Cooperative Extension Service
College of Tropical Agriculture and Human Resources
University of Hawaiʻi at Mānoa

Final Report for the Hawaii Invasive Species Council Project for FY17

Project Title
Advancing the Science of Miconia Management and Development of HBT capabilities in Unmanned Aerial Systems

Content Area:
Research

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Partners:
MISC, KISC and OISC (PCSU)

Executive Summary:

Miconia (*Miconia calvescens* DC) is a HISC-priority invasive plant species designated for local eradication and containment across the state. In 2017, history was made with the completion of the 5-year FIFRA 24c SLN registration for HBT-G4U200. Since 2012, under this registration, we have conducted over 600 hours of manned helicopter operations deploying HBT in collaboration with MISC, OISC and KISC; we have eliminated >25,000 incipient targets, protecting >20,000 ha of forested watersheds. The registration was renewed this year extending our program to 2022. This FY17 project completed two objectives contributing to developing novel technology and new science with implications for improving future management outcomes.

The first objective was to develop, validate and certify unmanned aerial systems with HBT capabilities (UAS-HBT) in remote target elimination. We have developed a first-generation prototype HBT gimbal with controlled flight tests proving concept with a vertical takeoff and landing (VTOL) octocopter able to lift the 6 kg payload and an independent operator able to remotely engage and accurately discharge projectiles to target. Accuracy and precision of the treatment system is <6 cm within a 10 m range. Limitations of this system continue to be lift capacity and endurance of the aircraft, necessary for conducting effective operations in the field. In collaboration with the UAS engineering team at UC Davis, we are conducting further tests of this gimbal mounted on a large class VTOL UAS with up to 60 minutes of sustained flight. We have further developed a basic training course for practitioners to prepare for CFR14 part 107 certification as remote pilots and finally we are also pursuing amendments of our current 333 exemption for the purpose of conducting agricultural aircraft operations using sUAS, including deployment of HBT for controlling invasive species. This would be a historical event for Hawaii and potential game-changer for conservation.

The second objective was to develop an adaptive spatial-temporal value system for cost effective management that results in maximum target impact reduction. Breakthroughs were made with new understandings on the biology of miconia in the East Maui Watershed (EMW) using (almost complete) historical data going back to 1992, including all HBT management data from 2012-2016. With GIS, we have interpreted a dispersal kernel where 99% of progeny are confined to within 587 m of the nearest maternal source, while the remaining 1% have been measured to disperse out to 1980 m, creating a total impact area of 1232 ha. Moreover, we have predicted the longevity of a seedbank based on progeny recruitment post-dated from the nearest maternal source with a model projecting 20-60 years of seed bank recruitment/extinction depending on the initial size and age. These spatial and temporal parameters are highly congruent to independent scientific interpretations of miconia in Australia and Tahiti, respectively. This offers great confidence to interpret the impact imposed by a single mature miconia. We further estimated the optimal management efforts (i.e., variable cost) for the most cost-effective outcome of exterminating a small incipient seed bank (x_i = 320; time to extinction = 26 years), obligating effort within the spatial and temporal parameters described above. In short, ~90% of the total effort would need to be invested in the first 10 years, with 71.1% of maximum effort optimal for eliminating all recruits before reaching maturity. Based on current pricing for helicopter HBT operations this is a total cost estimate <$57K, with >80% of this investment searching for the most distant 1% of the progeny. In a scenario that prioritizes the upper watershed of the EMW (Priority 1 above 1300' a.s.l.), we calculated the protection offered to this priority-designated area with HBT operations recorded from 2012-2017. In effect, the elimination of a single, incipient miconia target, preventing it from reaching maturity, establishes the benefit of avoiding the future cost to exterminate the progeny seed bank. Retroactively, management efforts within this priority upper watershed were only 27% of the total investment, but resulted in 86% of the total protection. The cost-effectiveness exceeded $5 of protection to every $1 invested. Management efforts outside of this priority area provided a less-economical fraction of protection, diminishing with distance. Miconia is not feasibly eradicable from the EMW without a more effective biocontrol program. Full containment of the invasion is also unachievable with the current resources invested. Protection of prioritized upper watershed is achievable when matched with the resources available. This process offers an approach to prioritize resource allocations with the best (most sustainable) return on that investment when the decision is to retreat from unmanageable situations.

This comprehensive miconia research and technology program is a collaborative effort with all of the ISCs, UHERO, UH Hilo and CTAHR and supported a PhD dissertation project at the University of Hawaii at Maona. This project was acknowledged in eight conference presentations (locally and nationally), a conference proceeding and peer-reviewed publication. This project was matched with ~$60K in extramural grant funding from two separate awards with another $497K pending from three more proposals in review.

Deliverables:

- An additional 2000 targets to be effectively treated- *4566 targets*
- Total protected area approaching 10,000 ha- *recalculated with a new, more accurate method that is 50% of previous calculations*
- Measurable reduction of herbicide dose rate (i.e., treating smaller targets)- *4.01* $grams_{ae}$ tgt^{-1} *is 10% below the 6-year average*
- Prototype HBT-UAS *complete*
- Certification of CTAHR HBT-UAS operations- *petition submitted to the FAA for review*
- Approved standard operating procedures for HBT-UAS- *in progress*
- A peer-reviewed article- *accepted for publication in IEEE Aerospace and Electronic Systems Magazine and proceedings was published In the 2017 ASABE Annual International Meeting of the American Society of Agricultural and Biological Engineers.*

Develop, validate and certify UAS with HBT capabilities

The purpose of this objective is to create new aerial management methods through the deployment of the HBT platform mounted on sUAS, offering an economical complement to manned helicopter operations by enhancing efficiency in ground operations to eliminate incipient miconia colonizing semi-remote terrain. The development of this technology is in collaboration with Dr. Ryan Perroy (UH Hilo) and the BIISC, as they progress in developing remote sensing surveillance technologies from fixed wing UAS. The concept is to integrate these actions in a choreographed process of surveillance, detection and engagement effectively neutralizing incipient miconia invasion. In order to make this future a reality, this project has designed a prototype HBT gimbal with experimental validation of the capabilities. We have further initiated the process of registration with the FAA for approving aerial agricultural operations with sUAS. We have commenced with training curriculum to develop competent end-users (i.e., pilots and applicators) of these technologies.

Design and Fabrication of 1st generation prototype HBT gimbal
In a collaboration with Tippmann Sports LLC. (Fort Wayne, IN), we have designed a remotely operated 2-axis gimbaled pneumatic HBT system for mounting to a vertical takeoff and landing (VTOL) UAS (Fig 1). The approximate weight of the total system is 6 kg with a majority of the frame architecture machined from aluminum. It has four mounting points for clamping to the undercarriage of the S1000+ octocopter (DJI Ltd., Shenzhen, China) The Gimbal has remote servo-operated pan/tilt functions with ~30^{o} range in both directions. The hopper is Cyclone® feed system with a 160-projectile capacity. The trigger, valve and bolt assembly are modified from the X7® Phenom marker system (Tippmann LLC., Ft. Wayne, IN). The entire system is operated with high-pressure, compressed air contained in a 26 in^3 aluminum tank at 3000 psi. A 720p camera is mounted on barrel for operator viewing. The pan/tilt and projectile actuation are remotely controlled with a radio-signal controller on a separate frequency from the aircraft pilot controller. The HBT gimbal operator interprets the environment with first-person view (FPV) googles or tablet interface for real-time display with centralized reticule for sighting the target to the calibrated ballistics.

