Reducing Nascent Miconia (*Miconia calvescens*) Patches with an Accelerated Intervention Strategy Utilizing Herbicide Ballistic Technology

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The miconia (*Miconia calvescens*) invasion of the East Maui Watershed (EMW) started from a single introduction over 40 yr ago, establishing a nascent patch network spread across 20,000 ha. In 2012, an accelerated intervention strategy was implemented utilizing the Herbicide Ballistic Technology (HBT) platform in a Hughes 500D helicopter to reduce target densities of seven nascent patches in the EMW. In a 14-mo period, a total of 48 interventions eliminated 4,029 miconia targets, with an estimated 33% increase in operations and 168% increase in recorded targets relative to the adjusted means from 2005 to 2011 data (prior to HBT adoption). This sequence of interventions covered a total net area of 1,138 ha, creating a field mosaic of overlapping search coverage (saturation) for each patch (four to eight interventions per patch). Target density reduction for each patch fit exponential decay functions ($R^2 > 0.88$, $P < 0.05$), with a majority of the target interventions spatially assigned to the highest saturation fields. The progressive decay in target density led to concomitant reductions in search efficiency (min ha^{-1}) and herbicide use rate (grams ae ha^{-1}) in subsequent interventions. Mean detection efficacy ($\pm$ SE) between overlapping interventions ($n = 41$) was 0.62 ± 0.03, matching closely with the probability of detection for a random search operation and verifying imperfect (albeit precise) detection. The HBT platform increases the value of aerial surveillance operations with 98% efficacy in target elimination. Applying coverage saturation with an accelerated intervention schedule to known patch locations is an adaptive process for compensating imperfect detection and building intelligence with spatial and temporal relevance to the next operation.

Nomenclature: Miconia, *Miconia calvescens* DC.

Key words: Adaptive management, aerial surveillance, GIS, nascent patch network, random search operation, mortality factor.

An exotic plant invasion is a phenomenon carried out by species with the capability to occupy niches already inhabited by other indigenous or endemic plant communities (Richardson et al. 2000). This invasion phenomenon is also a main driver in habitat fragmentation, leading to modification of an ecosystem's structure and function (Gilbert and Levine 2013). The resultant loss of endemic biological diversity is particularly detrimental for isolated island ecosystems that exhibit high endemism (Denslow 2003; Mack et al. 2000; Reaser et al. 2007).

A commitment to weed species eradication starts with an effective containment strategy targeting the nascent patch network that is expanding the invasion front (Cousens and Mortimer 1995; Moody and Mack 1988; Rejmánek and Pitcairn 2002). Reconnaissance and surveillance are fundamental activities for nascent weed detection and spatial delimitation (Baxter and Possingham 2011; Cacho et al. 2007; Hester et al. 2010; Lawes and McAllister 2006; Panetta and Lawes 2005; Rew et al. 2006; Taylor and Hastings 2004). Reconnaissance tends to be a more cursory

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Management Implications

The herbicide ballistic technology (HBT) platform is a herbicide delivery system registered as a 24(c) Special Local Need for use in Hawaii to treat nascent satellite miconia patches in remote natural areas that require helicopter operations. We define an intervention as a weed management operation with the combined actions of target detection immediately followed by effective elimination. In 14 mo, a total of 48 interventions were conducted for seven nascent patches, (1) eliminating 4,029 miconia targets and (2) encompassing a total net area of 1,138 ha, while (3) administering $< 1\%$ of the maximum allowable herbicide use rate. Target density reduction for the patch network was $> 86\%$, fitting an exponential decay function. This resulted in a threefold improvement in search efficiency (min ha^{-1}) and a 10-fold reduction in herbicide use rate (g ae ha^{-1}). Expansion of the total net area corresponded to improvements in search efficiency; less time was needed to saturate known target locations with reduced densities. These interventions are described as random search operations with imperfect detection. Efficacy of an HBT application to miconia can be confirmed in less than 1 mo, allowing for the acceleration of intervention schedules that can compensate for imperfect detection by saturating coverage with compounding sequential interventions. The goals of this accelerated intervention strategy are to rapidly reduce nascent patch populations to manageable or undetectable levels and build spatially and temporally explicit intelligence, where expected projections are accurate with observed values.

process of searching for new target locations, whereas surveillance is distinguished by a more intensive process of building explicit intelligence on known target locations with repeated visits (Anonymous 2007). In the early stages of strategy development, reconnaissance may be a necessary trade-off to actual treatment activities when a lack of intelligence compromises a sound priority decision process (Baxter and Possingham 2011). Otherwise, surveillance is a more common practice of gathering intelligence, usually as an ad hoc activity complementary to active management and relegated to within the immediate vicinity of the management area (Cacho et al. 2007; Fox et al. 2009). Detection of invasive plant species residing in their natural settings is an imperfect process (Moore et al. 2011; Regan et al. 2011). Good intelligence, regardless of the survey design, should account for imperfect detectability as an adaptive process for optimizing future operations (Moore et al. 2011; Regan et al. 2011; Thompson 2002).

Cacho et al. (2007) coined the term "mortality factor" to describe management of individual weed targets, accounting for both detection and effective treatment as complementary actions necessary to achieving target elimination. With an effective treatment technique, detection then becomes the determinant outcome of an operation (Leary et al. 2013; Lodge et al. 2006). Koopman (1946) introduced the mathematical framework for estimating the probability of detection (P_d) in a random search operation that would be expected within a terrestrial environment (Cooper et al. 2003). Search impediments (i.e., topography, weather, surrounding vegetation) imposing even slight randomness in coverage (c), have been shown to fit the exponential detection function (Equation 1) as a conservative estimate of an imperfect search effort (Cacho et al 2007; Frost 1999):

$$p_d = 1 - e^{-c} \qquad [1]$$

Herbicide Ballistic Technology (HBT) is a weed target intervention platform that was developed in Hawaii to enhance helicopter surveillance operations with the capability to dispatch satellite weed targets upon detection (Leary et al. 2013). The HBT platform discretely administers small-aliquot herbicide projectiles through a pneumatic application device to treat individual weed targets with long-range accuracy (i.e., 30 m [98 ft] effective range) from horizontal or vertical trajectories. It expands the capability to treat all detectable targets that might otherwise be untreatable with other conventional application methods. An effective HBT treatment application enhances surveillance operations with the full complement of a mortality factor (Leary et al. 2013).

