Cooperative Studies Unit, University of Hawaii and approval by the Hawaii Department of Agriculture for a FIFRA Section 24c Special Local Needs registration for HBT-G4U200 with Garlon® 4 Ultra (EPA SLN Reg. No. HI-120001), with miconia listed as a target species.

Miconia (*Miconia calvescens* DC.) is a mid-story tree, 12 to 15 m tall, native to Central and South America. It has large, bicolored leaves that are up to 80 cm in length, which made this species desirable to botanical hobbyists and horticultural professionals. This led to purposeful introductions to other suitable habitats throughout the Pacific (Meyer 1996). It is currently listed as one of the 100 worst global invasive species (Lowe et al. 2000), is a class 1 weed in Queensland, Australia (Hardesty 2011) and a state noxious weed in Hawaii, USA (Medeiros et al. 1997). The miconia infestation in Tahiti has been well characterized. After its introduction in 1937, it became the dominant vegetation to over 65% of the forest in less than 60 yr (Florence 1993; Meyer 1996). High densities of this shallow rooted species are known to shade out the understory vegetation and further suspected to promote soil surface erosion, particularly on steeper terrain (Giambelluca et al. 2010; Medeiros et al. 1997; Meyer 1996).

Miconia is an autogamous species that reaches maturity in 4 to 5 yr. A single plant has immense fecundity, with the ability to produce millions of propagules in a single reproductive cycle (Meyer 1998). Miconia produces a small, edible fruit, approximately 5.9 mm in diam (0.23 in) lending itself to frugivorous dispersal by a generalist avian population (Chimera et al. 2000). In Australia, both Hardesty et al. (2011) and Murphy et al. (2008) infer that 95% of dispersal events occur within 500 m, but with a maximum dispersal range that could go beyond 2000 m. The current recommendation is for maintaining radial management buffers that are at least 500 m, but preferably 1000 m (Hardesty et al. 2011). The most recent report from Tahiti has validated seed bank viability to be over 16 yr (Meyer et al. 2011). Thus, preventing satellite miconia populations from reaching maturity (i.e. elimination) is critical to mitigating the invasion.

Miconia was introduced to the Hawaiian Islands in 1961 (Medeiros et al. 1997). Thirty years later, the first management program was initiated on Maui and by 1996 management programs existed on the islands of Kauai, Oahu and Hawaii (Chimera et al. 2000). Population reduction (i.e. containment over eradication) was recently determined to be the optimal management policy for minimizing expected costs of control on Oahu, Maui and Hawaii. On Kauai, deferment of control was suggested due to the higher costs associated with searching in a much lower population density, (Burnett et al. 2007). Currently however, all islands, including Kauai, are operating under a more risk averse policy that implements surveillance and treatment operations focused on known incipient populations. This approach may have higher operational costs, but also presents greater opportunity to mitigate detrimental uncertainties regarding the extent of these invasions. Reduction of satellite populations can have a more mitigating effect on an invasion compared to control efforts in a higher density core infestation (Moody and Mack 1988). Search effort, particularly in remote natural settings, is a costly procedure, making plant detectability critical to effective containment (Cacho et al. 2007; Hester et al. 2010). Costs are further compounded when plant detection and treatment activities are performed in separate operations, which has often been the case for controlling miconia in Hawaii.

The herbicide active ingredient triclopyr is lethal to miconia in low doses as basal bark or foliar applications (Chimera et al. 2000; Medeiros et al. 1998). The aerial long line spray system currently used to treat miconia, was originally developed by the US Drug Enforcement Agency for marijuana (*Cannabis sativa* L.) control. A typical assembly consists of a 95 L tank (25 gal) mounted to the cargo hook of a Hughes 500-D helicopter and a tethered 30 m by 9 mm hose with a distal nozzle configuration for directed applications administered by the pilot. Most aerial operations are relegated to inaccessible locations and often require separate reconnaissance and treatment flights due to encumbrance of the long line sprayer (Burnett et al. 2007). This spray system relies on pilot dexterity to safely position the nozzle assembly directly overhead, and is typically limited to treating miconia in open tree canopy gaps and on shallow slopes. However, miconia is also able to reside on much steeper slopes up to 75° (Pouteau et al. 2011) and under impeding tree canopy (Meyer 1994), making it difficult or impossible for the long line sprayer to treat all targets. This limitation ultimately compromises the success of an effective containment strategy (Myers et al. 2000, Panetta 2009).

Herbicide Ballistic Technology (HBT) is a novel herbicide delivery technique designed to discretely administer encapsulated herbicide aliquots through a pneumatic device to individual weed satellites with long-range accuracy. The effective treatment range is 30 m in either horizontal or downward vertical trajectories, while maintaining submeter accuracy. The high velocity impact of the projectile to the plant (ca. 50 m s^{-1}) creates a circular spatter pattern that is approximately 1 m^2, with our observation that a majority of the fluid is retained at the point of impact. This precision delivery platform is uniquely suited to treating satellite miconia residing on extreme topography or under tree canopy that would otherwise impede the long line sprayer.

The objectives of this study were to determine triclopyr efficacy when delivered as HBT projectiles to miconia and evaluate the utility of an HBT aerial platform in helicopter surveillance calibrations. The empirical performance measures were further utilized in model simulations with expected cost analyses to project effective containment strategies of incipient miconia populations.

Materials and Methods

The HBT Projectile. Batch processing of HBT projectiles was conducted by the Nelson Paint Company (EPA Est. No. 86199-MI-001) using standard in-house procedures for producing spherical soft gelatin capsules (17.3 mm dia.) with a 2.6 ml (0.09 fl. oz) liquid fill capacity. The HBT-TCP200 herbicide formulation is a simple bipartite blend of triclopyr (3,5,6,-trichloro-2-pyridinyloxyacetic acid, butoxyethyl ester; Garlon® 4 Ultra, EPA Reg. No. 62719-527, Dow® Agrosciences LLC Indianapolis, IN) diluted with a modified vegetable oil concoction of surfactants and coupling agents to produce a projectile unit with 199.4 mg ae. The HBT-IMZ31 herbicide formulation is imazapyr (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-3-pyridinecarboxylic acid; Arsenal® Powerline™, EPA Reg. No. 241-431, BASF® Corp., Triangle Park, NC) blended with the same adjuvant concoction to produce a projectile unit with 31.2 mg ae. HBT-TCP200 and HBT-IMZ31 formulations are comparable to 16% and 5% v/v, respectively.

