Cooperative Extension Service
College of Tropical Agriculture and Human Resources
University of Hawai'i at Mānoa

Final Report for the Hawaii Invasive Species Council Project for FY15

Title:
Quantifying outcomes of miconia (Miconia calvescens DC) management projects through advancements in Herbicide Ballistic Technology (HBT)

Content Area:
Research

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Executive Summary

Miconia is a listed noxious weed in the State of Hawaii and a HISC-priority plant species for control and eradication. Originally introduced on the Big Island in the late 1960's; local, state and federal agencies have been cooperatively managing the spread of Miconia on the Big Island, Maui, Oahu and Kauai since 1990 (Chimera et al., 2000). In 2012, Herbicide Ballistic Technology (HBT) was introduced as a new, effective treatment that enhanced helicopter surveillance operations with a capability for real-time 'target' elimination of remote miconia populations. In the East Maui Watershed, this realization led to the adoption of a more comprehensive containment strategy with a greater emphasis on resources used in reducing satellite populations across the entire nascent patch network encompassing 22,000 ha beyond the core infestation. This 2015 project was a progression of the FY14 HISC project "HBT Targeting Miconia". We have improved our data management technology with a new telemetry system for greater spatial and temporal resolution of target and herbicide placement. Target density reduction continues with the implementation of effective containment strategies on Maui Oahu, Kauai and the Big Island, via cooperation of shared resources provided by MISC, OISC KISC and BIISC (e.g., helicopter flight time). We also present new projected timelines to reach extinction with continued management (FYI, It's a marathon…not a sprint!).

Original Project Deliverables (with 2015 accomplishments):

- Develop a custom HBT telemetry system (HBT-TS) (published)
- Improved data acquisition (>10,000 points analyzed)
- 6000 targets to be effectively treated (4,173 targets)
- Total protected area approaching 5000 ha (7229 ha)
- Target density reduction of the nascent patch network >90% (67% depletion)
- Measurable reduction of herbicide dose rate (i.e., treating smaller targets) (4.38 grams triclopyr, a 3% reduction from 2014)
- >80% of total treated area less than 1% of the max allowable HUR (see Fig. 5A for refined calculations; otherwise traditional calculation of 142 ha at 1.7% HUR)
- Current efficacy of treatment application >98% (current efficacy rating 98.8%)

Measures of Effectiveness

The basic unit of measure in this project is target density, which serves as an absolute value of progress (i.e., target reduction), but also serves as a direct influence on operational efficiency values. For example, target density establishes the slope coefficients for search efficiency and herbicide use rate. Thus, we expect to measure concomitant improvements in these functions with each sequential operation reducing target density.

As stated in previous reports, the current approach to calculating herbicide dose rate (i.e., herbicide applied to target) is a rudimentary, composite average of the estimated projectile consumption divided by the recorded total number of targets of a single operation. A telemetry sensor system was customized for the electro-pneumatic applicator (HBT-TS) to enhance the resolution of this calculation by assigning every projectile discharged to a target (i.e., providing an exact dose rate), which would then calculate a mean with standard deviation. This will ultimately provide better detail in spatial assignment of herbicide use rates across the landscape and potentially allow for anecdotal correlations of size class. Thus, the standard deviation can provide interpretations regarding the uniformity, or lack thereof, of a target population. For instance, a large standard deviation relative to the mean would suggest a bias of exceedingly high doses to a minority of individual targets, thus skewing the mean, while small standard deviations might suggest similar size class of an even-aged population.

The vision of this project is a continuation of the 2014 project to optimize future operations with an initial accelerated schedule leading to a steady-state condition of extreme low target densities and to build new intelligence into an adaptive decision-support strategy for optimizing management by characterizing the demographic profiles of each patch population with enhanced surveillance/intervention protocols. Hereafter, we report 2015 results.