A B

Figure 1. (A) CAD rendering of the HBT-UAS design. (B) Side view of gimbal-marker system.

Performance Validation
We determined the effect of the 6-kg payload on the flight characteristics of the octocopter in autonomous flight programmed to lift to an altitude of 10 m and circumvent a 10 x 15 m rectangle with a hover hold for 30 s at the midpoint to simulate target treatment (Fig 2A). The speed of the aircraft was

held constant at 0.4-0.5 m s^{-1}. Both flight paths had a horizontal RMSD less than 1.5 cm and three-dimensional RMSD less than 25 cm. Power consumption of the unencumbered aircraft displayed a linear draw consistent with the manufacturer specification (Fig. 2B). However, the added weight of the gimbal showed a substantial increase in power demand, particularly during the initial climb. This was displayed by a non-linear decay in battery capacity reducing operational flight time of one battery is < 4 min, with a recommended 20% battery capacity at landing.

A B C

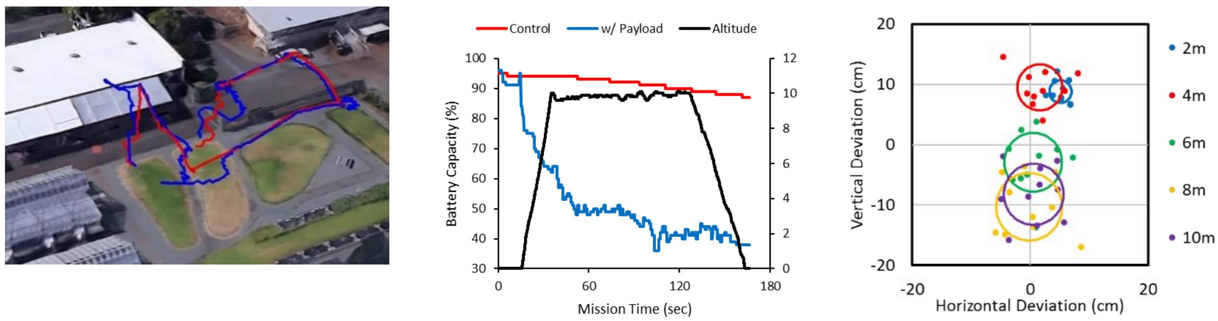


Figure 2. (A) the 10 x 10 m square flight paths of the unencumbered UAS (red) and HBT equipped UAS (blue). (B) Battery capacity for the missions depicted in (A). Note the large draw during the initial climb of the HBT equipped flight. (C) CEP relative to aiming point (0,0) ranging from 2-10 m.

We tested target precision and accuracy of projectiles discharged from the pneumatic delivery prototype in accordance with standards developed by the Army Research Laboratory, by calculating the circular error probable (CEP), which is the radius of the smallest circle containing 50% of the points of impact, and RMSD relative to the aiming point. Ten 0.68 caliber nylon projectiles were fired from ranges of 2, 4, 6, 8 and 10 m. The CEP gradually increased with range i.e., 5.6 cm max at the 10 m range.

A B

3. (A) Graduate Student Roberto Rodriguez installing the HBT gimbal platform to the S-1000® octocopter (DJI Co., Ltd, Shenzen, China) and (B) HBT gimbal installed on the Rmax® heavy-lift UAS (Yamaha Motor Corp. USA, Cypress, CA) in collaboration with Dr. Ken Giles (UC Davis).

Legal Certification

We have three team members with Part 107 certification. We are pursuing 333 exemption, which gives us the options otherwise prohibited in title 14 CFRs and are also pursuing collaboration with the Pan

Pacific UAS Test Range Complex (PPUTRC) under the Test Site National Certificate of Authorization (COA). The petition for exemption under section 333 has been sent to the FAA and is currently in review. PPUTRC is currently pending additional requested documentation for internal review prior to submission to FAA. We have also communicated with the Division Chief for Unmanned Aircraft Systems to ensure training and certification programs are OAS compliant.

Crew Member Training

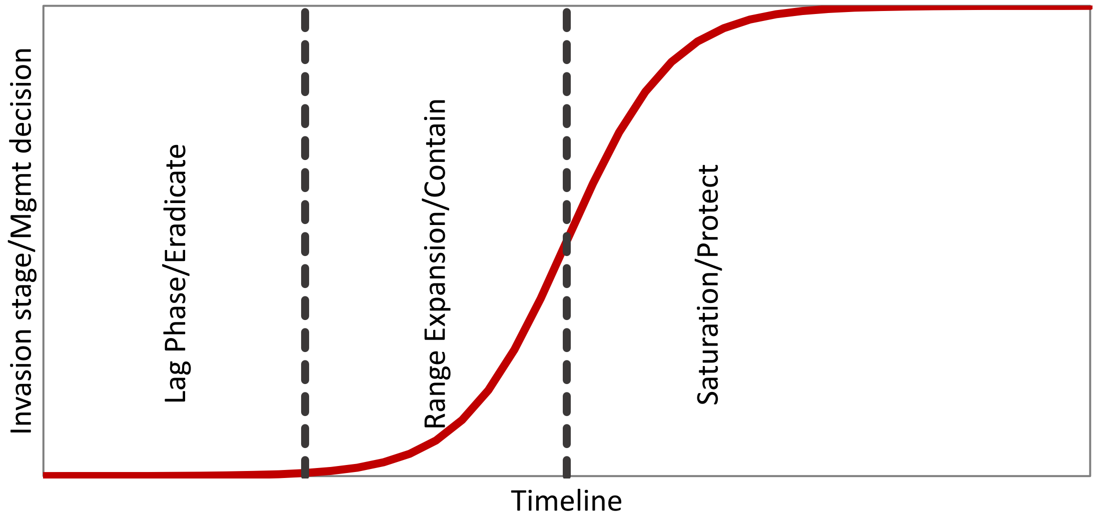
We conducted a semester course (BE491: Unmanned Aerial Systems Training) which comprehensively covered the theoretical knowledge in 14CFR part 107, including regulations, airspace, aircraft performance, weather, and operations, and practical knowledge, including basic and advanced maneuvers, emergency procedures and aerial data collection. There were six individuals enrolled, meeting twice a week over 18 weeks. The students were tested in the first week of the course with a truncated version of the FAA examination for Part 107 certification. All six of the students received a failing grade with a 30% class average (70% is passing). A similar truncated exam was administered at the end of the course with all, but one student passing with a class average over 80%. Thus, demonstrating the outcome of the course educating competent UAS pilots.

All three phases of this project will continue to progress in 2018 with matching support from the US Forest Service Special Technology Development Program.