Treatment Efficacy Validation. Two ground-based field trials were established in February 2010 to compare efficacy of the HBT-TCP200 and HBT-IMZ31 on miconia within the East Maui infestation (20°45′46″N, 156°01′17″W). The first experiment was conducted as a completely randomized design replicated three times with a 2 by 2 factorial treatment set comparing formulations (TCP200 vs. IMZ31) at two different application rates (5-unit vs. 10-unit). All experimental targets were juvenile miconia of relatively uniform size with a single leader stem between 3 to 5 m tall. Projectiles were administered at the lowest axial point from a 3 m range with a marker calibrated to discharge a projectile with a 100 m s^{-1} muzzle velocity. A second experiment compared the formulations as a 5-unit application rate targeting the base of the main leader stem approximately 30 cm from the soil surface. Visual confirmation of treatment lethality was conducted in September 2010 (227 DAT).

The Onboard HBT Platform. The three basic components of the onboard HBT platform include: (1) the HBT projectile inventory subdivided into pods (ca. 140 projectiles) serving as retention devices during transfer to the (2) electro-pneumatic application marker (BT® TM7™, Kee Action Sports LLC, Sewell, NJ) consisting of a microswitch-controlled solenoid actuating a 1380 kPa compressed air discharge for bolt-action propulsion of projectiles powered by (3) a regulated 1180 cm^3 aluminum reservoir tank pressurized up to 20,700 kPa. The marker was calibrated to launch projectiles through a 30 cm long, ceramic-coated, smooth bore barrel calibrated for a muzzle velocity of 100 m s^{-1} and a terminal range of just beyond 50 m. The tanks were connected to the marker via coiled high pressure remote line with quick connect coupler and sliding check valve for depressurized tank replacement. The complete onboard assembly consisted of forty pods (ca. 5,600 units), six tanks, and two markers. The platform was designed to match resource consumption (i.e. projectiles and compressed air) with operational flight time (ca. 100 min) and accommodate redundancy in the event of a minor component malfunction.

HBT Calibration Flight Segments and Site Locations. HBT platform calibrations were derived from flight segments of helicopter surveillance operations that were distinguished by date, time and site. Up to two segments were recorded from a single operation, although most operations had only one segment recorded. A total of thirteen calibration flight segments were recorded from October 2010 to November 2011 in three sites on the island of Maui: Wailua Nui (20°50′06″N, 156°08′06″W, three flight segments); Waiokamilo (20°50′03″N, 156°08′28″W, two sites with three flight segments each), and one site on the Island of Kauai: Opaekaa (22°04′50″N, 159°24′11″W, four flight segments).

In-flight HBT Calibration Protocols and Recorded Parameters. All calibrations were conducted onboard a Hughes 500-D helicopter with doors removed and a three-person crew configured with the applicator seated portside, posterior to the pilot and an additional spotter seated in the front, starboard side. All crewmembers were responsible for safety monitoring and miconia target detection. The target

Figure 1. An HBT operator positioned in the portside rear seat of a Hughes 500-D with a pneumatic device engaging two incipient miconia targets within effective range and a clear line of sight. Photo credit to Josh Atwood.

acquisition process between the pilot and the applicator was initiated by positive identification of the miconia target followed by the aircraft safely approaching to within a 30 m range and clear line of sight (PCSU 2011; see Figure 1). A target window was designated for the applicator to safely discharge projectiles within a 270° to 300°horizontal trajectory (i.e. 9 to 10 o'clock position) and a 200° to 270° vertical trajectory (i.e. landing skid to eye level). With the aircraft in a stationary position, the applicator obtained permission from the pilot to treat the target, discharged projectiles, recorded GPS waypoint and cued the pilot to continue with the operation. Detection from the helicopter was typically limited to miconia plants that were at least 1 m tall with fully expanded leaves (i.e. assumed to be at least 2nd-yr juveniles). All applications were administered as a 5-unit treatment to each visible axial point of the plant. Juvenile plants were supported by a single leader stem that could range from 1 to 4 m tall and typically had < 5 axial points, while larger (potentially mature) plants would display a spreading canopy with ≥ 5 axial points. All plant target waypoints and corresponding logs of the flight path were recorded with a GPS device (Foretrex® 301; Garmin® Olathe, KS) set to record geographical position, timestamp and velocity on 30-s intervals. Discrepancy between the recorded applicator location and the actual offset distance of the target should be noted. In most cases, closely approaching the target would have been hazardous or impractical and would also have confounded the time parameter of the calibration. All of the targets were located within 30 m of the recorded waypoint. Survivors of earlier treatments were also recorded for repeat calibrations and were identified as symptomatic targets with viable intact canopy and were administered retreatment to those living portions. Pod (ca. 140 projectiles) inventory consumption was recorded for each flight segment.

Platform Performance Calculations. Operational flight segments containing first and last recorded miconia targets were spliced from raw track logs by removing the ferry portions (determined by flight segments to and from the landing zone that exceeded 20 km hr^{-1}) using Mapsource® (version 6.12.4; Garmin® Olathe, KS). Net surveillance areas were calculated with a 50 m buffer on each side of the operational flight segments with overlapped portions dissolved using the buffer analysis tool in ArcGIS® (version 10.0; ESRI® Redlands, CA). The time interval between the timestamps of the start and end points were recorded. Plant target density was the product of targets acquired divided by the segment area, reported as targets ha^{-1}. Target acquisition rate was the product of the targets acquired divided by the segment time, reported as targets hr^{-1}. Search efficiency was the product of segment time divided by segment area, reported as min ha^{-1}. Detection efficacy was based on the assumption that all targets acquired in the subsequent overlapping segment were not detected in the previous segment and was calculated as the product of targets acquired in the previous segment divided by the composite of all targets acquired in the previous and subsequent segments. This is a conservative, but reasonable assumption that newly recorded miconia targets is more likely the result of crew detection errors in the previous operation than actual recruitment within the short time intervals between flight segments (i.e. 89 to 171 days). Operational treatment efficacy was the product of effectively treated targets divided by the total targets acquired. Effectively treated targets were deciphered by subtracting the number of survivors identified in the subsequent segment. Mortality factor as described by Cacho et al. (2007) is the product of the probability of detection multiplied by treatment efficacy. For this study, the mortality factor was empirically derived as the product of detection efficacy multiplied by operational treatment efficacy calculated from the repeated overlap areas. Target herbicide dose was calculated as the product of pod inventory consumption divided by the targets acquired in a flight segment. Similarly, herbicide use was calculated as the product of pod inventory consumption divided by the buffered surveillance area. Both projectile consumption parameters were reported in triclopyr acid equivalents based on a known quantity of each projectile (e.g. 199.4 mg ae).