Results

The HBT platform is a refined pesticide application system that pneumatically delivers encapsulated, herbicide projectiles (i.e., paintballs) from long range (up to ~30 m) and varying attitude. When integrated into helicopter surveillance operations, this onboard system provides accurate, effective treatment of individual plant targets occupying remote, inaccessible portions of the forested landscape. Operational performance is characterized through GIS analyses of recorded GPS data assigned to treated plant targets. A telemetry system for HBT applications (HBT-TS) was developed to provide time stamped, geo-referenced attribute data including, (i) target assignment, (ii) azimuth, (iii) tilt and (iv) range determined from the applicator position, for every projectile discharged (Rodriguez et al. 2015). The telemetry sensor hardware is externally mounted to the electro-pneumatic marker and consists of printed circuit board populated with several sensors, including

A B

Figure 1. (A)HBT-TS mounted to an electro-pneumatic marker with sensor platform in Bluetooth communication with Android device and (B) Real-time user interface application displaying HBT operations telemetry on android device.

barometric altimeter, gyroscope, magnetic compass, and triple axis accelerometer (see Fig. 1A), transmitting data via Bluetooth® to a devoted software application written in Android open source code (Fig. 1B). The phase II model now includes a laser range finder (LRF) capable of integrating distance up to 40 m and a 6600 mAh lithium ion battery pack for extended performance of these power-hungry processes.

The azimuth, tilt, and range describe the location of the target relative to the applicator in a local spherical coordinate system centered at the applicator (Fig. 2A). In order to superimpose the local coordinates of the target over the geodetic coordinates of the applicator, the spherical coordinates are converted into a Cartesian coordinate system centered at the applicator using the following relationships:

$$x_{A\to T} = \rho\cos\phi\cos\theta \qquad (1)$$

$$y_{A\to T} = \rho\cos\phi\sin\theta \qquad (2)$$

$$z_{A\to T} = \rho\sin\phi \qquad (3)$$

where x, y, and z (with subscript A→T) designate the components of the vector from applicator to target in the Cartesian coordinate system and ρ, θ and φ describe the vector in the spherical coordinate system. The short range of an HBT application relative to the radius of the Earth allows for simplified calculations using a local flat surface projection. The final target offset coordinates are calculated from the following relationships:

$$\varphi_T = \varphi_A + \frac{x_{A\to T}}{R_{Earth}} \qquad (4)$$

$$\lambda_T = \lambda_A + \frac{y_{A\to T}}{R_{Earth}\cos\varphi_A} \qquad (5)$$

$$h_T = h_A + z_{A\to T} \qquad (6)$$

where φ, λ and h are geodetic coordinates latitude, longitude and elevation, respectively, (with subscripts T and A representing target and applicator, respectively) and R_{Earth} is the local radius of the Earth calculated using the WGS 84 model:

$$R_{Earth} = \bar{R}_{Earth}\left(1 - F\sin^2\varphi_A\right) \qquad (7)$$

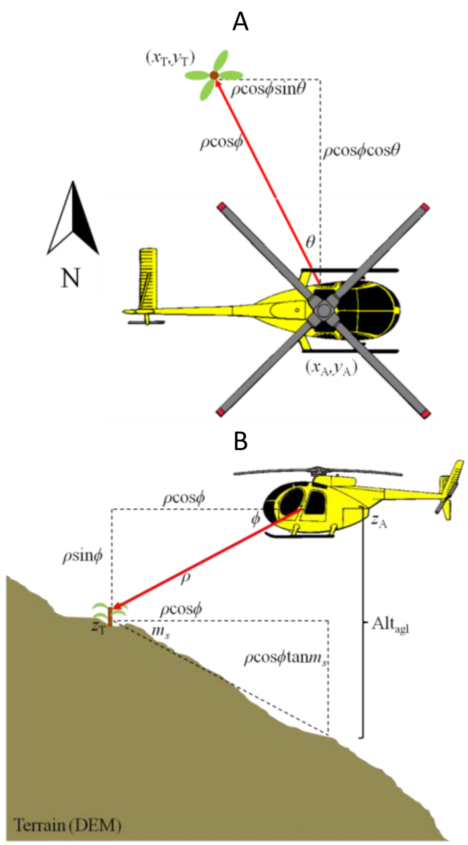

Figure 2. Trigonometry of a target engagement process in an aerial surveillance operation. (A) Horizontal offset derived from horizontal component of range and azimuth. (B) Altitude above ground level (Alt_{agl}) derived from the range (ρ) and tilt (ϕ) telemetry terrain model slope (m_s) of the nadir position.

where the flattening coefficient F is 1/ 298.257 223 563.