Develop a spatial-temporal value model for cost effective management of miconia

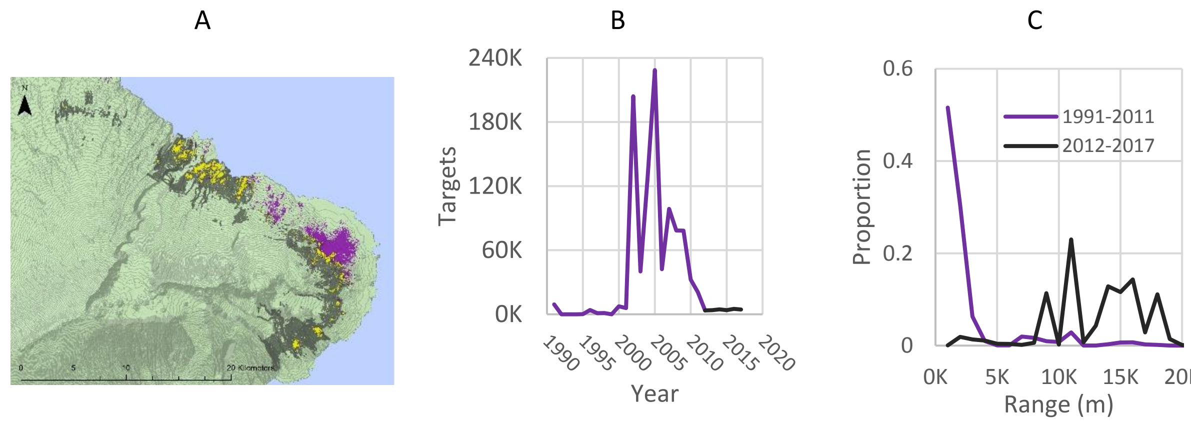
Shigeseda et al. (1994) describes three stages of an invasion: incipient establishment, range expansion, and habitat saturation. Miconia was introduced to Hana, Maui as a botanical specimen (i.e., founder population) in the early 1970s and not realized as a major invader of the East Maui Watershed (EMW) until two decades later, when active management commenced. The very first volunteer effort, in 1991, removed 9320 miconia plants, around the original point of introduction (Gagne et al. 1992). With plant maturity achieved in as little as four years, it stands to reason that several generations were reproduced within that 20-yr period leading up to the first harvest. Invasion lag phases have been associated with passive dispersal, low fecundity and inconspicuous occupation (Frappier et al. 2003, Cousens and Mortimer 1995). Le Roux et al. (2008) suggested miconia lag phases in the Pacific were likely due to absolute growth rates of small inconspicuous founder populations; only to become noticed after 20 years of unchecked colonization. It also seems plausible that the general community was naïve to miconia being invasive, considering that it was originally promoted as a desirable "attractive" species, stochastically introduced to several suitable garden locations without realizing the future outcomes. By 1995, deliberately introduced miconia were found >26 km from the original point of introduction with range expansion driven by stratified dispersal with long-distance (i.e., human-mediated) translocation and local diffusion (e.g., fecundity, frugivory and recruitment) (Shigesada et al. 1995, Hengeveld 1989). Since that time, over the next quarter century, >1M miconia plants have been removed from the EMW. Despite these efforts, the invasion is saturating >2000 ha surrounding the point of origin, along with multiple incipient invasions spread to over 30% of the EMW (Fig. 5).

Successful (i.e., successional) invasion of a non-native species in novel landscapes, at least, requires suitable environmental conditions (e.g., temperature, precipitation, edaphic, etc..) with possible advantages gained from reduced herbivory, disease and competition, typically experienced in its native range (i.e., Enemy Release Hypothesis; Keane and Crawley 2002). Thus, invasion success (unchecked) may be measured, in part, by its basic life-history traits in growth, reproduction and dispersal. The hypothetical invasion curve (adopted from Chippendale 1991 & Hobbs and Humphries 1995) intuitively uses the logistic growth function as a successional timeline for adopting strategies presuming management decisions are budgeted as counter-measures on pace with recruitment, undermining fecundity, ultimately, mitigating dispersal (Cacho et al. 2007, Hauser et al. 2009, Hester et al. 2010, Mehta et al. 2007).



4. The hypothetical invasion curve depicted by a logistic growth function to determine effective management counter-measures

Since that volunteer effort in 1991, sporadic grass roots efforts continued until 2001, when the National Park Service accelerated a comprehensive eradication strategy with objectives to reduce the core infestation and intercept all incipient populations (Fig. 5). The program peaked in 2004 and was able to maintain strong efforts until 2011, resulting in >983K plants eliminated (Fig. 5B). In 2012, Herbicide Ballistic Technology (HBT) was introduced as a treatment platform with the capability of eliminating incipient miconia more efficiently with long range precision and accuracy (Leary et al. 2014). Adoption of HBT coincided with budget reductions and opportunistically transitioned the strategy from comprehensive eradication to containment (Fig. 5C). To date, >500 hours of HBT operations have been recorded with >25K incipient miconia eliminated, with the resulting trade-off being the core infestation (~2000 ha) virtually unmanaged since 2011. As a result, mature, fruiting trees are now starting to coalesce into monotypic stands “saturating” the landscape surrounding the point of introduction. Under current management levels, scattered incipient populations will begin to coalesce and saturate suitable habitat below 400 m a.s.l. and expand into the higher priority, upper watershed above 400 m a.s.l.



5. (A) Strategic transition from comprehensive eradication (1991-2011; purple) to invasion front containment via HBT (2012-2017; yellow) Note helicopter surveillance for all HBT operations (dark grey). (B) The number of eliminated miconia recorded each year. (C) The frequency distribution of range distances from the founder population centroid of miconia eliminated from 1991-2011 (n=981,630) and 2012-2017 (n=25,510)

Miconia is not economically eradicable from the EMW and should transition to a long-term management program protecting only the most critical asset areas. The objective of this FY17 project was to develop a spatio-temporal value model for cost effective management of miconia. Herein, we explore some of the critical life-history traits of miconia utilizing empirical data from an almost complete recording of miconia management in the EMW from 1991-present and complemented by strong scientific literature on the biology and management of miconia in Tahiti and Australia. Estimated spatio-temporal parameters will be further derived into management counter-measures matching dispersal range and recruitment rate. Finally, we will calculate cost effectiveness of HBT operations from 2012-2017 in a scenario retroactively valuating the EMW with a demarcation at 400 m a.s.l. separating the upper and lower watershed.

Methods

Miconia calvescens

Miconia (*Miconia calvescens* DC) is a mid-story canopy species native to South and Central America. It is also a highly invasive, ecosystem modifier to many tropical regions of the Pacific Rim (Mederios et al. 1997, Meyer and Florence 1996, Nanko et al. 2015). Miconia is shade tolerant and able to displace diverse endemic vegetation communities; transforming landscapes into dense mono-specific canopies impoverishing the understory vegetation, exposing the soil surface below canopy (Meyer and Florence 1996). Miconia have large elliptical leaves (i.e., up to 750 cm^2) creating coalesced water drops with high-impact throughfall that could accelerate localized soil erosion (Nanko et al. 2013 and 2015, Giambelluca et al. 2009). Miconia have been observed with a disproportionately large canopy supported by a shallow root system unable to support its aboveground weight. This, along with a propensity to colonize steep slopes, has triggered catastrophic sloughing, observed in Tahiti (Gagne et al. 1992).