Simulation Models and Expected Cost Analyses. Simulations of 1-yr population reduction strategies within buffered isotropic management areas (1 km radius = 314 ha) were performed to compare different management frequencies: (1) quarter-annual (four operations), (2) semi-annual (two operations) and (3) annual (one operation). The population density range was 0 to 315 targets. A

Table 1. Time and costs estimates ($USD) for helicopter operations.

	OFT[a]			Ferry[b]			Crew[c]		
	1/3 ops	2/3 ops	Full ops	1/3 ops	2/3 ops	Full ops	1/3 ops	2/3 ops	Full ops
1 heli	1.7 ($1,667)	3.3 ($3,300)	5.0 ($5,000)	1.1 ($1,133)	1.5 ($1,467)	1.8 ($1,800)	12.0 ($300)	19.5 ($488)	27.0 ($675)
2 heli	3.3 ($3,300)	6.7 ($6,700)	10.0 ($10,000)	2.3 ($2,267)	2.9 ($2,933)	3.6 ($3,600)	20.0 ($500)	32.5 ($813)	45.0 ($1,125)
3 heli	5.0 ($5,000)	10.0 ($10,000)	15.0 ($15,000)	3.4 ($3,400)	4.4 ($4,400)	5.4 ($5,400)	28.0 ($700)	45.5 ($1,138)	63.0 ($1,575)

[a] Operational flight time is the flight time dedicated to surveillance and target acquisition calculated from a fuel cycle of a Hughes 500D performing low-level hovering tactics, estimated at 120 total min minus 20 min round-trip ferry to and from the LZ. A full ops session accommodates 3 fuel cycles providing 5, 10, or 15 hours of operational flight time for 1, 2, or 3 helicopters, respectively. Utility helicopter flight services are $1000 hr^{-1}.

[b] Ferry time is non-operational flight time for round-trip transport of aircraft from the heliport (0.8 hrs rt) to the LZ and from the LZ to the management containment area (0.33 hrs rt). Each aircraft is committed to one round-trip heliport ferry and each ops fuel cycle is committed to one round-trip LZ ferry.

[c] Crew management consists of an operations manager plus two crew members for each aircraft. Logistical responsibilities include onboard HBT platform assembly, replenishment, refueling, flight following, navigation, surveillance and application. Wage is $25 person-hr^{-1}.

mortality factor of 0.542 (the average derived from the repeated flight segments) was imposed on each operation.The undetected targets were calculated from the subtracted product of the mortality factor, which served as the target population for the subsequent operations for quarter- and semi-annual strategies, respectively.

A structured matrix model developed for miconia by Hester et al. (2010) was adopted in this study to simulate strategies for eradicating incipient miconia populations. The model estimates annual population growth based on the probabilities of survival and succession of the (1) seed bank, (2) four distinct juvenile stages and (3) small and large mature plants generating positive-feedback by fruit production augmenting the seedbank. The model was modified using Meyer (1998) fecundity data where the average fruit per panicle was 208 with 195 seeds per fruit. For this model, a small mature plant only produced two panicles which is equivalent to 81,120 seed, while a large mature plant produced 50 panicles with 2,028,000 seed. The population vector (X_t) of this matrix model started with a seed bank of 668,075 propagules, 210 juvenile plants and 2 small mature plants (see Appendix 1). The average mortality factor of the HBT platform (0.542; see Table 5) was imposed on the matrix model targeting the juvenile stages 2 to 4 yr and adult stages, with the assumption that first-yr juveniles were undetectable. Population densities (mature/juvenile) were selected as management starting points that included: (1) 2/48, (2) 20/74 and (3) 209/1518 representing increasing levels of invasion identified along the growth model. The management frequencies were as described above and also included bi- and triennial strategies.

Expected cost estimations for both models were based on a helicopter flight cost of $1000 USD hr^{-1}, HBT projectile inventory consumption with a projectile price of $0.31 USD (Nelson Paint Company, personal communication) and crew costs of $25 USD person-hr^{-1}. Operational flight times were determined by solving for search efficiency (min ha^{-1}) dependent on plant target density and the lowest cost determined by the number of helicopters needed to accommodate that operation along with corresponding ferry times and crew labor (Table 1). Similarly, projectile inventory consumption was based on the equation that solves for herbicide dose, which was estimated to be 25 units per target. The 1-yr population reduction strategies were reported as basic cost estimates that would accommodate a manager submitting an annual budget request. The matrix model simulation calculated the net present values (NPV) of projected eradication timelines at a 6% discount rate applied to the annual cost of operations (Hester et al. 2010).

Regression analyses were performed using ordinary least squares to determine the effect of plant target density on empirically derived search efficiency, target acquisition rate and herbicide use ($n = 13$) and on expected cost estimates for the 1-yr population reduction strategies (SPSS. 2009. PASW Statistics 18, Release Version 18.0.0. SPSS, Inc., Chicago, IL).

Results and Discussion

The herbicide efficacy experiment determined HBT-TCP200 to be lethal with 5- and 10-unit treatments, applied either to canopy axial points or the base of the leader stem (Table 2). The HBT-IMZ31 treatments were not effective. The high velocity projectiles penetrated the thin epidermis of branches with a fraction of the herbicide creating a ‘‘water soaked’’ mark at the point of impact and

Table 2. Miconia survival after treatment with TCP200 and IMZ31 at the main stem axial points with 5- and 10-unit applications and basal treatments with 5-unit applications. Recorded 224 DAT.

	ri		rii		riii	
	Alive	Dead	Alive	Dead	Alive	Dead
Axial						
TCP-5		X		X		X
TCP-10		X		X		X
IMZ-5	X		X		X	
IMZ-10	X		X		X	
Basal						
TCP-5		X		X		X
IMZ-5	X		X		X	

the remaining portion scattered on to the leaf canopy, including the undersides. The option to effectively treat either the base or canopy of miconia is useful in an operational setting where a clear line of site at the base of the plant may not be available due to adjacent impeding vegetation. This herbicide efficacy experiment allowed us to proceed with further evaluating the utility of HBT in a helicopter platform using the HBT-TCP200 projectiles.