The altitude above ground level (Alt_{agl}) is approximated using the relative z-coordinate of the target and the height of the triangle formed by the slope aspect (m_s) of the terrain and the relative horizontal coordinate (Fig. 2B):

$$\mathrm{Alt}_{\mathrm{agl}} = \rho \sin\phi + \rho \cos\phi \tan m_s \qquad (8)$$

As stated above, one of the main qualifying attributes of HBT is the capability to efficiently and effectively treat targets occupying extreme terrain that are otherwise inaccessible. This includes situations where the applicator can engage a target from different lines of sight (see Fig. 3B) or multiple targets from a single applicator position with different trajectories (see Fig. 3C).

Operations were recorded with the TS acquiring several thousand points for operational flight time (OFT; x=4464) and projectiles discharged (x=6845), all with corresponding spatial telemetry and timestamp attributes. Operational flight lines followed parallel to the terrain contour with a bias on the port side (see Fig. 4A; blue) In normal procedures the target engagement process commences with detection. From there, the pilot maneuvers the position of the applicator within effective range and a clear line of site to target. In these recorded operations, targets were confronted antiparallel to terrain aspect with a median azimuth of the applicator at 191° (Fig. 4A; red) and the median range at 15.2m (Fig. 4B). The pilot always approached the target from above, where the median tilt of the applicator was -33° (Fig. 4C). Terrain aspect is the vector normal to the terrain surface projected into the horizontal plane, and assumed to also be the aspect for the plant colonizer. The interquartile azimuth was 163°-222°, where angles >180° could be interpreted as an efficiency in approaching the target immediately upon detection, while lines of sight at <180° might relate to efforts in repositioning the aircraft for a better line of sight, free of obstacles (e.g., circumventing tree canopy). The average terrain slope surveyed was 31.5°, with a direct (non-linear) correlation to Alt_{agl} of

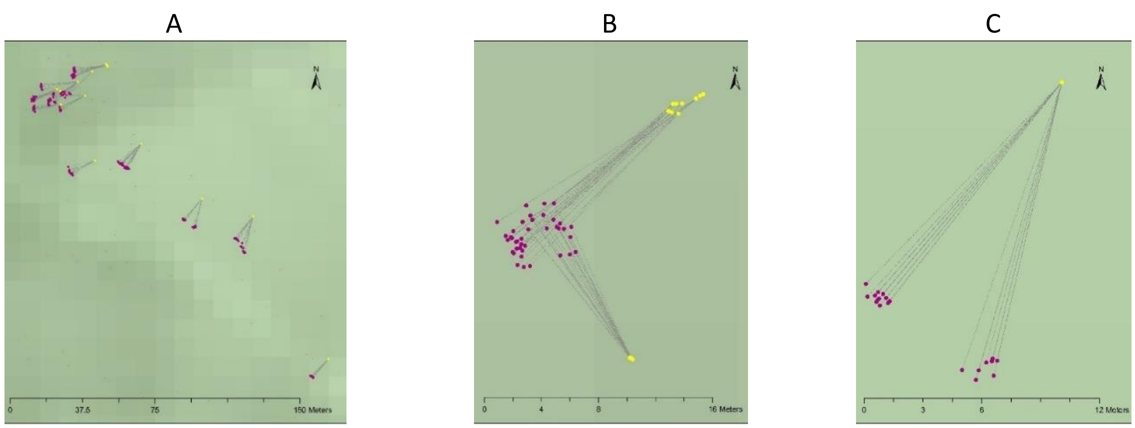

Figure 3. (A) Display of applicator (yellow) and target offset (purple) positions calculated from range, azimuth and tilt values (grey lines) overlaid on 10m digital elevation model. (B) Depiction of a target treated from multiple applicator positions. (C) Multiple targets treated from a single applicator position.

the helicopter/applicator (see Eq. 8). On average, the Alt_{agl} for target engagement (red) was 7 m less than the Alt_{agl} for OFT, i.e., surveillance (Fig. 4D). This again highlights the pilot's maneuvering to bring the applicator within close, effective range of the target and dropping back to expand the field of view while in surveillance.