Miconia is a highly fecund, autogamous species, with propagules typically dispersed by avian frugivores (Meyer et al 1998, Murphy et al 2008, Spotswood et al. 2013). Trees reach maturity in 4-5 years (or longer; *see Murphy et al 2008*) and in that first year of reproduction usually only produce two panicles (Meyer 1998a, Murphy et al 2008). Self-fertilization (i.e., autogamy) is possible in isolation from cohorts (Meyer 1998a) and considered a facultative trait for long-distance translocation (Baker 1965). The small (ca. 6–7 mm) spherical fleshy fruits contain very small seeds (ca. 0.65 mm), which are edible to a wide range of frugivores present in tropical forests (Meyer 1998a, Murphy et al 2008). In Tahiti, Meyer (1998a) reports an average of 210 fruits/infructescence and 195 seeds/fruit. Thus, a single miconia has the potential to produce over 80K seed propagules at first maturation and produce millions of seed in a single fruiting cycle in more advanced maturity. In a long term *in situ* seed bank study, survival was observed after 16 years, but with the mean number of viable seeds reducing from >4,300 seeds/m² in 1992 (Meyer and Malet 1997) to 190 seeds/m² in 2008 (Meyer 2010). A modest fit of an exponential decay function projected seed bank extinction ~24 yrs. This persistence in the natural environment has been attributed to physiological dormancy and asynchronous germination (Meyer et al., 2011; Silveira, et al. 2013). A miconia dispersal kernel was modeled in Australia based on recorded gut retentions and displacement distances of native frugivores consuming native tree fruits with similar size characteristics (Dennis and Westcott 2007, Hardesty et al. 2011, Murphy et al. 2008, Fletcher and Westcott 2013). Mean and maximum dispersal distances have been reported at >200 m and >1700 m, respectively (Murphy et al. 2008, Fletcher and Westcott 2013).

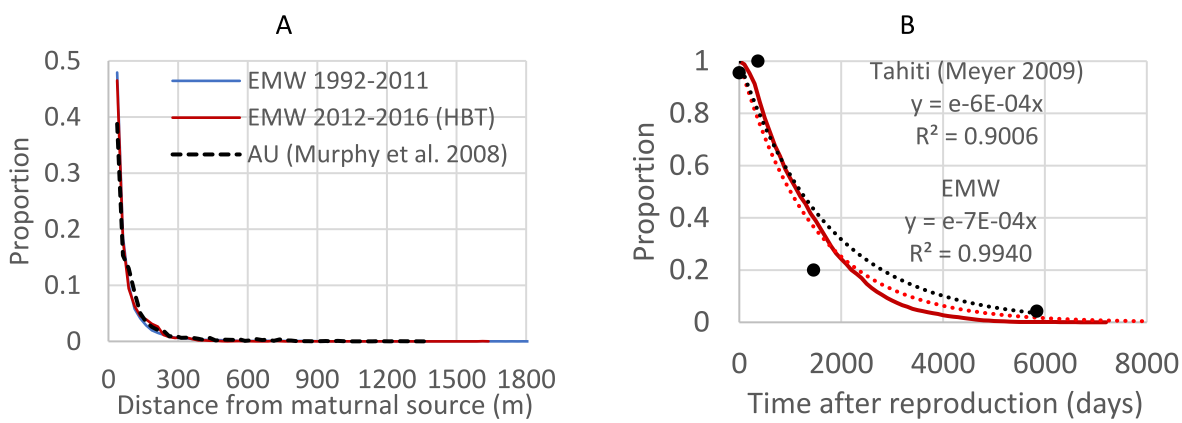
East Maui Watershed

The East Maui Watershed (EMW) is ~50,000-ha forested landscape on the windward slope of Haleakala Volcano extending from coastline to crater, with an elevation gradient of 0-3055 m a.s.l. It provides critical habitat to over one hundred threatened and endangered species and annually recharges over 300 billion gallons of fresh groundwater (Shade 1999), which are vital ecosystem services to life and agriculture on Maui. This area is climatically diverse, with wide mean annual gradients for peak temperature (9-26^{o}C), precipitation (652-10,271 mm). Much of the landscape is inaccessible to ground operations with 72 separate drainage basins all having slopes >30^{o}, relegating much of the strategy to aerial operations.

Management History and Demographics

We have an almost complete 26-year history of miconia management in the EMW with timestamped, georeferenced locations of treated targets eliminated from 1991-2011 (n=98,524 representing 981,630 miconia individuals) and aerial surveillance operations deploying HBT from 2012-2017 (n=25,510). Management efforts over time come from a wide range of partner agencies and projects including: The Nature Conservancy Maui Program, Haleakala National Park, Pacific Island Exotic Plant Management Team and the Maui Invasive Species Committee. Demographically the most important attribute is the designation of maturity, which has been consistently determined by the presence of flower or fruit panicles. Moreover, the number of mature miconia from 1991-2011 (n=11,749) and 2012-2017 (n=282) has consistently represented ~1.2% of total recorded population. Just over 90% of all mature miconia from 1991-2011, were recorded within 2000 m of the founder population. This location has been effectively unmanaged since then with the population saturating into mono-specific canopies with 1000s of mature plants continually observed (personal observation).

Life History Traits
Fecundity of a first mature miconia is estimated to reproduce ~80K seed as described above (Meyer 1998). Meyer (1998) determined three flowering periods per year, but a single plant is typically only observed to flower once annually (Hardesty et al 2008, Hester et al. 2010). Ellison et al. (1993) measured up to 0.4% progeny survivorship after one year for other species of Melastomataceae. In this study, we assume with this “penalty” that a first mature miconia might then only produce 320 surviving progeny, succeeding into maturity. Miconia becomes sympodial after maturity (Meyer and Malet 1997), which again for this study, we assume an annual doubling phenology, e.g., a single miconia is estimated to produce 1.28M seed, but only 5120 progeny, in the 5th year of maturity. A dispersal kernel was estimated from the distance between each miconia point temporally subsequent to the nearest mature point using Near Analysis tool in ArcGIS (v. 10.2; ESRI Company, Redmond, CA) of point locations from 1991-2016 (n=118,960) and displayed as a probability density function (PDF) binned in 1m intervals out to the maximum distance and as decimal or centesimal fractions for spatial displays and model interpretations (Fig. 6A). Recruitment (i.e. seedbank) longevity was similarly measured, but instead with the preceding time intervals of progeny assigned to the nearest mature miconia and again displayed as a PDF with 100-day intervals out to the longest time interval (Fig. 6B).



6. Dispersal kernels (A) displayed from histograms of progeny distances from the nearest mature predecessor for all recorded miconia targets eliminated from 1992-2011 (blue line; n= 97,888) and from HBT operations from 2012-2016 (red dash; n=21,072). Seed bank depletion (B) displayed as a histogram of the time interval of targets treated posterior to the assigned mature (red line; n=118,960). Seed bank is predicted to be 99% depleted in 18.3 years (i.e., ~6700 days). These spatial and temporal functions are shown to be highly congruent with presentations in Australia (black dash; Murphy et al. 2008) and Tahiti (black dots; Meyer 2009), respectively.