A total of thirteen HBT calibration flight segments were recorded with a single applicator, three different pilots and six spotters. Segment time intervals ranged from 13 to 92 min (Table 3). Segment lengths ranged from 508 to 16,276 m with corresponding buffer areas ranging from 4.9 to 121.4 ha. Target acquisitions ranged from 4 to 164 targets per segment and HBT projectile consumption from 2 to 27 pods per segment. Search efficiency, target acquisition rate and herbicide use were all correlated to plant target density, showing significant positive trends. Simple linear equations produced best fits for search efficiency (Figure 2; $R^2 = 0.933$; $P_{0.05} < 0.001$) and herbicide use (Figure 4; $R^2 = 0.966$; $P_{0.05} < 0.001$), while target acquisition rate was best fit with a logarithmic equation (Figure 3; $R^2 = 0.927$; $P_{0.05} < 0.001$).

According to the linear search efficiency equation (Figure 2), a helicopter surveillance operation was estimated to search one hectare in 1.13 min (ca. 68 s) where no targets were detected within the buffered area, while the slope coefficient estimated the complete target acquisition process to take 0.418 min (ca. 25 s) (Table 4). Thus, in areas with ≥ 3 targets ha^{-1}, the target acquisition time exceeded surveillance time. According to the logarithmic equation (Figure 3), the maximum target acquisition rate was projected to be 143 targets hr^{-1}, which was achieved at a density of 164 targets ha^{-1}, but exceeded 100 targets hr^{-1} when the density ≥ 8 targets ha^{-1}. This was represented in 5 of the 13 calibration flight segments (Figure 3). According to the linear herbicide use equation, each miconia plant received a mean herbicide dose of 4.79 g ae triclopyr (0.17 oz) which back calculates to an estimate of 24 projectiles per target. This would suggest an average plant size with 4 to 5 axial points assuming 100% accuracy of the designated 5-unit application rate. A majority of the

Table 3. Recorded HBT calibration flight segment data.

Island/Site	Date	T[a]	Lngt[a]	Area[b]	Targets	Pods[c]
		min	m	ha		
Maui						
Wailua Nui	11/10	61	1,896	7.8	134	27
	05/11	69	2,372	8.1	114	19
	08/11	64	3,125	15.6	71	15
Waiokamilo 1	04/11	60	1,402	8.2	140	22
	08/11	45	1,343	8.7	96	15
	08/11	92	3,849	19.8	164	23
Waiokamilo 2	05/11	26	756	6.3	33	5
	08/11	13	508	4.9	16	3
	08/11	13	571	5.1	19	3
Kauai						
Opaekaa	04/11	39	8,447	58.7	8	3
	06/11	73	9,048	70.0	5	2
	07/11	48	5,984	51.8	4	2
	10/11	69	16,276	121.4	7	2

[a] Flight segment time and length recorded from the start and end points of the track log.

[b] Area calculated from a 50 m buffer on both sides with overlap areas dissolved (see Materials and Methods).

[c] Estimated 140 projectiles per pod.

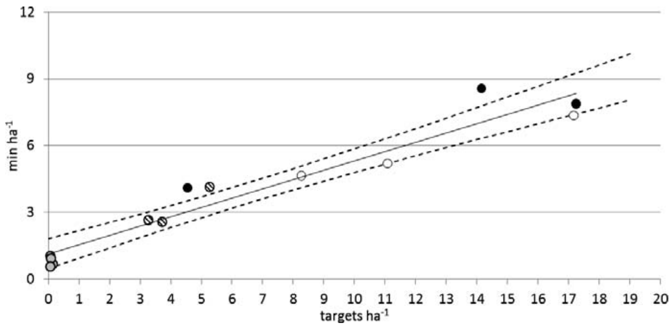

Figure 2. A scatter plot with best fit line ($R^2 = 0.927$; $P < 0.001$) with 95% confidence interval (dash lines) of search efficiency (min ha^{-1}) versus target density (targets ha^{-1}) for HBT calibration flight segments ($n = 13$) conducted in Wailua nui (black), Waiokamilo 1 (white), Waiokamilo 2 (stripe) and Opaekaa (grey) from November 2010 to October 2011. See Table 4 for regression coefficients.

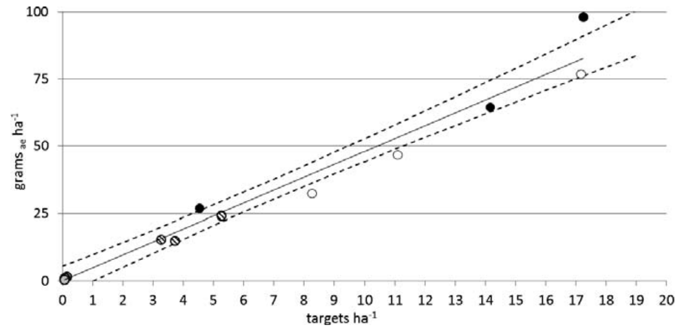

Figure 4. A scatter plot with best fit line ($R^2 = 0.966$; $P < 0.001$) with 95% confidence interval (dash lines) of herbicide acid equivalent amount (grams ae ha^{-1}) versus target density (targets ha^{-1}) for experimental HBT helicopter operations ($n = 13$) conducted in Wailua nui (black), Waiokamilo 1 (white), Waiokamilo 2 (stripe) and Opaekaa (grey) from November 2010 to October 2011. See Table 4 for regression coefficients.

targets had 3 to 4 axial points and the accuracy of the application was not measured during the calibrations, but it was less than 100%. Furthermore, an axial point may have received > 5 units, but not more than 10 units. In comparison to other registered triclopyr products, the highest use rate of HBT-TCP200 was 1.09% of the maximum allowable rate of 8.96 kg ae ha^{-1}(8 lbs ae $acre^{-1}$) while the remaining twelve calibration flight segments had calculated use rates that were $< 1\%$. As described below, these low use rates resulted in $> 94\%$ treatment efficacy. These calibrations highlight the efficiency of a surveillance operation that combines effective target control, which is fundamental to an effective containment strategy and further contributes to a limited knowledge base relating control effort to weed density (Buddenhagen and Yañez 2005; Cacho et al. 2007, Campbell et al 1996; Hester 2010; Panetta 2009; Panetta and Lawes 2005).