Herbicide use rate (HUR) is the amount of pesticide applied per unit area (e.g., grams acid equivalent ha^{-1}). An HBT projectile contains 0.1994 g ae of the active ingredient triclopyr and is estimated to produce a circular spatter pattern that has a radius of ~1 m (i.e., 3.14 m^2). Spatial analyses were performed to calculate the area of the footprint and HUR using ArcMap® 10.1 (ESRI, Redlands, CA). Area footprints were calculated for each projectile, target and total net treated area using the Buffer Analyses tool with 1m radius. To determine the HUR distribution across the entire treated area, a Point Density Analysis was performed with a 0.0625 m^2 cell size and a 1 m circular neighborhood to measure the magnitude of the herbicide dose (0.1994 g ae $projectile^{-1}$; x = 6845) overlaid on to the total net area footprint created by the offset placement of the projectiles.

A single projectile creates a treatment footprint with an equivalent HUR of 634.7 g ae ha^{-1} that is 9.4% of the maximum allowable rate (i.e., 6,720 g ae ha^{-1}). The mean target HUR in these operations was 2,460 g ae ha^{-1} with 98.3%

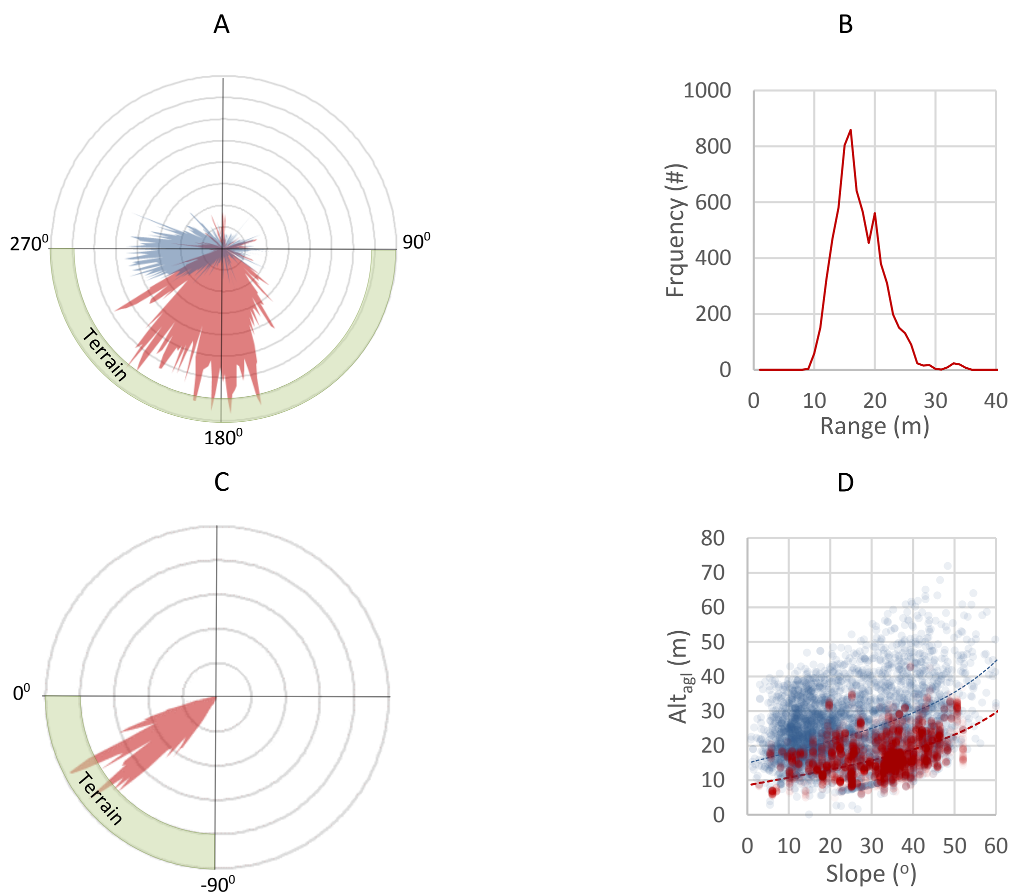

Figure 4. Depictions of the target engagement process with frequency plots for azimuth (A), range (B) and tilt (C) to terrain, and a scatter plot of Alt_{agl} against slope for target (x= 6845; red) and operational flight time (x= 4464; blue).

of targets below the max HUR (Fig. 5A). The average target dose and area footprint were 3.6 g ae and 15.1 m^2 for targets below max HUR (Fig. 5B). On the other hand, for those six targets that exceeded max HUR, the average area footprint was only slightly higher at 17.2 m^2 while the average dose increased to 13.8 g ae. These high doses were likely to be artifacts of treating larger (mature) targets or due to inaccuracies when treating smaller targets. The total area footprint of these excessive targets was 103 m^2, or 1.9% of the total target area. The