Individual-Based Models
Individual based models were developed to track the management efforts to extinguish the colonizing progeny of a single incipient miconia reaching first maturity (n=320). Spatially, point density raster annuli were created from miconia point locations by decimally binned radial (i.e.,

near) distances calculated from the dispersal PDF, described above (Fig. 6A; see Fig. S1). Hence, each annular ring contained 3.2 progeny (e.g., 10% of total). Temporally, Miconia was assumed to reach maturity in 4 years, producing 320 progeny in the first year of maturity and annually doubled fecundity after that. Recruitment longevity was derived from a first order decay fitting the PDF described above (see Fig. 6B). For this model, effort was pre-determined as a harvest rate (i.e., search and destroy) proportional to annual recruitment. Recruits surviving up to 4 years were assumed reproductive maturity, compounding the depleting seed bank, while annual cohort populations harvested to <0.5 individuals within 4 years were considered extinct.

Detection of a miconia target is based on a random search effort described previously by Cacho et al. (2007) and later by Leary et al. (2014):

$$p_d = 1 - e^{-c}$$

where the probability of detection (p_d) is an imperfect process asymptotically approaching one with increasing coverage (*c*) (see Fig. S2). Search is performed from a helicopter with a 3-person crew at speeds <8 m s^{-1} with flight lines parallel to contour and normal to terrain aspect with a mean sight range of 16 m (Rodriguez et al. 2015) creating an oblique view for the observers with a central macular field of view of ~100 m^2 (see Fig. S3), which is approximate to the pixel dimensions of most GIS rasters. In this model, we estimate coverage to equal a search encounter of 1 s $pixel^{-1}$. If the p_d of a target increases with coverage, the same should apply to the probability of not detecting a target. In other words, confirming that an area encountered with random search operations would have a comparable probability confirming no targets occupying the pixel (p_{nd}; see Fig. S2). Thus, spatially complete search coverage is the combination of encounters finding all of the targets, subsequently proving no targets thereafter in those occupied areas (e.g., pixels) and further proving no targets in all of the unoccupied pixels as well.

$$\mathrm{c}_{pixel} = -((\ln p_d \times \rho_{target}) + \ln p_{nd})$$

where coverage of a pixel area (c_{pixel}) is dependent on target density (ρ_{target}) and spatially, all areas are obligated to some level of coverage to achieve a probability of no targets detected (p_{nd}). Temporally, coverage is optimally proportional to known recruitment rates over time (i.e. exponential decay). Methods to treat miconia are highly reliable and effective (personal observation), thus, making miconia elimination practically dependent on detection achieved with search effort (i.e., coverage). If an incipient miconia were to succeed to maturity and establish a seed bank, the strategic goal would be to extinguish the seed bank by eliminating all progeny recruits before they reach maturity. The life history traits described above will serve as model inputs to estimate total optimal management effort by determining where, how much and when coverage is to be administered.

Variable Costs of Operations

As described above the basic tactics are to search, detect and eliminate miconia from a helicopter platform. Previous studies have determined that operations are target density dependent with strong linear fits for search effort (i.e., flight time) and herbicide use rate (Leary et al. 2014).

Utility helicopter services on Maui have been contracted at \$1200 hr^{-1}, reduced to \$0.33 s^{-1} $pixel^{-1}$. The mean dose per target is 23.3 projectiles with a projectile price point of \$0.31 for a treatment cost of \$7.20. We've estimated flight time to engage target at 39.6 s for an added cost of \$13.07, bringing the total cost to eliminate one miconia plant at \$20.27 USD.

Prioritizing and Protecting EMW Assets

To consider a strategic transition from containment to asset protection, we established the upper catchment basins above 400 m a.s.l. as a high priority asset. It was confined to 1220 m a.s.l., which is assumed to be the approximate threshold for miconia habitat suitability (Pouteau et al. 2011). This total asset area was estimated to be 14,460 ha. Secondary (3390 ha) and tertiary (6667 ha) priority containment buffers were extended below the 400 m a.s.l. contour, based on range of the dispersal kernel, where proportionally up to 50% and <1% of the dispersal events could deposit propagules into the upper asset area, respectively. All HBT operations data, i.e., operational flight time and treated miconia targets from 2012-2017 were retroactively superimposed to these buffer areas and assigned the treatment cost, described above. We assumed impact of a novel, invaded area to be created by a single, incipient miconia succeeding to first maturity, with the life history traits spatially and temporally applied. The impact area was calculated as a composite of annular density rasters radially determined by decimal proportions of the dispersal PDF. For instance, a first-mature miconia producing 320 progeny will disperse 32 of those in each of the 10 annular rings of varying area. When a miconia plant is eliminated prior to maturity it is assumed that costs are avoided to subsequently eliminate all recruits towards extinguishing the seed bank. This calculated "debt" investment is measured against the estimated