The term "intervention" is used here to distinguish from other surveillance operations with the inclusion of a mortality factor accommodated by the integration of an HBT platform. This study expands on platform calibrations described by Leary et al. (2013) with the accelerated deployment of an adaptive intervention strategy targeting the primary nascent patch network of the miconia (*Miconia calvescens* DC.) invasion in the East Maui Watershed (EMW; Hawaii). We report on spatial and temporal parameters of performance measures associated with patch target density reductions incurred by these intervention sequences.

Materials and Methods

Target Species: *Miconia calvescens*. Miconia is a midstory tree, 12 to 15 m tall, native to Central and South America. It was introduced to the Hawaiian Islands in 1961 and was presumably introduced to the island of Maui by 1970, where the first management program in the state was initiated 20 yr later (Chimera et al. 2000; Medeiros et al. 1997). Miconia is an autogamous species that reaches maturity in 4 to 5 yr. A single plant has immense fecundity, producing millions of propagules in a single reproductive cycle (Meyer 1998). Its fruit are small and edible, lending itself to frugivorous dispersal by a diverse avian community (Chimera et al. 2000; Spotswood et al. 2013). In Australia, the dispersal range of a nascent patch had been estimated to exceed 2,000 m, but with 95% of the recruitment contained within 500 m of the maternal source (Hardesty et al. 2011; Murphy et al. 2008). Viable seed persistence has been measured beyond 16 yr (Meyer et al. 2011), contributing to the long-term recruitment potential of a latent seed bank.

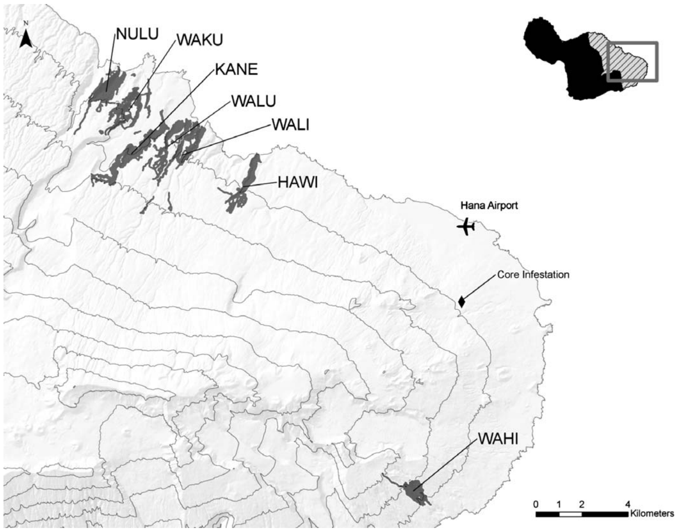

Figure 1. Map of East Maui Watershed with mean center of the miconia core infestation (CORE; black diamond) and the final net areas of the patch units (shaded buffers with corresponding four-letter acronyms; black). See Experimental Units in the Materials and Methods section. 300-m contours displayed on the base map.

Suitable Habitat: The EMW. The EMW encompasses over 55,000 ha (136,000 ac) on the windward slope of Haleakala Crater on Maui. The core miconia infestation occupies < 1,000 ha on the easternmost portion of EMW (20°47′44″N, 156°00′52″W), while the spatial distribution of the nascent patch network is spread across an estimated 20,000 ha (Figure 1). The invasion is below 1,000 m above sea level (m_{asl}) with invasion fronts advancing south 8 km (5 mi) and west 18 km from the core infestation (CORE), respectively. The mean annual precipitation range within this area is 3,000 to 6,000 mm (118–236 in) (Giambelluca et al. 2013). The mean annual temperature from Hana Airport (24 m_{asl}) is 23.4°C (74.1 F; 1950 to 2005; WRCC 2013) with a lapse rate of −0.64°C per 100 m elevation (Jacobson 2005). These climatic conditions are consistent with the description of a suitable habitat in French Polynesia (Pouteau et al. 2011). The dominant vegetation types include a wet coastal forest with mixed exotic canopy species (e.g., African tulip tree [*Spathodea campanulata* P. Beauv.], eucalyptus [*Eucalyptus robusta* Sm.], guava [*Psidium* spp.]) that transitions to a wet montane forest at higher elevations, represented by endemic assemblages (e.g. ohi'a [*Metrosideros polymorpha* Gaudich] and koa [*Acacia koa* Gray]) (Wagner et al. 1999) that also serve as critical habitat for 59 other threatened and endangered plant species (Anonymous 2000). Miconia is capable of invading EMW critical habitat above 1,000 m_{asl} (Medeiros et al. 1997; Meyer 1996; Meyer and Florence 1996; Pouteau et al. 2011), making mitigation of its spread into these areas a strategic priority.

Over the last decade, systematic surveys of the entire watershed have identified all major nascent patch populations along with hundreds of incipient satellites. These patches are comparably smaller and phenologically distinguishable from the CORE, with plant maturity observed less frequently. They are most often identified as juvenile understory saplings (ca. < 3 m tall) that may be aggregating into monotypic midstory canopies. These patches also tend to colonize the extreme topography associated with the ravines and drainages of EMW's heterogeneous landscape (see Pouteau et al. 2011 for similar topographic features).

Experimental Units: The Miconia Patch Network. Seven of the most prominent patches within the network were selected to test an accelerated intervention schedule (see below): Nuuailua (NULU), Waiakuna Pond (WAKU), Keanae Wall (KANE), Wailua nui (WALU), Wailua iki (WALI), Hanawi (HAWI), and Waihiumalu (WAHI) (Figure 1). Five of the patches (NULU, WAKU, KANE, WALU, and WALI) were located along the western front of the invasion, 12 to 18 km from the CORE. Each of the western-front patches was within a 1,000-m radius of the next adjacent patch, creating a viable interpatch network for frugivorous dispersal (Hardesty et al. 2011; Murphy et al. 2008). The HAWI patch was approximately 3,000 m from the nearest patch (WALI). However, several targets interspersed between these patches had been dispatched in separate operations that were not a part of this study. The WAHI patch was located on the southern front of the invasion and was closest to the CORE (ca. 8 km from centers). One other known patch was just south of WAHI, and was also being managed independently of this study.