total net area footprint was 4,938 m^2, which was saturated 435.5% by the gross projectile footprint area (i.e., 3.1416 m^2 x 6845 projectiles) with a net HUR that was 41.1% of the maximum allowable rate. In this case, 6.1% of the total pixel area (i.e., 371.1 m^2) exceeded the max HUR but was heterogeneously scattered on a sub-meter scale (data not shown). The analyses of HBT-TS data highlights the fine-scale presentation of an herbicide application and the opportunity for high resolution analyses. These results were published in the Proceedings of the American Society of Agricultural and Biological Engineers and in the peer-reviewed journal IEEE Sensors, with HISC support acknowledged in both cases.

For FY15 we conducted 29 aerial missions on Maui, Oahu Kauai and the Big Island combining for a total 109 hours OFT. In this time, we protected 7229 ha (gross) of watershed. We consumed an estimated 91,676 projectiles in treating 4,173 miconia targets, resulting in a composite average dose of 4.38 grams triclopyr, which is a 3% reduction from 2014; a continuing trend also reported last year. Again, the East Maui Watershed (EMW) received the highest level of protection with over 90% of resources dedicated to the effort. With Maui,and Kauai, we have up to 4 years of management strategies deployed allowing for an early investigation in projecting timelines towards accomplishing containment and eradication. We also report on Oahu with modest, early presentation of a 2-year timeline.

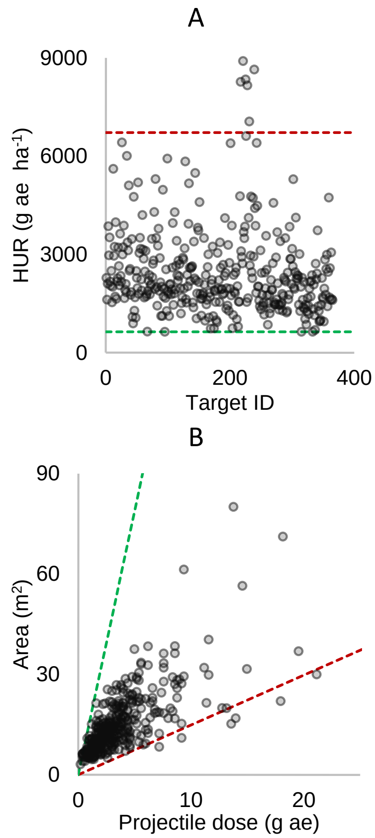

Figure 5. (A) Target herbicide use rate (HUR; grams acid equivalent ha^{-1}; n = 365; x = 6845) calculated from the projectile dose and net area of the projectile offset locations buffered with a 1m radius. (B) Net target offset area created by projectile dose. Note the green dashed line is the HUR for a single isolated projectile and the red dashed line is the maximum allowable HUR according to the registered pesticide label.