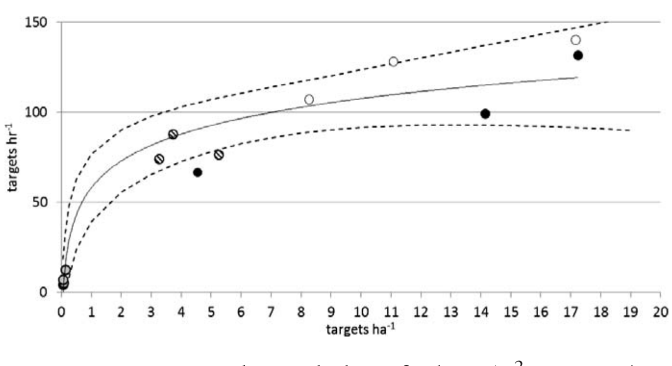

Figure 3. A scatter plot with best fit line ($R^2 = 0.924$; $P < 0.001$) with 95% confidence interval (dash lines) of target acquisition rate (targets hr^{-1}) versus target density (targets ha^{-1}) for experimental HBT helicopter operations ($n = 13$) conducted in Wailua nui (black), Waiokamilo 1 (white), Waiokamilo 2 (stripe) and Opaekaa (grey) from November 2010 to October 2011. See Table 4 for regression coefficients.

Previously undetected targets were identified and treated in subsequent overlapping operations. The range of detection efficacy calculated among the sites was 0.427 to 0.708 with a mean of 0.560 (Table 5). Operational treatment efficacy was determined in repeat segments by identifying survivors of a previous application. Typical symptoms included severe defoliation and necrosis associated with the herbicide treatment, but with intact lateral branches retaining photosynthetic leaf canopy. Thus, survivorship was not likely due to a malfunction of the HBT-TCP200 projectiles, but rather a condition of the application under a simulated operational setting. Regardless, the lowest operational treatment efficacy recorded was 0.941 at Opaekaa with a mean of 0.972 for all of the segments. Mortality factors (i.e. product of detection and treatment efficacies) among the segments had a range of 0.424 to 0.667 with a mean value of 0.542 (Table 5). These calibrations suggest that detection efficacy is a more influential correlate of mortality factor, highlighting the difficulty of plant detection in these natural environments, but also validates the consistency of this herbicide application platform (e.g. 5-unit dose).

This study recognizes mortality factor (Cacho et al. 2006) as an important parameter generated from these HBT calibrations. A mean of 0.542 would suggest a need to improve miconia detection through better surveillance techniques. Panetta and Cacho (2012) suggest that a structured search effort with uniform coverage and overlap should optimize target detectability. According to Cacho et al. (2007) coverage is a product of speed, time and detectable sight distance. This study utilized three different pilots and six different spotters for conducting the calibration flight segments ($n = 13$). All participants had several years of experience in helicopter surveillance operations and miconia detection. The speeds observed

Table 4. Regression coefficients as performance analytics for search efficiency, target acquisition rate and herbicide dose from empirical calibrations (n = 13) and cost components for simulated 1-yr extirpation strategies of different management frequencies, all relative to target density (T ha^{-1}).

Dependent variable	Coefficients *m*	*b*	R^2	P
Empirical[a]				
Search efficiency (min ha^{-1})	0.4183	1.1307	0.933	< 0.001
Target acquisition rate (targets hr^{-1})	21.533*ln	57.885	0.927	< 0.001
Herbicide dose (g ae t^{-1})	4.7937	0	0.966	< 0.001
Simulation[b]				
Qrt; MF 0.96 ($USD)	23.81	39,111	0.996	< 0.001
Semi; MF 0.79 ($USD)	20.39	19,468	0.994	< 0.001
Annu; MF 0.54 ($USD)	13.40	9,811	0.987	< 0.001

[a] Refer to Figures 2, 3 and 4 for search efficiency, target acquisition rate and herbicide dose, respectively.

[b] Refer to Figure 5 for simulations.

for these flight segments could be described as a slow hover within a "comfort" zone for efficient target detection, which was estimated at 5.3 km hr^{-1} (see y-intercept for search efficiency in Table 4). Speed reduction might improve target detection but with an added expense and the possibility of increasing pilot fatigue.

Miconia detectability is impeded by heavy vegetation and extreme topography, which are typical of tropical wet forest ecosystems. Plant size was also a factor in detectability. A majority of the acquired plant targets were at least 1 m tall, indicating a minimum age of 2 yr, while a majority of the incipient populations may consist of undetectable 1-yr juveniles. This highlights two points: (1) miconia detection is likely to be less than 100% and (2) recruitment of new detectable miconia can be expected in management areas within 1 yr following initial population reduction. These two conditions warrant a commitment to frequent, repeated surveillance operations of a management area that extends beyond reaching an undetectable level, if the ultimate goal is to actually achieve complete eradication of the incipient population. Ideally, this would occur under a policy that minimizes expected costs based on knowledge of the target species' biology and performance of the operational strategy (Burnett et al. 2007).

Operational costs were projected for simulated 1-yr population reduction strategies with different surveillance frequencies and plant target densities (Figure 5; Table 4). Costs for all strategies exhibited significant positive linear trends to plant target density (Table 4; $R^2 = 0.987–0.996$, $P_{0.05} < 0.001$) with semi- and quarter-annual strategies costing two- and four-fold higher than the annual strategy, respectively, where no targets were present. However, treatment costs (i.e. slope) progressively increased from lowest to highest frequency. With the cost of the herbicide

Table 5. Empirical Estimates for Detection Efficacy[a] (DE) and Operational Treatment Efficacy[b] (OTE) to calculate Mortality Factors (MF) from overlapping areas with repeated calibrations.

	Wailua Nui (7.8 ha)			Waiokamilo 1 (7.3 ha)		Waiokamilo 2 (5.7 ha)		Opaekaa (121.4 ha)	
Segments	1	2	3	1	2–3[c]	1	2–3[c]	1–3[c]	4
Targets	134	110	65	140	188	33	35	17	7
Survivors	—	4	5	—	1	—	0	—	1
DE	—	0.549	0.629	—	0.427	—	0.485	—	0.708
OTE	—	0.970	0.955	—	0.993	—	1.000	—	0.941
MF	—	0.533	0.600	—	0.424	—	0.485	—	0.667

[a] DE is calculated as the ratio of the previous targets from the total combined targets with the subsequent operation and it is assumed that all new targets in the subsequent operation were previously undetected and not new recruits.

[b] OTE is the ratio of effectively treated targets from the total targets, which is derived from the number of confirmed survivors identified in the subsequent operation.

[c] Combined calibrations overlapping the entirety of the of the previous/subsequent calibration and were conducted within 1 week of each other with targets and survivors reported as a composite value.