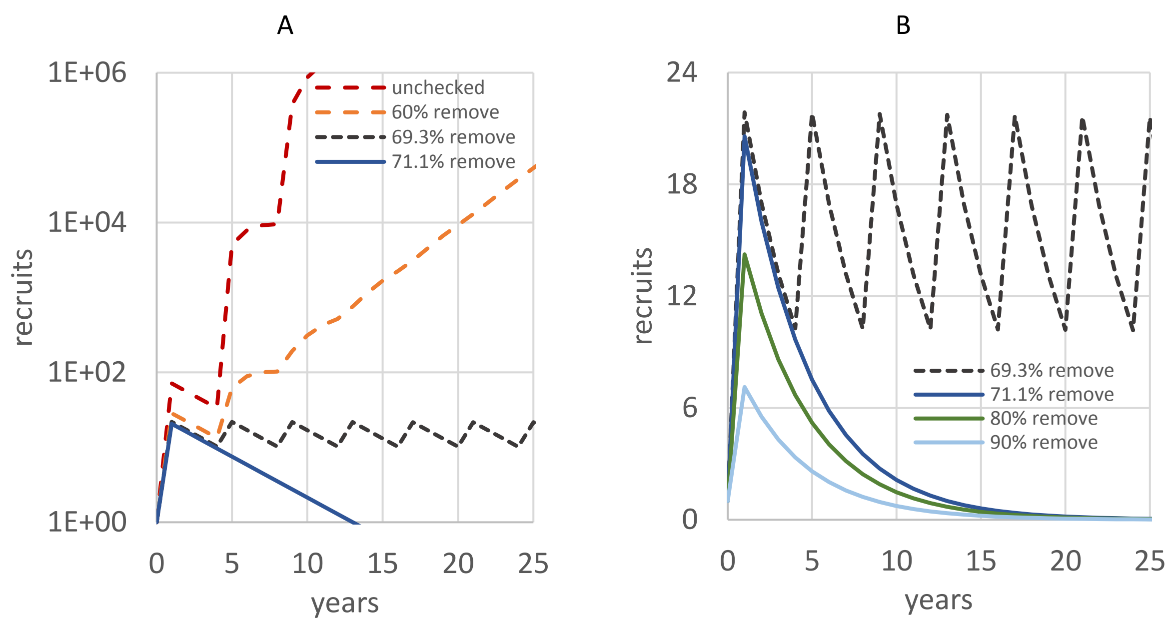
Results and Discussion

Spatial ecology in seed propagule dispersal is critical to understanding community dynamics succession and especially non-native invasions (Clark et al. 1994, Murphy et al. 2008, Nathan and Muller-Landau 2000, Shigesada et al. 1995). Separate dispersal kernels were created from data miconia collected 1991-2011 (1st epoch) and 2012-2016 (2^{nd} epoch) (Fig. 6A). While temporally distinct, there was substantial overlap of points from these known incipient populations. In fact, many of the 2^{nd} epoch points were assigned to 1^{st} epoch mature. These two distributions expectedly show a strong congruent fit (RMSE = 0.003). Both appear as leptokurtic distributions characterized by sharp concave peaks with fat-tail extremes (Nathan and Muller-Landau 2000, Clark et al. 1994). The peaks, where half of the recruitment was confined within 41 m, denote unconsumed fruit drop with short distance, autochorous vectors (e.g. slope gravity) or allochorous frugivory with short gut-retention times or home range. Ninety percent of the recruitment observed within the EMW was within 170 m of the assigned maternal, while 99% of all dispersal events were within 587 m. The remaining 1% of recruitment events are a display of stochastic, long distance dispersal of miconia (Hardesty et al 2011). The maximum distances measured for the 1^{st} and 2^{nd} epochs were 1636 and 1980 m, respectively. Applying these range distances, this creates isotropic impact areas between 840 to 1231 ha, respectively. Murphy et al. (2008) developed a dispersal kernel for miconia in Australia estimated from native fruits similar to miconia with methods developed by Dennis and Westcott (2007). Their model predicted a maximum range of 1750 m, but over-estimated the size and spatial extent of the actual infestation in North Queensland, AU. Interestingly, the EMW dispersal kernels are strong fits with this AU kernel (RMSE= 0.013-0.015), where the largest residuals are at the peak (Fig. 6A). This establishes a high confidence of our spatial interpretation of miconia dispersal in suitable habitat across the EMW. While most progeny are found in the vicinity of the maternal source, it's the "fat-tail" dispersal that contributes to rapid, stratified colonization into novel areas, an unknown risk, obligating significant amount of resources in surveillance with detection (Murphy et al. 2008).

Seed bank longevity was translated from the time intervals of recruitment events posterior to the detection of the assigned mature miconia and displayed as a PDF over time. This was fit to a first-order negative exponential function ($R^2 = 0.994$) as a simple decay measure showing 50% of the recruitment to occur in 2.7 yrs after reproduction and ~18 yrs to exhaust 99% of the seed bank. Meyer and Malet (1997) initiated an *in situ* soil seed bank viability study with all mature plants removed with four recruitment measures recorded over a 16-yr period. Meyer (2010) first reported continued viability of the seed bank but with an estimated 96% reduction. Physiological seed dormancy has been reported in *Miconia* spp. and suggested as a mechanism for preserving seed (i.e., preventing germination) in unsuitable microsite conditions (Ellison et al. 1993, Meyer 1994, Silveira et al. 2013). The fit of these decay functions (RMSE = 0.033) from apparently disparate sources is intriguing and again offers some anecdotal confidence in how to establish a long-term strategy with management interventions coinciding with recruitment activities. Life history traits vary widely among species (Nathan and Muller-Landau 2000). Founder populations of miconia in the Pacific and Australia are the result of minor, but deliberate, introductions displaying low genetic diversity and a lack of geographical structure, suggesting these naturalized invasions being highly related and probably of the same source (Hardesty et al. 2012 and Le Roux et al. 2008). Apparently, this has not been an impediment to invasion success in these different locations, but, moreover, may help explain the highly congruent life history traits described in Hawaii with Tahiti and Australia.

A single miconia propagule deposited in a novel location, isolated from cohorts, can rapidly create large scale and long-term impact on a landscape. Eliminating these incipient targets before reaching maturity offers the most cost-effective form of landscape-level protection. An incipient miconia undiscovered and growing unchecked will eventually achieve reproductive maturity, where in our example one target becomes 320 first-generation progeny spread across 1231 ha and germinating asynchronously over two decades. With the assumption of annual panicle doubling, a single miconia would produce over a million progeny within 12 years saturating the impact area to an unmanageable infestation (Fig. 7A). Harvest rates at less-than-optimal will result in undiscovered progeny also reaching maturity, coalescing with the original seed bank, expanding the impact area and extending longevity (Moody and Mack 1988, Shigesada et al. 1995).

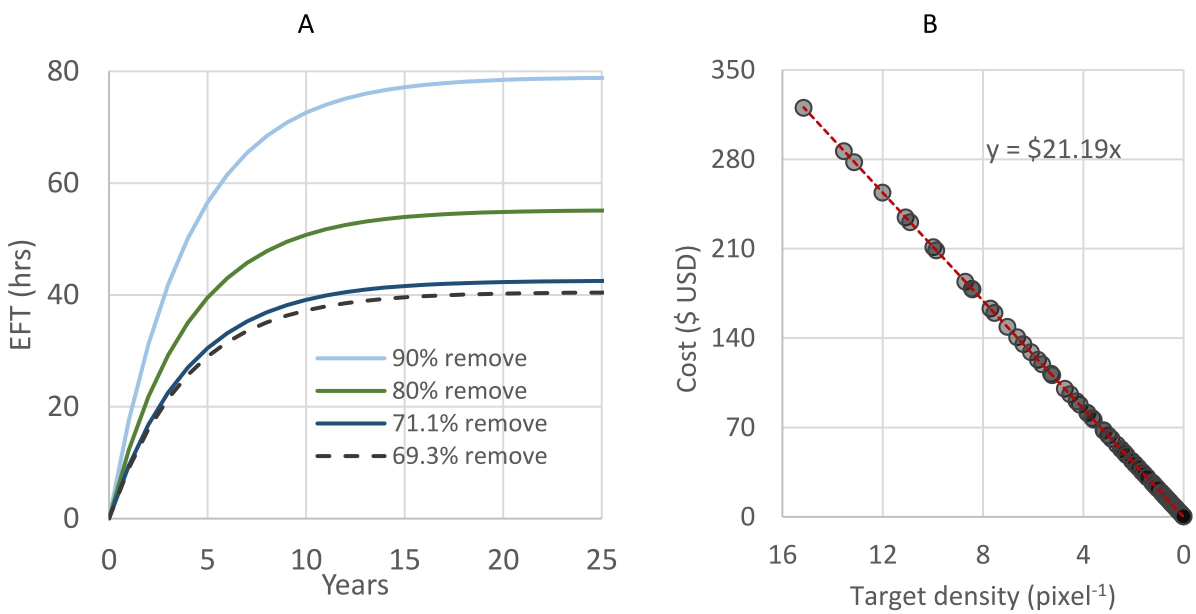
Optimal harvest rates need to match the pace of recruitment. In the model example we show an annual harvest rate of 71.1% to be optimal for preventing the first cohort from reaching maturity at year four and the subsequent cohorts thereafter (Fig. A and B). The decay fit above (see Fig. 6B) suggests that exhaustion of seed bank, i.e., the last recruit, occurs at 20.7 years. At optimal harvest rate, the last recruit is eliminatd at 24.7 years, just prior to reaching maturity. The partial control exhibited at 60% harvest rate, while slowing recruitment levels, will ultimately continue to colonize suitable habitat, albeit at a reduced rate (Cacho 2008). The annual harvest rate at 69.3% is an example of true containment, where management interventions perfectly match the biology of the of the incipient miconia with a perpetual volley. Seed bank is inconspicuous to standard search efforts. We've described above how harvest rates are largely dictated by detection (e.g., highly effective treatment method). Hence, harvest rates being strictly dependent on detectable recruits, *ergo* seed bank exhaustion determined by an independent life history trait (see Fig. 6B) and the obligation to match search efforts ensuring detection after recruits become realized. As examples, harvest rates at 80-90% achieve the same result (i.e., extinction after 20.7 years) by detecting targets earlier with more effort (Fig. 7B).