The Accelerated Intervention Schedule. The strategy implemented for this study consisted of an accelerated deployment schedule of sequential interventions. A total of 48 interventions were conducted on eight separate dates over a 14-mo period, with all patches receiving at least four interventions and three of the seven receiving eight interventions (Table 1). The time intervals between interventions ranged from 18 to 182 d with the median/mode interval at 32 d. Based on previous recorded operations conducted in these patch areas (2005 to 2011), the intervention schedules for this study were accelerated by 33% (Supplemental Table 1, http://dx.doi.org/10.1614/IPSM-D-13-00059.TS1). All helicopter operations were conducted with a full fuel load, providing 70 to 100 min of operation flight time. Starting locations were typically at the lowest elevation point for each patch, proceeding with an adaptive process of deliberating search efforts to known target locations based on intelligence derived from previous interventions (Fox et al. 2009; Thompson 2002). Any remaining flight time would accommodate expansion of search coverage to surrounding adjacent areas, typically into higher elevations. Flight lines were anisotropic, running

Table 1. Intervention data recorded for the seven nascent miconia patches.

Patch	Intervention[a]	Gross area[b] (ha)	Net area[c] (ha)	Targets	OFT[d] (min)	PC[e]
HAWI	4	302.0	130.8	471	574.1	14,698
WAHI	6	275.8	94.4	465	574.3	11,431
WAKU	7	329.1	194.0	412	562.8	12,167
WALI	7	478.1	175.0	401	684.9	14,127
WALU	8	412.9	154.4	676	764.7	17,174
NULU	8	586.7	174.6	508	785.8	14,294
KANE	8	688.8	214.9	1096	1169.8	31,674
NETW[f]	48	3073.4	1138.1	4029	5116.4	115,565

[a] Interventions conducted in February 2012, May 2012, June 2012, October 2012, November 2012, December 2012, February 2013, March 2013, and April 2013.

[b] Momentary gross area.

[c] Cumulative net area.

[d] Abbreviations: OFT, operation flight time; PC, projectile consumption; HAWI), Hanawi; WAHI, Waihiumalu; WAKU, Waiakuna Pond; WALI, Wailua iki; WALU, Wailua nui, NULU, Nuuailua; KANE, Keanae Wall; NETW, network.

[e] Projectile consumption estimated from the pod inventory (ca. 140 projectiles pod^{-1}).

[f] Total values for the entire patch network.

along the contours of the steep topography and with iso-altitudinal transects spaced $<$ 50 m of elevation apart for ensuring visual search overlap from valley floor to ridgeline.

Helicopter HBT Platform and Intervention Procedures. All aerial operations were conducted in a Hughes 500D helicopter by a three-person crew with a portside bias creating a 210° field of view and a detectable sight range estimated at 50 m. Operation speeds were maintained at $<$ 20 km h^{-1} while actively searching. Miconia targets were treated with 17.3-mm soft-gel projectiles encapsulating 199.4 mg ae (0.007 oz) of the active herbicide ingredient triclopyr. Applicators administered three to five projectiles to each stem axial point (e.g., larger targets with more axial points received higher doses). The applicator, seated portside behind the pilot, administered an effective herbicide dose to target within a 30-m effective range. Operation data were recorded with a Fortrex® 301 global positioning system (GPS) data logger (Garmin®; Olathe, KS) with flight lines recorded as 5-sec vertex track logs and dispatched targets recorded as waypoints, which were actually recorded from the position of the application and not the actual location of the target (i.e., within 30 m). This protocol was consistently applied to all recorded points due to flight safety considerations. Projectile consumption was determined at the end of each operation. For further details on these protocols refer to Leary et al. (2013).

Geographic Information System Data Analyses. All GPS data were projected in the NAD 1983 UTM Zone 4N coordinate system and processed in ArcMAP® 10.1 (Esri®; Redlands, CA). Tracks logs were manually spliced into operation flight segments that were $\leq$ 16 km h^{-1}. Search coverage areas were calculated from these operation flight segments using buffer tool procedures with a full 50-m radius and dissolved overlap. Operation times were calculated by tabulating the number of vertices in these same flight segments (e.g., 12 vertices min^{-1}). All buffers for each patch were superimposed with a union tool procedure creating a field mosaic of the cumulative net area. Coverage saturation levels for each field were scored by the number of overlapping buffers. As an example, an area mosaic created by eight interventions contained fields representing all levels of saturation (i.e., 1 to 8). All target waypoints were spatially joined to their respective buffer unions for saturation field assignment.

Operation data sets consisted of (1) area, (2) time, (3) targets, and (4) projectile consumption, which were used to calculate target density (targets ha^{-1}), search efficiency (min ha^{-1}), and herbicide use rate (g ae ha^{-1}). The data and calculations were each assigned to three separate subcategories:

1. momentary intervention assignment (momentary)—an independent intervention data set with no saturation field assignments, generating gross area and operation performance values of the moment;
2. cumulative intervention assignment (cumulative)—a compilation of sequential data sets scaled by the number of interventions with progressive assignments made to a changing saturation field mosaic, generating net area and compounded operation performance values; and
3. historic intervention assignment (historic)—all sequential data sets were retroactively assigned to the final saturation field mosaic, generating gross area and operation performance values for each momentary operation in retrospect.

Momentary data sets were used to calibrate search efficiency and herbicide use rate corresponding to encountered target densities from independent flight segments ($n = 103$) contributing to the sequential interventions ($n = 48$).

Cumulative data sets were used to calculate weighted mean saturation ($\overline{Csat_n}$) from the net area field mosaic with the sum of each (ith) saturation level adjusted by the respective proportion of assignments, divided by the total field assignments within the entire mosaic (Equation 2). In this study, x_i includes either area or target assignments with the highest (ith) level of saturation equivalent to (n) interventions.

$$\overline{Csat_n} = \sum\nolimits_{i=1}^{n} (ix_i) \Big/ \sum x_i \qquad [2]$$

Cumulative target densities (Ctd_n) were adjusted by dividing the compounded values with their respective number (n) of contributing interventions (Equation 3). The influence of sequential interventions on the adjusted target density was fit with an exponential decay function for each patch (Equation 4).

$$Ctd_n = (Ca_n / Ct_n)/n \qquad [3]$$

$$f(x) = y_o e^{-\lambda n} \qquad [4]$$

Momentary and historic target densities only represent outcomes of the moment, which is dependent on the area searched and targets detected within that intervention. Cumulative target densities, on the other hand, account for targets dispatched in all previous interventions for the entire net area, providing a more spatially accurate presentation of progress.