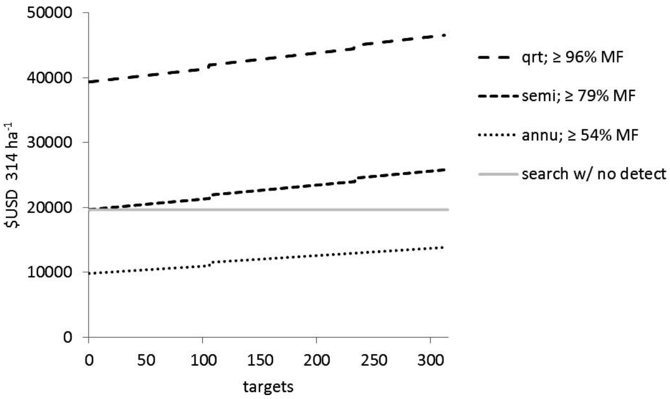

Figure 5. Expected operational cost projections of simulated 1-yr extirpation strategies within a 314-ha buffer management area with incipient population densities up to 1 target ha^{-1}. Each operation is assigned an MF = 0.542 with different management frequencies: Qrt (4 ops; MF = 0.96), Semi (2 ops, 0.79) and Annu (1 operation; MF = 0.54). Calculations based on single-helicopter operations. The solid line represents a semi-annual helicopter surveillance strategy with two operations where no targets are detected to confirm extirpation. See Table 4 for regression coefficients.

dose remaining static at $7.75 per plant, the cost increases corresponded to the extra flight time for overlapping coverage of the same area, regardless of whether the target was undetected in a prior operation or with treatment confirmation in the subsequent operation. The increases in population reduction potential (i.e. mortality factor) for the more frequent strategies is less than the corresponding cost increases, which reflects the difficulties of treating the last remaining targets to achieve undetectable levels and corroborates with Burnett et al. (2007) suggestion to defer management at extremely low target densities. The cost to search a 314-ha management area with no targets detected, along with an added surveillance operation to confirm no targets was estimated to be $19,657 USD, and served as a reference to opportunity cost for the other management options (Figure 5). For instance, this cost is comparable to a single surveillance operation of the same size management area, but with the opportunity to treat up to 734 targets at a mortality factor of 0.54, while conversely the higher frequency strategies lose opportunities to confirm undetectable levels in other management areas.

The matrix model simulated these same strategies, and included bi- and triennial schedules over a multi-yr period until complete eradication was achieved by exhausting predetermined seed banks, (Table 6). For all simulations, NPVs decreased proportionally to operational frequency and were largely influenced by the total number of operations and the discount rate applied each year across the timeline. The quarter-annual strategy achieved eradication with the shortest timelines, but also with the highest number of operations and at the least discounted rates, thus, resulting in the highest NPVs. The triennial strategy eradicated the smallest population with the lowest NPV, resulting from the longest timeline with the most discounted rates. However, this strategy failed to eradicate the two larger vector populations with reduction being outpaced by recruitment. The biennial strategy eradicated these larger vector populations, with the longest timelines and most discounted rates resulting again in the lowest NPVs. This illustrates the value of maximizing discounted rates with long-term extensions to strategies. However, this could only be accounted for with a reliable commitment to sustained resources and if those resources were actually invested on years where management was not scheduled. Miconia management programs in Hawaii operate under no such mandate and experience fiscal fluctuations with annual renewals.

These short- and long-term projections (Figure 5; Tables 4 and 6) are deterministic by producing expected outcomes, which can vary from actual results, but should continue to improve with updates in quantitative ecology and operations research (Hester et al. 2010). Cost estimates and NPVs reported in this study are within range of reported projections from Australia (Hester et al. 2010). These expected cost and NPV projections assume complete surveillance of a 314-ha isotropic buffer, but is likely to be an impractical management unit in heterogeneous environments (Murphy et al. 2008). Spatial analyses of population distribution and suitable habitat will become valuable contributions in management area prioritization and resource allocation. For example, ravines and gullies are known to serve as conduits in frugivorous dispersal and gravitational migration of propagules (Metcalf et al. 1998; Murphy et al. 2008). New information from Tahiti has identified several parameters, including topgraphic slope and aspect, as identifiers of suitable habitat for miconia (Pouteau et al 2011). The projections from this study are likely to over-estimate resource requirements to accomplish population reduction goals, although the performance of the HBT platform should be consistent regardless of management area designation. Future operational use patterns of the platform are expected to improve the calibrations with larger data sets generated by multiple applicators and a broader range of scenarios. The protocols adopted in this study for recording basic operational parameters and calibrating performance should be universal to most weed management techniques in natural areas where search effort and treatment efficacy are both critical features to successful operations (Cacho et al 2007). The HBT platform is presented as a complement to existing ground and aerial efforts for miconia management in Hawaii. Accurate calibrations of these conventional techniques will further support decisions for future assignments where HBT might be best suited.

Table 6. Projected long-term management strategies to eradicate incipient miconia populations within a 314 ha isotropic buffer management area with an operational mortality factor (MF) = 0.542.

X_t[a] (adult/jv)	Schedule[b]	Years/ops[c]	Adult/jv[d]	Mean MF[e]	NPV[f] ($1000×)
2/48	Qrt	13/38	2/264	0.977	272.87
	Semi	13/23	2/277	0.819	158.90
	Annu	13/13	3/329	0.565	87.46
	Bi	19/10	17/455	0.325	58.48
	Tri	58/20	123/1,736	0.225	57.17
20/74	Qrt	15/46	20/543	0.971	317.12
	Semi	15/27	24/628	0.809	180.22
	Annu	16/16	34/856	0.556	102.69
	Bi	29/15	110/1,653	0.306	72.99
	Tri	—	—	—	—
209/1518	Qrt	21/69	218/8,887	0.961	526.56
	Semi	21/38	281/10,111	0.782	319.58
	Annu	25/25	550/13,587	0.542	213.49
	Bi	63/32	1,491/23,050	0.405	164.79
	Tri	—	—	—	—

[a] Initial vector population of adults and detectable juveniles (yr 2 to 4).

[b] Operation frequency: Qrt - four operations yr^{-1}; Semi- two operations yr^{-1}; Annu- one operation yr^{-1}; Bi- one operation two yrs^{-1}; Tri- one operation three yrs^{-1}.

[c] Total yr and operations projected to achieve incipient population extirpation.

[d] Total adults and juvenile (yr 2 to 4) targets acquired to achieve incipient population extirpation.

[e] Mean annual mortality factor based on an operational mortality factor of 0.542 compounded by the number of operations.