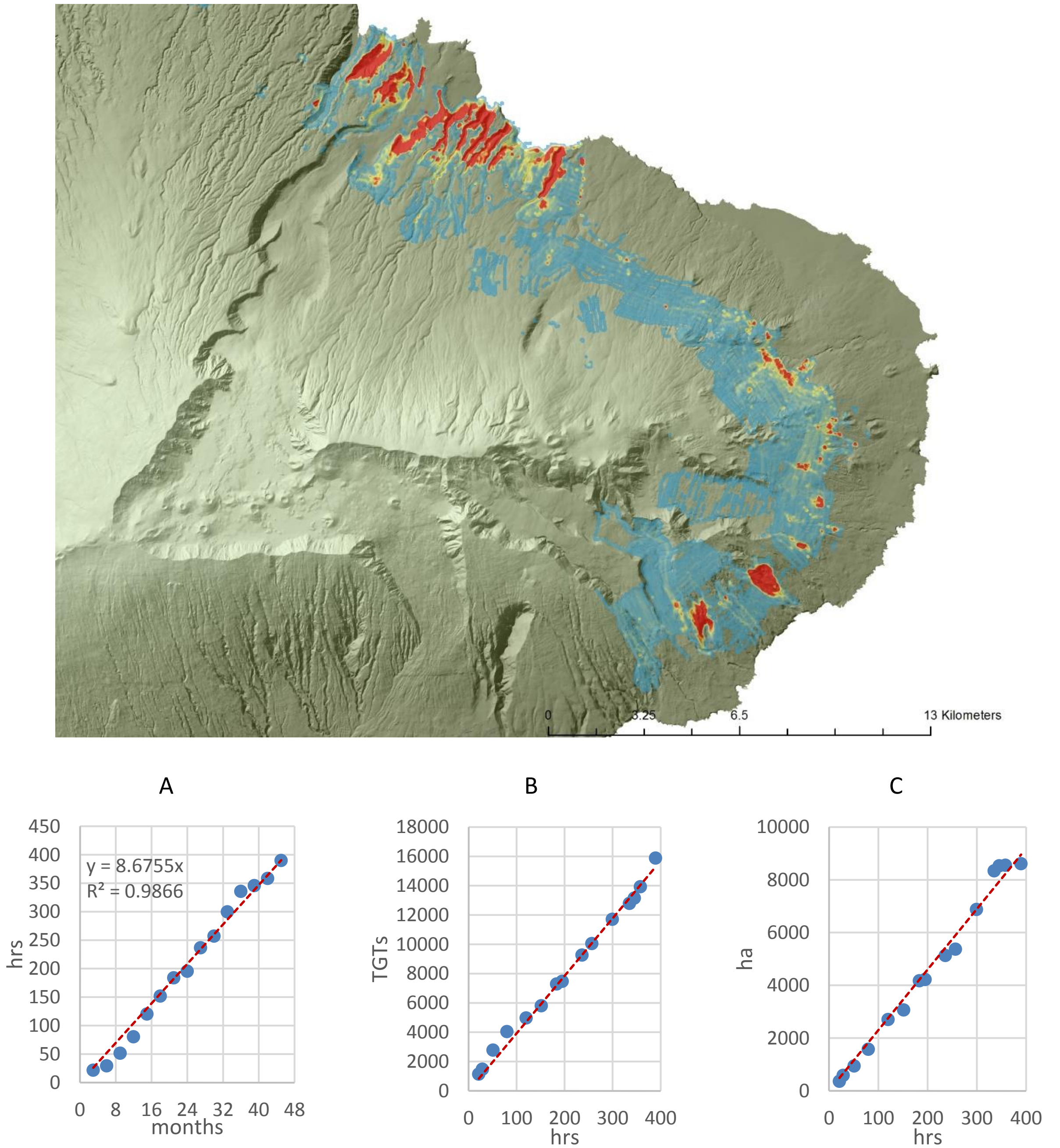

Figure 6. East Maui Watershed cumulative metrics for flight time inputs (A) with targets treated (B) and area searched (C) outputs from 2012-2015. The raster depicts the discrepancy of flight time allocated between surveillance of known target locations (red) and reconnaissance of surrounding areas (blue).