Detection efficacy (de), as described by Leary et al. (2013), is the ratio of targets (x) recorded between sequential interventions (n) spatially assigned to the same saturation fields (Equation 5).

$$de = x_n / x_n + x_{n+1} \qquad [5]$$

Retroactive proportions of cumulative target and net area totals ($Cprop_x$) of each intervention were calculated from the final total (Equation 6).

$$Cprop_x = Cx_n / Cx_{final} \qquad [6]$$

Cumulative target proportions were plotted against their corresponding coverage (c), which was calculated as the weighted mean net area saturation (Equation 4) multiplied by the cumulative net area proportion for each intervention (Equation 7).

$$c = \overline{Csat_n} \times Cprop_n \qquad [7]$$

Coverage of the last interventions ($Cprop_x = 1$) of each patch were equal to the highest weighted mean saturation levels. These values were plotted with search theory concepts postulating probabilities of detection (P_d) for a random search operation (Equation 1) (Koopman 1946, 1980) and also a theoretically perfect "definite range" sensor (Equation 8) where P_d is proportional up to complete coverage ($c = 1$), resulting in perfect detection that cannot be exceeded with added coverage:

$$\lim_{c \to 1} (P_d \propto c) \qquad [8]$$

Polynomial linear and two-parameter exponential decay functions were used to fit momentary and cumulative sequential data plots, respectively, using SigmaPlot® (version 12.0, (Systat Software, Inc., San Jose CA).

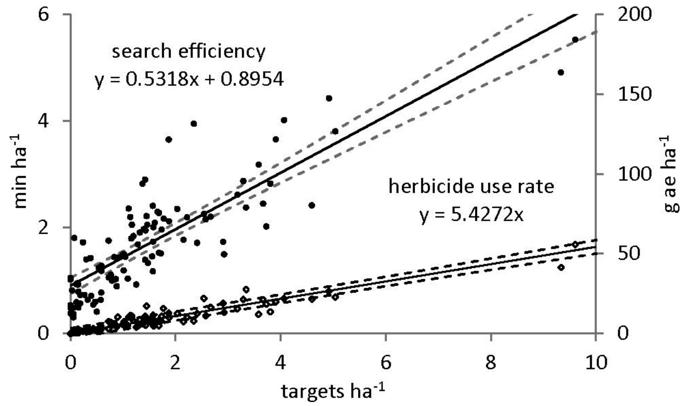

Figure 2. A scatter plot with best-fit lines and 95% confidence intervals (dashed lines) for surveillance efficiency (dark circles; min ha^{-1}; P < 0.001; $R^2 = 0.78$) and herbicide use rate (open diamonds; g ae ha^{-1}; P < 0.001; $R^2 = 0.91$) corresponding to encountered target densities (targets ha^{-1}) derived from momentary operation flight segments ($n = 103$).

Results

In a 14-mo period, starting in February 2012, a total of 48 interventions were administered to the seven patches, covering 1138.1 net ha and dispatching 4,029 targets (Table 1). In total, 5,116.4 min of operation flight time (ca. 85.3 h) and 115,565 projectiles were utilized to accomplish these results. HAWI was the last patch on which the accelerated strategy was initiated and it was administered only four interventions, whereas WALU, NULU, and KANE were administered twice as many. Except for WAHI, all patch net areas were > 100 ha, with KANE being the largest at 214.9 ha, which also recorded the highest number of dispatched targets (i.e., 1,096 targets). Effective applications of previous interventions were visually confirmed even for the shortest time interval (i.e. 18 d). Only 88 survivors were retreated, indicating 98% efficacy with the HBT platform (data not shown).

Linear fits for search efficiency and herbicide use rate were highly significant when plotted against target densities

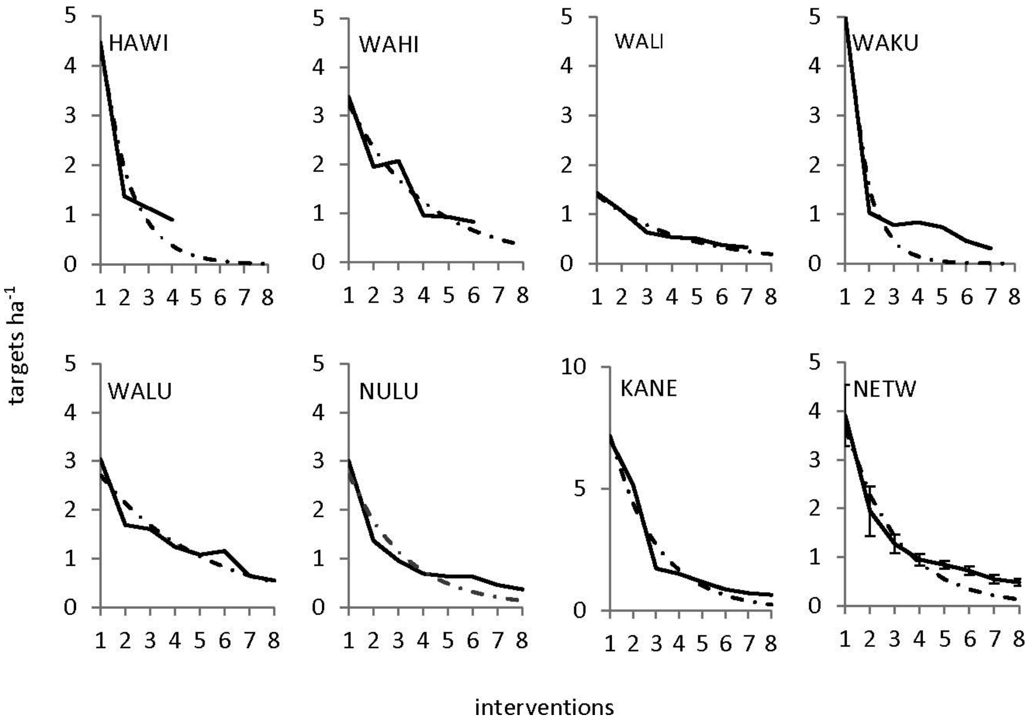

Figure 3. Adjusted cumulative target densities (targets ha^{-1}; solid black lines) of each patch and the entire network (± SE; $n = 7$ for one to four interventions; $n = 6$ for five or six interventions; $n = 5$ for seven interventions and $n = 3$ for eight interventions) with best-fit exponential decay functions (black dot-dash lines; $P < 0.05$; $R^2 > 0.88$). Notice KANE with a larger target density scale on the y-axis.

encountered ($P < 0.001$; $n = 103$) (Fig. 2). Search efficiency was measured at 0.90 min ha^{-1}, dispatch time at 0.53 min target^{-1}, and herbicide dose was estimated at 32 projectiles target^{-1}. All herbicide use rates were < 1% of the maximum allowable rate (i.e. 672.0 g ae ha^{-1}). The high coefficients of determination illustrated a strong dependence to target density, and validated platform consistency with previously published results (Leary et al. 2013), despite the use of multiple pilot/applicator teams across seven different sites.