[f] Net present value investment ($USD) based on cost of helicopter operations (see Table 2), projectile inventory consumption and annual discount rate of 6%.

A comprehensive miconia management strategy is limited by available fiscal resources, which force decisions to be made between risk aversion and budget optimization (Burnett et al. 2007; Hester et al. 2010). An optimal policy for miconia management minimizes the present values of management costs and residual damages along an infinite timeline, that would even dictate management deferment for low-density populations, where the marginal cost to search and treat these remaining individuals is extremely high (Burnett et al. 2007). Murphy et al. (2008) recommended the establishment of management units with a minimum 1000 m radial buffer, but in the same report identified 95% of the targets treated within a 500 m buffer. According to Burnett et al. (2007) and in this study (see Figure 5) elimination of that last 5% becomes exceedingly more difficult and costly. This study suggests a triennial schedule as an optimum strategy for the smallest incipient population, although it must accommodate a 58-yr timeline with an 8-fold recruitment of the mature population. Anecdotally, we have encountered multiple occasions confirming the establishment of mature stands when reentry to a site exceeds 2 yr. From a practitioner's standpoint, a budget optimization approach is likely to be viewed as too risky, particularly when funding provisions fluctuate annually with no permanent mandate of support.

For invasive weed management, marginal costs can be interpreted different ways, with incremental units based on target numbers or net treated area (Buddenhagen and Yañez 2005; Campbell et al. 1996; Rejmánek and Pitcairn 2002). Resources dedicated to control inputs may be negligible compared to resources dedicated to search effort (Hester et al. 2010). Helicopter flight time was a dominant cost component for analyzing HBT platform performance. We identified surveillance operations confirming undetectable levels (i.e. no targets detected) to have the lowest marginal cost that could be applied to a management area. Delimiting incipient populations is critical to effective containment of miconia, and should include expanding surveys into unknown areas despite the probability of not detecting new populations (Brooks et al. 2009; Cacho et al. 2010) However, the strategy must acknowledge the conundrum of an opportunity lost in reducing (i.e. target treatment) known, incipient populations.

This study does not attempt to provide concrete decisions in favor of extreme risk aversion or expected cost minimization. However, miconia is an autogamous species with rapid maturity, high fecundity and a large dispersal range making a single plant in a remote area a high value target that can only be detected with resources dedicated to frequent, overlapping surveillance operations. The best utility identified so far for the HBT platform is through integration into aerial surveillance operations where nominal herbicide use rates translate into significant flight time cost savings and provides streamlined efforts towards effective miconia containment.

Acknowledgments

Funding for this project was provided in part by the Maui County Office of Economic Development Special Grants Program, Hawaii Invasive Species Council Technology Grants Program, USDA-CSREES Tropical Subtropical Agriculture Research Program, USDA-NIFA Rural Resources Extension Act, and the USDA- NRCS Conservation Innovation Grant. We thank Nelson Paint Company, Dow Agrosciences LLC., BASF Corp. and The Wilbur Ellis Company for their current and past collaborations. We thank Keren Gundersen, Lloyd Loope, Chuck Chimera and two anonymous reviewers for improving this manuscript with thoughtful suggestions.

Literature Cited

Brooks, S. J., F. D. Panetta, and T. A. Sydes. 2009. Progress towards the eradication of three melastome shrub species from northern Australian rainforests. Plant Protect. Quart. 24(2):71–78.

Buddenhagen, C. and P. Yañez. 2005. The costs of Quinine *Cinchona pubescens* control on Santa Cruz Island, Galapagos, Galapagos Res. 63:32–36.

Burnett, K., B. Kaiser, and J. Roumasset. 2007. Economic Lessons from Control Efforts for an Invasive Species: *Miconia calvescens* in Hawaii, J. For. Econ. 13(2–3):151–167.

Cacho, O. J., S. Hester, and D. Spring. 2007. Applying search theory to determine the feasibility of eradicating an invasive population in natural environments. Aus. J. Agric. and Res. Econ. 51:425–433.

Cacho, O. J., D. Spring, P. Pheloung, and S. Hester. 2006. Evaluating the feasibility of eradicating an invasion. Bio. Inv. 8:903–917.

Cacho, O. J., D. Spring, S. Hester, and N. MacNally. 2010. Allocating surveillance effort in the management of invasive species: a spatially-explicit model. Environ. Modelling and Software 25:444–454.

Campbell, S. D., C. L. Setter, P. L. Jeffrey, and J. Vitelli. 1996. Controlling dense infestations of *Prosopis pallida*. Pages 231–232 *in* R.C.H. Shepherd, ed. Proc. 11th Aus. Weeds Conf.. Weed Science Society of Victoria, Frankston.

Chimera, C. G., A. C. Medeiros, L. L. Loope, and R. H. Hobdy. 2000. Status of management and control efforts for the invasive alien tree *Miconia calvescens* DC. (Melastomataceae) in Hana, East Maui. Honolulu, HI: University of Hawaii Pacific Coop. Studies Unit, Tech Rep #128. 53 p.

Denslow, J. S. 2003. Weeds in paradise: thoughts on the invasibility of tropical islands. Ann. MO Bot. Gard. 90:119–127.

Florence, J. 1993. La végétation de quelques îles de Polynésie. Planches 54–55. *in* F. Dupon, coord. ed. Atlas de la Polynésie franç aise. ORSTOM, Paris, France.

Giambelluca, T. W., R. A. Sutherland, K. Nanko, R. G. Mudd, and A. D. Ziegler. 2010. Effects of Miconia on hydrology: a first approximation. Pages 1–7 *in* L. L. Loope, J. Y. Meyer, B. D. Hardesty, and C. W. Smith, eds. Proceedings of the International Miconia Conference, Keanae, Maui, Hawaii, May 4–7, 2009. Honolulu, HI: University of Hawaii, Maui Invasive Species Committee and Pacific Coop Studies Unit, www.hear.org/conferences/miconia2009/pdfs/giambelluca.pdf. Accessed March 2012.

Hardesty, B. D., S. S. Metcalfe, and D. A. Westcott. 2011. Persistence and spread in a new landscape: dispersal ecology and genetics of Miconia invasions in Australia. Acta Oecol., 37:657–665.

Hester, S. M., S. J. Brooks, O. J. Cacho, and F. D. Panetta. 2010. Applying a simulation model to the management of an infestation of *Miconia calvescens* in the wet tropics of Australia. Weed Res. 50(3):269–279.

Hulme, P. E. 2006. Beyond control: wider implications for the management of biological invasions. J. Appl. Ecol. 43:835–847.