The EMW is a steep, forested landscape extending from Honomanu to Kipahulu, encompassing the entire windward slope of Haleakala Volcano. Its total area is ~120,000 acres and produces over 3 trillion liters of fresh surface water annually. Starting in 2012, forty-one missions have been completed with over 389 hours OFT in the EMW. This equates to a mission conducted every 33 days with a monthly consumption of 8.7 hrs OFT (Fig.6A). It should be noted that there are up to 16 known target populations that consume ~30 hours OFT to complete, thus, an estimated 3-month cycle between interventions for each of these populations. In 2015, we were slightly below the pace of previous years with 90.35 hours OFT, with a noticeable gap without interventions between February and August, due to logistical reasons in replenishing projectile inventory. There were 3844 targets treated this year bringing the total to 15,837 targets treated in four years of operations. The historical incipient target foot print has surpassed 1000 ha this year and is steadily expanding at a rate of 23 ha each month, equivalent to 2.5 new incipient targets being detected in each hour OFT (based on a 1-ha buffer analysis). However, the expansion trend appears to be leveling off bringing us closer to complete intelligence on the extent of the incipient target occupation. Of the 5963 ha gross searched in 2015, the total net area only expanded by 271 ha, bring the total historical net area searched to 8604 ha. With the current intervention schedule, the total net area searched is expanding at a rate ten times faster than the comparable rate of expansion of the target footprint; a simplistic measure of management interventions outpacing biological fortitude.

Starting in October of 2013 (and restarting in July 2014), HBT operations commenced on Oahu with focus on two known target locations in Manoa and Kaalaea Valleys in the Koolau Mountain range (Fig. 7). These populations are managed on the same schedule with interventions now being conducted every three months and similar total OFT at 8.6 and 9.7 hours for Manoa and Kaalaea, respectively (Fig. 7A). While total net areas for Manoa and Kaalaea are comparable at 190 and 199 ha, respectively, total targets treated are quite distinguishable at 116 compared to 214 (Figs. B and C). There's early evidence of both target populations being reduced with imposed interventions, but will present better projections in the near future.

Aerial HBT operations have commenced in the Wailua Game Management Area on Kauai since 2012, for a total of eleven interventions every 135 days on average, consuming a total of 16.3 hours OFT (Fig. 8A). The total net area searched 459 ha, with a total of 71 targets treated over the four years of interventions. Interestingly, target acquisition rates remain linear at five targets treated per hour OFT, where interventions have never exceeded ten targets, but have always treated at least one target. Despite this management area being the smallest incident population, this brings to light the challenge of maintaining operations with diminishing (asymptotic) returns towards achieving eradication.

The three scenarios described above are exhibiting progressions from consistent intervention schedules (i.e., 3-4 month intervals), with most producing predictable outcomes of target density reduction (Fig. 9). These reductions modestly fit non-linear, exponential decay functions, which allow for anecdotal projections of timelines to extinction. The EMW has a decay rate of 0.3% (per hour OFT) with a projected timeline of 822 hours OFT (i.e., year 2020) to achieve 90% target depletion and 2468 hours OFT (i.e., year 2036) to achieve 99.9% target depletion. With an 8.5% decay rate, Kaalaea Valley is projected to be 90% depleted in 12 hours OFT (i.e., year 2016)