All patches displayed reductions in cumulative target densities (adjusted by the number of interventions), following their respective intervention sequences. All reductions were significantly fit to exponential decay functions ($P < 0.05$; $R^2 > 0.88$; coefficient of variation for the root mean square residuals between observed and fitted values < 0.393) despite the variability of initial target densities (1.4 to 7.0 target ha^{-1}) and intervention sequences (four to eight interventions) (Figure 3; Table 2). Two general observations were made: (1) the sharpest reductions in target density occurred within the first three interventions and (2) targets were dispatched in every operation. Similar reductions were also observed for momentary target density sequences, but with greater peak deviations from the best-fit decay functions (data not shown). Cumulative target densities are comprehensive values of the entire patch, with reduction observed when target density of the last intervention was less than the net value of all previous interventions. These decay functions were influenced by a diminishing number of targets recorded in the latter interventions, with the curve asymptotically approaching zero, which will continue even beyond the point of eventually recording momentary undetectable levels.

Mean momentary search efficiency and herbicide use rate were reduced with each sequential intervention, corresponding to lower target densities encountered (Figure 4). Search efficiency is optimized when no targets are detected (Leary et al. 2013). As target density reduced to < 1 target ha^{-1} (i.e., operations 7 and 8), mean search efficiency was approximate to the calculated y-intercept coefficient (see Figure 2), suggesting some discrepancy between these independent derivations. Herbicide use rate showed a similar reduction trend with the final mean value equivalent to 0.06% of the maximum allowable use rate. Thus, the efficacy of previous interventions contributed to improved performance efficiencies for subsequent interventions on these accelerated schedules.

Mean net area increased with every sequential operation (Figure 5). This is due in part to improved search efficiencies making operational flight time available for expanding area coverage (see Figure 4). Net area expansion influenced the exponential decay of the cumulative target densities, with fewer targets being dispatched in these surrounding areas.

Table 2. Parameters of the exponential decay function estimated for each patch.

Patch	TD_i[a,b] (targets ha^{-1})	λ[c]	P[d]	R^2	$CV_{(RMSR)}$	TD_f (targets ha^{-1})
HAWI	4.5	0.808	0.041	0.92	0.222	0.9
WAHI	3.4	0.322	0.003	0.91	0.165	0.8
WAKU	5.0	1.170	0.001	0.89	0.392	0.3
WALI	1.4	0.286	< 0.001	0.96	0.113	0.3
WALU	3.0	0.239	< 0.001	0.90	0.176	0.5
NULU	3.0	0.434	0.003	0.90	0.259	0.4
KANE	7.0	0.488	< 0.001	0.95	0.215	0.6
NETW[e]	3.9 ± 0.2	0.476	< 0.001	0.94	0.229	0.5 ± 0.1

[a] Abbreviations: TD, target density; $CV_{(RMSR)}$, coefficient of variation for the root mean square residuals between observed and fitted values; TD_f, final adjusted cumulative target densities; HAWI, Hanawi; WAHI, Waihiumalu; WAKU, Waiakuna Pond; WALI, Wailua iki; WALU, Wailua nui, NULU, Nuuailua; KANE, Keanae Wall; NETW, network.

[b] Initial adjusted cumulative target densities.

[c] Decay function exponent.

[d] P value for nonlinear regression.

[e] The mean $TD_{i–f}$ ± SE of the entire patch network with the other calculations based the best-fit exponential decay curve.

Mean saturation for net area and target assignments increased with each sequential operation (Figure 6). The positive trends are an indication of the strategy's adaptive quality for revisiting known target locations. The rate of cumulative target saturation advanced nearly three times faster than net area saturation as determined by slope coefficients of best-fit linear models ($P < 0.001$, $R^2 > 0.98$; data not shown). Cumulative target saturation was influenced by progressive reassignment of former dispatched targets to their next level of saturation, along with continued detection of new targets in these same saturated fields. Net area saturation was influenced by the same adaptive paradigm of saturation reassignment, and was also counter influenced by net area expansions with new unsaturated fields where less targets were detected, as stated above (see Figure 4).

Distinct differences in saturation field assignments were observed between final net areas and historic target points were distinct for all patches (Figures 7 and 8). Net area assignments were overrepresented by the lowest saturation level, whereas historic target assignments were overrepresented by the highest saturation levels. For instance, the expanded area for the entire patch network was almost six times larger than the highest saturation levels of each patch combined. By comparison, historic target assignments in

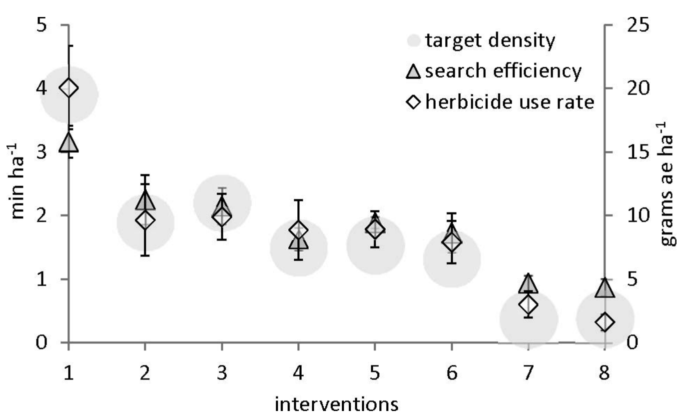

Figure 4. Mean search efficiencies (dark triangle) and herbicide use rates (light diamond) derived from momentary interventions (± SE; $n = 7$ for one to four interventions; $n = 6$ for five or six interventions; $n = 5$ for seven interventions and $n = 3$ for eight interventions) with mean momentary target density serving as a backdrop for each sequential operation. Backdrops appear oversized and transparent for the sole purpose of referencing target densities to the intervention performance values in focus and do not constitute any variance or deviation of the mean.