7. Recruitment and fecundity of a single incipient miconia (A; B closeup of A) with initial maturity producing viable propagule bank (x_i = 320), at time 0 years, projected to germinate (exhaust) over the next ~24.7 y (see Fig. 6B). Recruitment unchecked (red dash) results in exponential fecundity, whereas, management coinciding with recruitment, will lead to extinction, with 71.1% removed annually (dark blue line) being optimal. Note higher efforts (e.g., 80-90% removed; green and light blue lines, respectively) cannot force recruitment and shorten the timeline to extinction (i.e., wasted effort) while lower efforts (e.g., 69.3% removed; black dash) leads to undetected/untreated recruits reaching maturity, replacing the seed bank with no extinction.

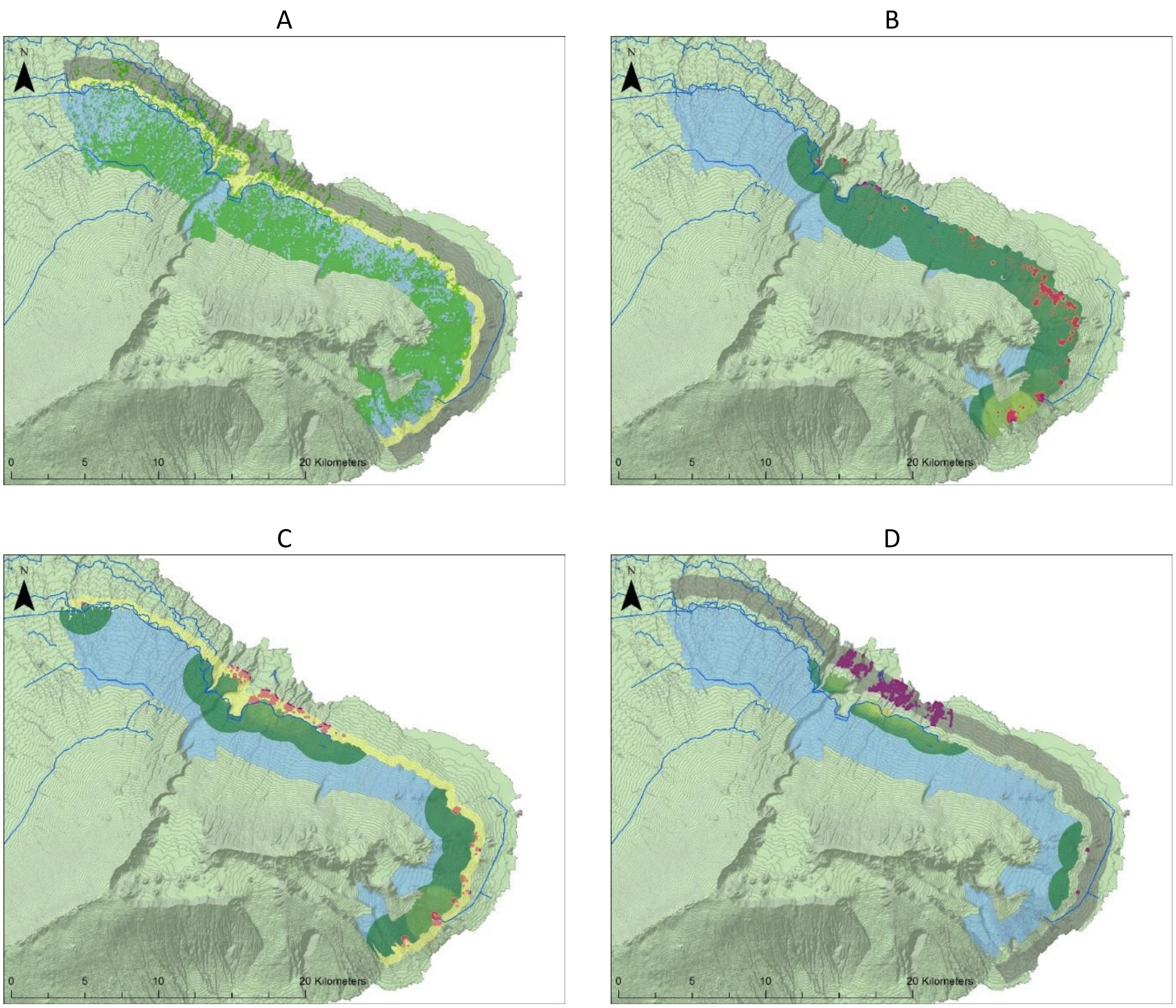
Total effort to extinguish an incipient seed bank over 25 years has been optimally established (i.e., 71.1% harvest rate) at just over 42 hours of search effort over the 1231-ha impact area, noting 90% of the total effort expended with in the first 10 years (Fig. 8A). As a point of reference, 80% and 90% harvest rates increased those efforts by 31% and 88% of optimal, respectively, for practically the same result. However, it should be further noted in this model that efforts at or below 40 hours would result in failed eradication. Besides actually knowing when a seed bank is extinct, the amount of long-term effort to eradicate remains a conundrum for the practitioner.

Cacho et al. (2007) describes the mortality factor as a product of target detectability and treatment efficacy. Hester et al. (2010) further determined that treatment cost was negligible to the search cost in Australia's miconia management strategies. The costs of controlling a weed invasion are influenced by a number of factors including ease of plant detection, accessibility of the area and methods used (Cacho 2008, Hester et al. 2010, Leary et al. 2014). The HBT treatment platform greatly enhanced helicopter surveillance of inaccessible areas in the EMW. The variable costs were also determined to be target density dependent. In this case, the costs including: (i) search effort to detect, (ii) flight time to engage (e.g., hold hover) and (iii) treatment dose. The dispersal kernel creates a spatial raster assigning progeny densities to pixels (Fig. S2). The variable cost of the optimal harvest rate for each of these pixels is multiplied by a total target cost of $21.19 (Fig. 8B). Where the gradient follows the dispersal kernel, the cost range per pixel is $320.58 to $0.41. The total cost to eliminate 320 progeny from 1231 ha over a 24.7 year period is calculated to be just over $57.1K USD, where 81% of the total cost would be invested searching for the 1% of the long-distance progeny. Finally, successful strategies with 80% and 90% harvest rates have appreciably higher costs at $72.1K USD and $100.3K USD (data not shown). On the other hand, investments not exceeding $54.6K USD would fail to eradicate.