Kueffer, C., C. C. Daehler, C. W. Torres-Santana, C. Lavergne, J.-Y. Meyer, R. Otto, and L. Silva. 2010. A global comparison of plant invasions on oceanic islands. Persp. Plant Ecol. Evol. Syst. 12: 145–161.

Lowe, S., M. Browne, S. Boudjelas, and M. De Poorter. 2000. 100 of the World's Worst Invasive Alien Species A selection from the Global Invasive Species Database. The Invasive Species Specialist Group (ISSG) a specialist group of the Species Survival Commission (SSC) of the World Conservation Union (IUCN), 12 p.

Mack, R. N., D. Simberloff, W. M. Lonsdale, H. C. Evans, M. Clout, and F. A. Bazzaz. 2000. Biotic invasions: causes, epidemiology, global consequences and control. Ecol. Appl. 10:689–710.

Medeiros, A. C., L. L. Loope, P. Conant, and S. McElvaney. 1997. Status, ecology and management of the invasive plant *Miconia calvescens* DC. (Melastomataceae) in the Hawaiian Islands. B. P. Bishop Museum Occasional Papers 48:23–36.

Medeiros, A. C., L. L. Loope, and R. W. Hobdy. 1998. Interagency efforts to combat *Miconia calvescens* on the island of Maui, Hawai'i. Pages 45–51, *in* J-Y. Meyer and C. W. Smith, eds. Proceedings of the first regional conference on Miconia control. August 26–29, 1997, Centre ORSTOM de Tahiti.

Metcalfe, D. J., P. J. Grubb, and I. M. Turner. 1998. The ecology of very small-seeded shade-tolerant trees and shrubs in lowland rain forest in Singapore. Plant Ecol. 134:131–149.

Meyer, J-Y. 1994. Mecanismes d'invasion de Miconia calvescens en Polynesie Francaise. Ph.D. thesis, l'Universite de Montpellier I1 Sciences et Techniques du Langueduc; Montpellier, France. 122 p.

Meyer, J-Y. 1996. Status of *Miconia calvescens* (Melastomataceae), a dominant invasive tree in the Society Islands (French Polynesia). Pac. Sci. 50:66–76.

Meyer, J-Y. 1998. Observations on the reproductive biology of *Miconia calvescens* DC (Melastomataceae), an alien invasive tree on the island of Tahiti (South Pacific Ocean). Biotropica. 30:609–624.

Meyer, J-Y., L. L. Loope, and A. C. Goarant. 2011. Strategy to control the invasive alien tree Miconia calvescens in Pacific islands: eradication, containment or something else? Pages 91–96 *in* C. R. Veitch, M. N. Clout, and D. R. Towns, eds. 2011. Island Invasives: Eradication and Management. Gland, Switzerland: IUCN.

Moody, M. E. and R. N. Mack. 1988. Controlling the spread of plant invasions: the importance of nascent foci. J. Appl. Ecol. 25: 1009–1021.

Murphy, H. T., B. D. Hardesty, C. S. Fletcher, D. J. Metcalfe, D. A. Westcott, and S. J. Brooks. 2008. Predicting dispersal and recruitment of *Miconia calvescens* (Melastomataceae) in Australian tropical rainforests. Biol. Inv. 10:925–936.

Myers, J. H., D. Simberloff, A. M. Kuris, and J. R. Carey. 2000. Eradication revisited: dealing with exotic species. Trends Ecol. Evol. 15:316–20.

PCSU (Pacific Cooperative Studies Unit). 2011. Standing Operating Procedure for Herbicide Ballistic Technology Operations: Ground and Aerial Herbicide Application. Safety Management Program. RCUH-PCSU SOP no. 32. 19 p.

Panetta, F. D. 2009. Weed eradication: an economic perspective. Inv. Pl. Plant Sci. Manag. 2(4):360–368.

Panetta, F. D. and O. J. Cacho. 2012. Beyond fecundity control: which weeds are most containable? J. Appl. Ecol.. doi: 10.1111/j.1365-2664.2011.02105.

Panetta, F. D. and R. Lawes. 2005. Evaluation of weed eradication programs: the delimitation of extent. Div. Distr. 11(5):435–42.

Pouteau, R., J-Y. Meyer, and B. Stoll. 2011. A SVM-based model for predicting the distribution of the invasive tree *Miconia calvescens* in tropical rainforests. Ecol. Model. 222:2631–2641.

Reaser, J. K., L. A. Meyerson, Q. Cronk, M. DePoorter, L. G. Eldrege, E. Green, M. Kairo, P. Latasi, R. N. Mack, J. Mauremootoo, D. O'Dowd, W. Orapa, S. Sastroutomo, A. Saunders, C. Shine, S. Thrainsson, and L. Vaiutu. 2007. Ecological and socioeconomic impacts of invasive alien species in island ecosystems. Environ. Conserv. 34:98–111.

Rejmánek, M. and M. J. Pitcairn. 2002. When is eradication of exotic pest plants a realistic goal? Pages 249–253 *in* C. R. Vietch and M. N. Clout, eds. Turning the Tide: The Eradication of Island Invasive. Gland, Switzerland: IUCN SSC Invasive Species Specialist Group.

Taylor, C. M. and A. Hastings. 2004. Finding optimal control strategies for invasive species: a density-structured model for *Spartina alterniflora*. J. Appl. Ecol. 41:1049–1057.

Wittenberg, R. and M.J.W. Cock, eds. 2001. Invasive Alien Species: A Toolkit of Best Prevention and Management Practices. Wallingford, Oxon, UK: CAB International. 241 p.

Received April 2, 2012, and and accepted January 7, 2013.

Appendix 1. Stage matrix (H) and vector populations (X_t) adopted from Hester et al 2010.

H =	0	0	0	0	0	0	Fsa	Fla	X_t =		*2/48*	*20/74*	*209/1518*
	Pfruit	Psb	0	0	0	0	0	0		SB[a]	20.80	47.99	675.45
	0	G	0	0	0	0	0	0		jv_1	3,418	4,872	95,440
	0	0	Pjv1	0	0	0	0	0		Jv_2	37	44	1012
	0	0	0	Pjv2	0	0	0	0		Jv_3	8	11	257
	0	0	0	0	Pjv3	P6	0	0		Jv_4	3	19	249
	0	0	0	0	0	Pjv4	P7	0		sa	0	8	83
	0	0	0	0	0	0	Psa	Pla		la	2	12	126

[a] Seed bank values reported in $\times 10^6$.