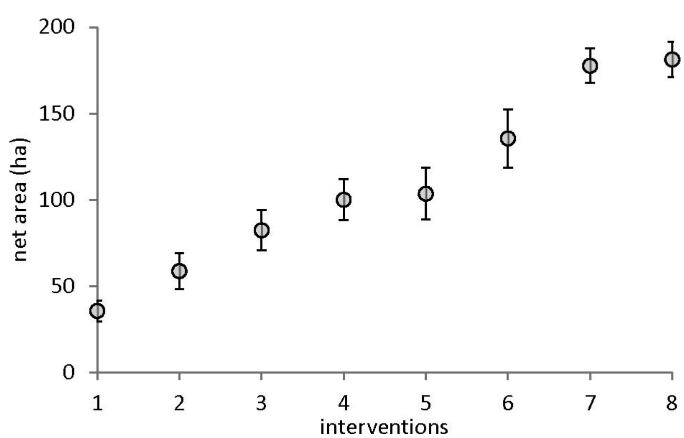

Figure 5. Mean cumulative net areas of sequential interventions (± SE; $n = 7$ for one to four interventions; $n = 6$ for five or six interventions; $n = 5$ for seven interventions and $n = 3$ for eight interventions).

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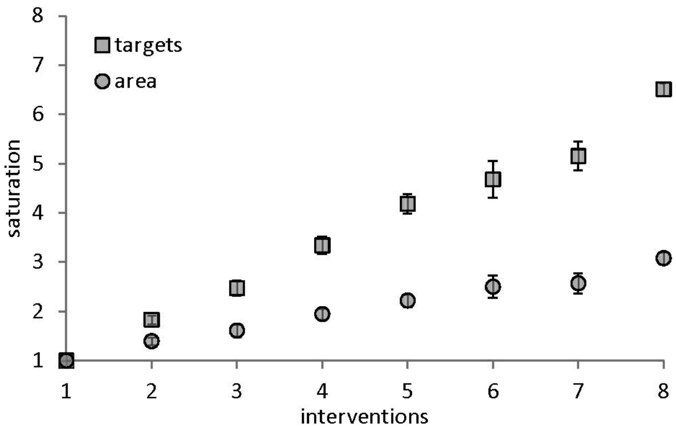

Figure 6. Weighted mean saturation for cumulative target (dark squares) and net area (light circles) field mosaic assignments (± SE; n = 7 for one to four interventions; n = 6 for five or six interventions; n = 5 for seven interventions and n = 3 for eight interventions).

the highest saturation levels were 20 times greater than total representation in the lowest saturation level. In practical terms, this highlights the basic elements of an adaptive surveillance process for delimiting satellite populations by continuing to revisit known target locations as long as new targets are being detected, while also progressively expanding surveillance coverage into new territories where finding targets is a more anomalous occasion.

As an example, Figure 9 shows the spatial dynamics of the sequential interventions imposed on the KANE patch. Similar to all of the other patches, this adaptive sequence depicts (1) target reduction and (2) net area expansion and increased complexity of the saturation field mosaic. Also, target detections are recorded throughout the net area, but with a majority of targets consistently recorded in the highest-saturation fields.

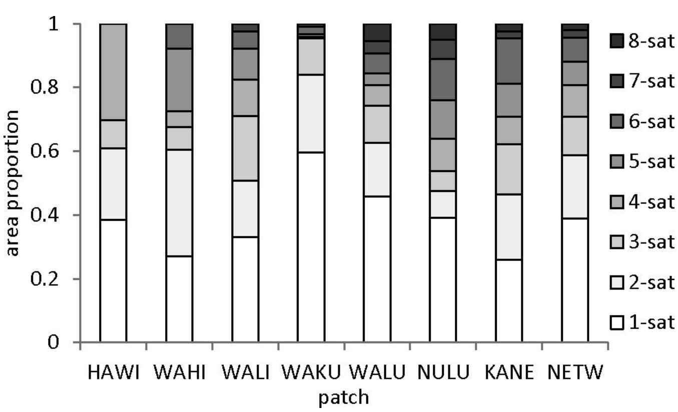

Figure 7. Proportion of the final cumulative net area assignments to the saturation field mosaic of each patch. NETW represents the proportion of the total assignments for all seven patches.

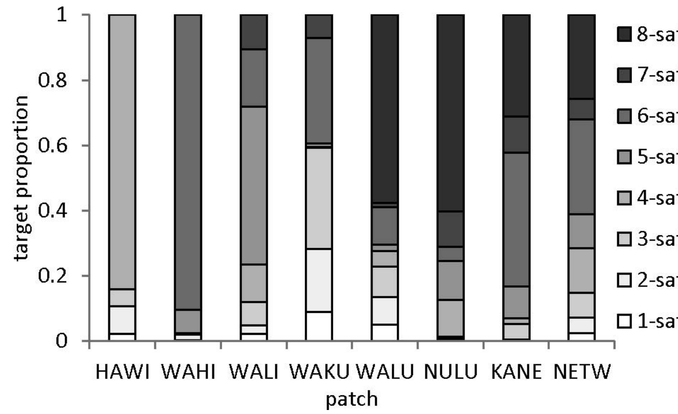

Figure 8. Proportion of historical target assignments to the final saturation field mosaic of each patch. NETW represents the proportion of the total assignments for all seven patches.

Mean detection efficacy of all interventions ranged from 0.56 to 0.76 (Figure 10). The phenomenon of imperfect detection is likely the artifact of two conditions: (1) false negative (type II) error with a failure to detect or (2) biological recruitment of target individuals achieving stature that exceeds the threshold of detectability. Mean detection efficacy of the entire patch network was 0.62 ± 0.3, which is conspicuously close to the probability of detection (P_d) of a random search operation (i.e. 0.63) where coverage (c) equals 1 (Koopman 1946, 1980). Detection efficacy, as measured in this study, is an empirical value between sequential interventions where coverage of the overlapped field is equal to 1. Cumulative target proportions (n = 41) plotted against their corresponding coverage values also fit closely with the exponential detection function for a random search operation (Figure 11).