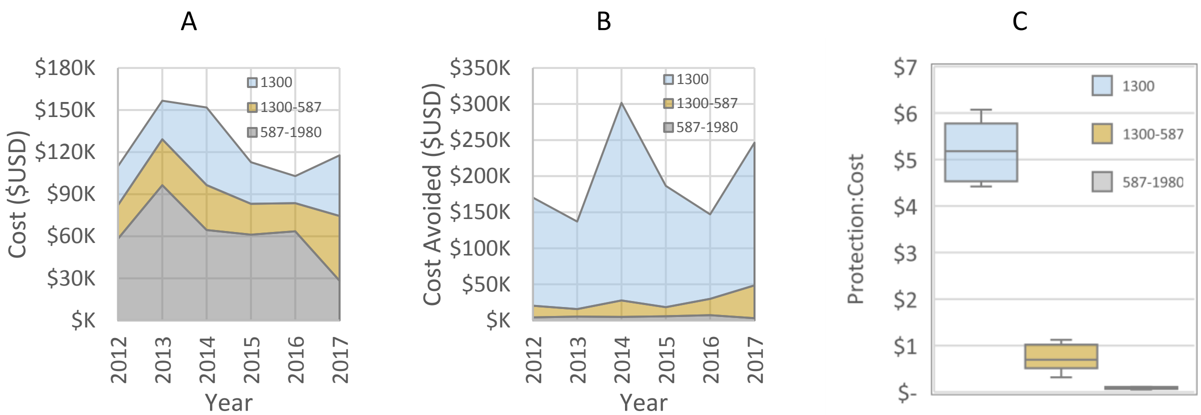
8. The total cumulative effort over time (A) and density (B; note reverse order of the x-axis) to extinguish the seed bank of a new mature incipient (x_i = 320) with the variable cost per pixel to maintain optimal effort (i.e., 71.1%).

From 2012-2017, a total of 486 hours of operational flight time was invested in search and destroy of over 25K incipient miconia targets. With a strategy focused on containment, only 28% of operations were invested in the priority watershed asset, while secondary and tertiary buffers were 24% and 49 % of operations, respectively. This was comparable to the number of miconia targets eliminated in these areas, e.g., 23, 24 and 53%, respectively. Direct management within the priority watershed asset resulted in 61% of the total area receiving some level of protection (Fig. 9B), while secondary and tertiary management offered protection to only 21% and 8% of the total watershed asset (Fig. 9C and D). The highest cost investments were recorded in the tertiary buffer from 2012-2016, exceeding the average cost investments in the priority watershed asset by 2.4-fold until 2017 when in the tertiary buffer was the minor investment (Fig. 10A). The inverse was displayed with cost avoidance assigned to the protected areas, where again direct management within the priority watershed asset avoided the most costs, not only a result of area protected but also compounded by the density assignments in the vicinity of the target location (Fig. 10B) resulting in dramatic differences in cost effectiveness (Fig. 10C). Management within the priority watershed asset avoided $5 a for every $1 invested, while investments in secondary and tertiary buffers resulted in negative returns. This is a retroactive review of cost effectiveness and it might be expected that more deliberate investments in the priority watershed asset may not provide the same level of return, especially with the increase in search effort. None the less, it would continue to exceed any future investments outside of the buffer area. Notwithstanding, it does not completely absolve the demand to manage these areas, which would continue to saturate and expand towards the edge; this being a major trade-off with switching from containment to asset protection.



9. The priority asset area in the EMW above 1300’ a.s.l. (blue), with a high density of Priority 1 Watershed (green pixels) designated by Hawaii-DLNR (A). Protection (green/yellow/red raster) to this

upper-elevation asset is calculated from the elimination of targets, before they become mature (pink points), occupying directly inside this area (B), the 587 m zone below (yellow) where up to 99% of the dispersal events could impact the priority asset area (C) and the zone out to 1980 m (grey buffer) where the remaining 1% of dispersal events could impact the priority asset area.



10. Management investments (A) in each of the priority zones and costs avoided in the priority asset area above 1300' from each of those investments (B) from 2012-2017 HBT operations resulting in a basic measure of cost effectiveness in protection monetarily gained (i.e., cost avoidance) for the management investment.

Conclusions

There was a 20-year lag period between introduction to initial management (ca. 1970-1991) in the EMW. It was quickly realized to be established in multiple locations, which conceivably in hindsight, might already have been beyond eradication. Regardless, the perseverance of a local grass roots effort continued, eventually proceeding with a comprehensive eradication strategy (ca. 2001-2011). As funding levels dropped eradication switched to containment (ca. 2012-2017). Cacho et al. (2008) described how strategic decisions should be used to identify the 'switching points' where it is no longer optimal to attempt eradication and further on no longer optimal to contain. The biology of miconia has outpaced the efforts to contain, most likely constrained by a limited resource budget. We must expect a flat to reduced level of funding moving forward, relegating us to the final switching point to protect the most critical assets yet to be impacted by miconia. The current invasion occupies over 30% of the EMW and is commencing with saturating its occupied areas. The actual suitable habitat has yet to be determined, but will be critical to restructuring the final strategy for long-term protection of watershed function and critical habitat with cost-effective measures. The science of miconia out of Tahiti and Australia corroborate our report of the invasion in the EMW. The knowledge gained on the life history traits will continue to serve our development of optimal protection strategies and tactical counter measures.

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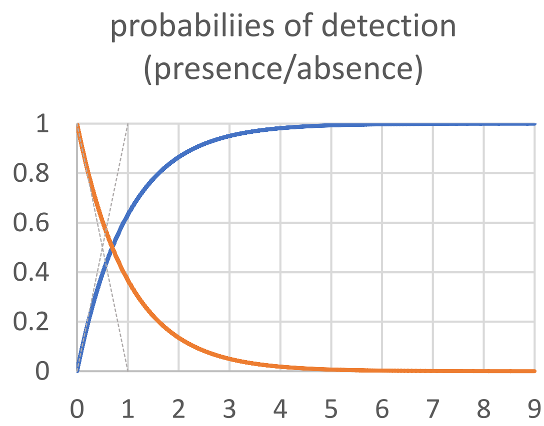
Supplemental



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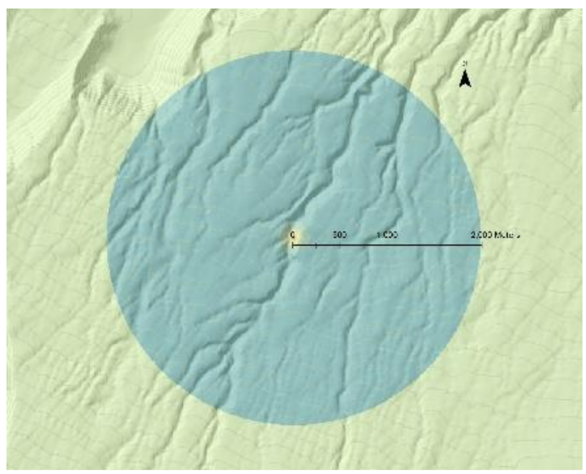

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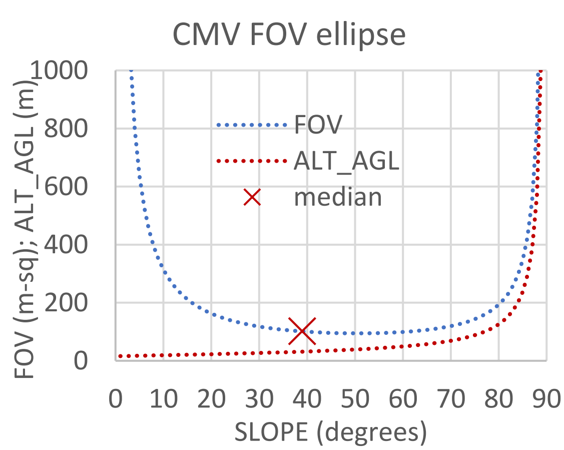

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