Discussion

Miconia has been naturalizing in the EMW for over 40 yr, with the extant of the invasion approaching 20,000 ha, making containment the current management goal (Duncan and Leary 2013). Over the last two decades, fluctuations in funding have guided management decisions. Efforts to reduce high-density infestations have been prioritized in well-funded years, although more often the priority is to focus efforts on reducing low-density nascent foci (Taylor and Hastings 2004). The HBT platform is specifically designed for treating individual weed targets, and is ideal for administering interventions to low-density patch populations. Adoption of this technology has invigorated the miconia containment strategy with accelerated interventions measurably reducing the nascent patch network within a short period of time. In the 14-mo period reported here, operations increased by 33% over the average number of operations (per 14 mo) conducted for

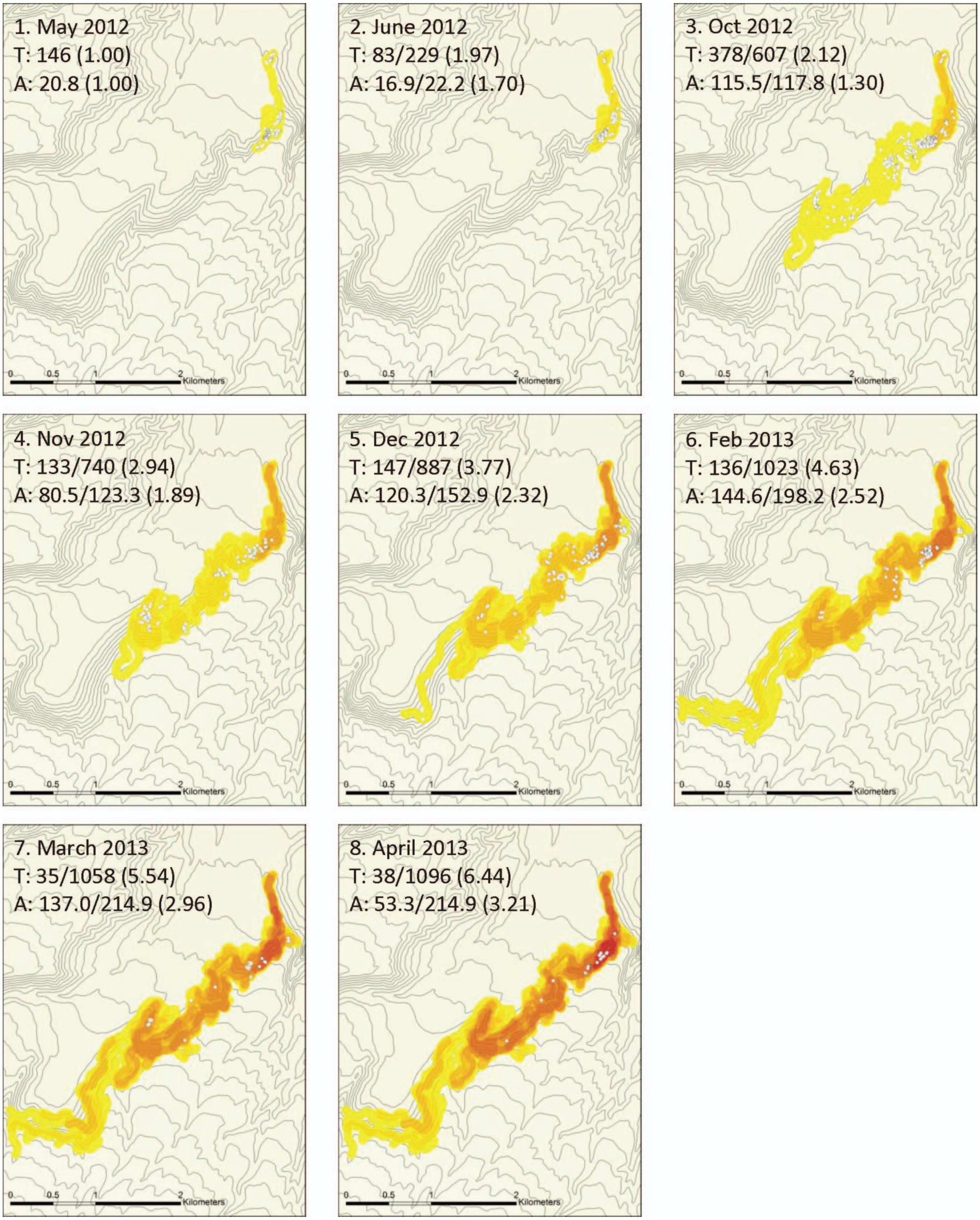

Figure 9. Intervention sequence (1 to 8) for KANE patch showing targets dispatched (white circles) and the net area field mosaic with increasing levels of saturation (yellow-to-red). Targets (T) and area (A) are presented (momentary/cumulative) along with weighted mean saturation levels shown in parentheses. 30-m contours displayed on the base map. (Color for this figure is available in the online version of this paper.)

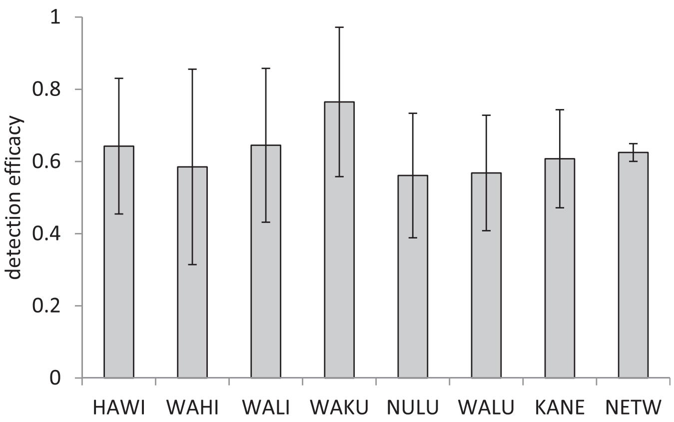

Figure 10. Mean detection efficacy (± SD; n = no. of interventions − 1; refer to Table 1) of each patch including the entire patch network (NETW; mean of all patches ± SE, n = 7).

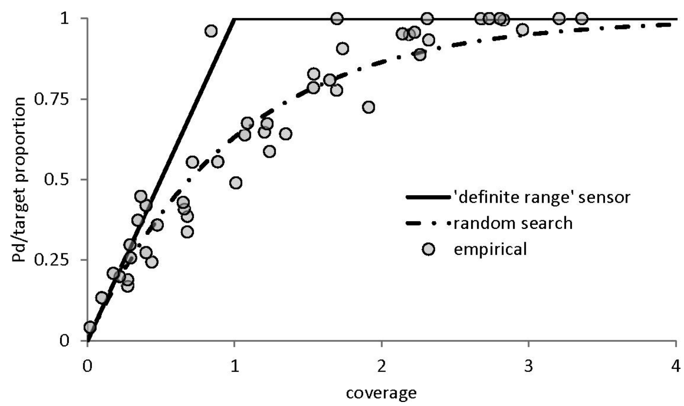

Figure 11. Sequential cumulative target proportions (n = 48) plotted against their respective weighted mean saturation values, along with P_d of a theoretical "definite range" sensor (solid black line; Equation 8) and a random search operation (black dot-dash; Equation 1) (Koopman 1946, 1980).

the entire patch network from 2005 to 2011. Consequently, the number of targets eliminated increased by 168% (Supplemental Table 1, http://dx.doi.org/10.1614/IPSM-D-13-00059.TS1). It is worth reiterating that these patch networks are in remote areas, accessible only to aerial operations. In these cases, the HBT platform improves target accessibility with capabilities in delivering an effective herbicide dose with horizontal trajectory and long range accuracy, relative to current aerial treatment options that must line up directly over the target (e.g., long line sprayer). We are also continuing to validate high treatment efficacy of HBT. In reference to the mortality factor, the HBT platform provides assurance that detectability is the limiting factor (Leary et al. 2013). This study shows how detectability can be improved by accelerating the intervention schedule. Eventually, future operations will begin recording momentary undetectable target levels with intermittent detection of recruitment events leading to exhaustion of a latent seed bank.

The entire spatial distribution of a weed invasion must be properly delimited to ensure effective containment (Panetta and Lawes 2005). The surveillance/intervention approach used in this study shares some of the qualities for a delimiting process described by Leung et al. (2010), in which they highlight the (1) approach, (2) decline, and (3) delimitation of a patch as an inside-out tactic for determining an effective containment boundary. All of the patches in this study are in the "decline" stage, where the least number of targets are assigned to the lowest-saturation fields (Figure 8), which also tend to be spatially located on the peripheries of the respective net area mosaics (see Figure 9). This strategy will not proceed to the "delimit" stage until all targets have been assigned to multi-saturated fields and net area has expanded beyond the most distal target assignments.

The detection efficacies recorded for these interventions fit the description of a random search operation (Cooper et al. 2003). A theoretically perfect search of a "definite range" sensor detects 100% of all targets with complete uniform coverage, making any further investment in search effort a waste of resources (Koopman 1946, 1980). However, any randomness in a search effort will reduce P_d (Cacho et al. 2006, 2007; Cooper et al. 2003; Frost 1999). In fact, for a random search operation, it would take three successive interventions with no detections recorded in order to assume a high probability of 0.98 that no targets are in the area. Only two of the seven patches have a final coverage > 3.0 in this study. However, targets continued to be recorded up to the last intervention, which strongly suggests the possibility of target recruitment taking place during the course of this study. This is further supported by a significant linear decline in detection efficacy from 18 to 182 d between interventions ($P < 0.039$, $R^2 = 0.127$; data not shown), suggesting a greater possibility of new recruitment with longer time intervals. With the combination of imperfect detection and active recruitment, future interventions that record undetectable levels should not serve as absolute confirmation of population extirpation. However, it does provide the opportunity to more accurately record intermittent detections as intrapatch recruitment (i.e., spatially assigned to high-saturation fields) or stochastic dispersal events (i.e., spatially assigned to low-saturation fields).

In a weed management scenario, randomness resulting in type II errors might include (1) physical stature of a plant target, (2) spatial arrangement of cohorts within the landscape, or (3) search capability (Cacho et al. 2004). Individual miconia targets can grow > 1 m in height in 1 yr, reaching a detectable threshold within that time period. Thus, what was undetectable in the previous interventions will eventually become detectable in subsequent interventions. These patch populations tend to be well hidden in topographic drainages and ravines as an understory to a complex forest canopy structure, creating impediments to clear sight lines. As a frugivore-dispersed propagule, miconia targets have been commonly found hiding behind the trunks of canopy trees that have presumably served as bird defecation perches. The helicopter operations performed in these extreme three-dimensional spaces are also likely incurring randomness during the search effort. The operation flight lines are not perfectly spaced parallel tracks on a two-dimensional plane (as in ocean search and rescue), but instead are anisotropic to the terrestrial landscape with intent by the pilot to overlap the fields of view for each track with altimeter adjustments and visual cues in the landscape. The exponential detection function (P_d) is solely dependent on the amount of search effort applied uniformly to an area, regardless of whether it is applied all at once or incrementally (Koopman, 1946, 1980). Admittedly, the adaptive approach to saturating coverage in known target locations is not a uniform process, yet net coverage derived from the weighted mean saturation values still show good correspondence to the P_d of a random search operation. Furthermore, if recruitment and growth to detectable target size is actively occurring, total search effort applied to a single intervention would likely be ineffective. The early development of herbicide symptoms on miconia was critical to distinguishing new (untreated) targets in subsequent interventions. This feature alone allowed for the acceleration of intervention deployments, leading to an increased probability of target detection in rapid succession.

In this study, there are three potential outcomes to an intervention:

1. expansion—initial area coverage naive to any target encounters, which could be the first operation or a subsequent, sequential operation expanding beyond known target locations;
2. saturation—sequential interventions covering known locations with measurable reductions in target detection; or
3. confirmation—the final sequence of interventions monitoring momentary undetectable target levels with the likelihood of intermittent detections characterized as recruitment events, particularly in known target locations.

As the net area surveyed for each patch continues to expand, major portions of the network will amalgamate into a contiguous and complex saturation field mosaic. Continuing to build on this intelligence will provide clear depictions of active target locations surrounded by confirmed protected areas. The fit of empirical target values to exponential decay and detection functions prove that this accelerated intervention strategy is outpacing the biological recruitment of this highly invasive species. As progress continues, new strategies will lead to a deceleration of interventions and a refinement of coverage, optimizing future operations within the framework of an efficient, long-term containment strategy.

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