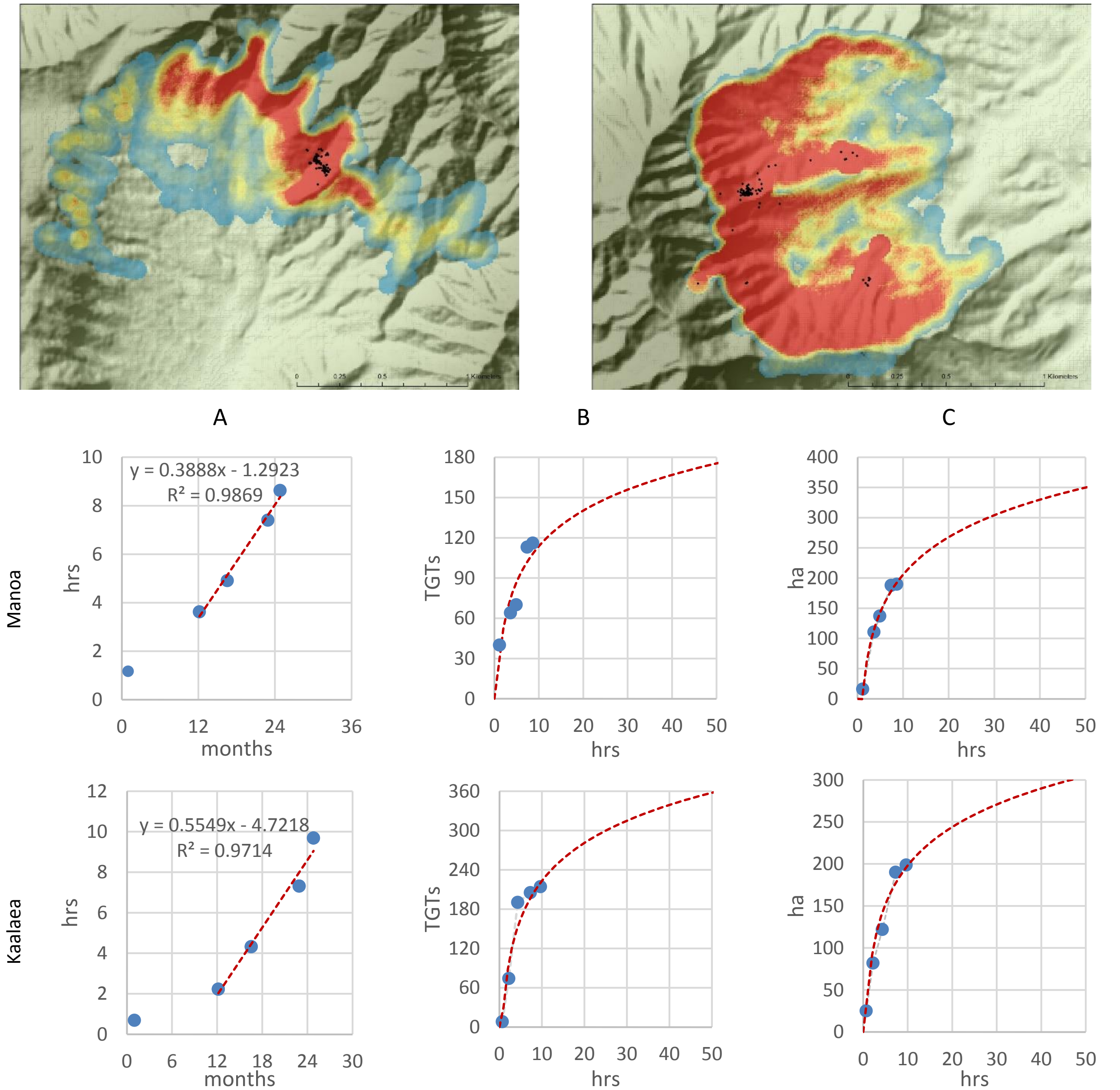

Figure 7. Kaalaea and Manoa Valley (Oahu) cumulative metrics for flight time inputs (A) with targets treated (B) and area searched (C) outputs from 2013-2015. The raster depicts the discrepancy of flight time allocated between surveillance of known target locations (red) and reconnaissance of surrounding areas(blue). Black points are locations of targets acquired.

and 99.9% depleted in 36 hours OFT (i.e., 2024). On the other hand, the current projections for Manoa Valley best fits a positive exponential function. This is a dubious interpretation and would expect to see adjustments in the decay rate with fluctuations of targets encountered over time. Finally, Wailua with a 4.0% decay rate is projected to be 90% depleted in 58 hours OFT (i.e., year 2030) and 99.9% depleted in 173 hours OFT (i.e., year 2066).

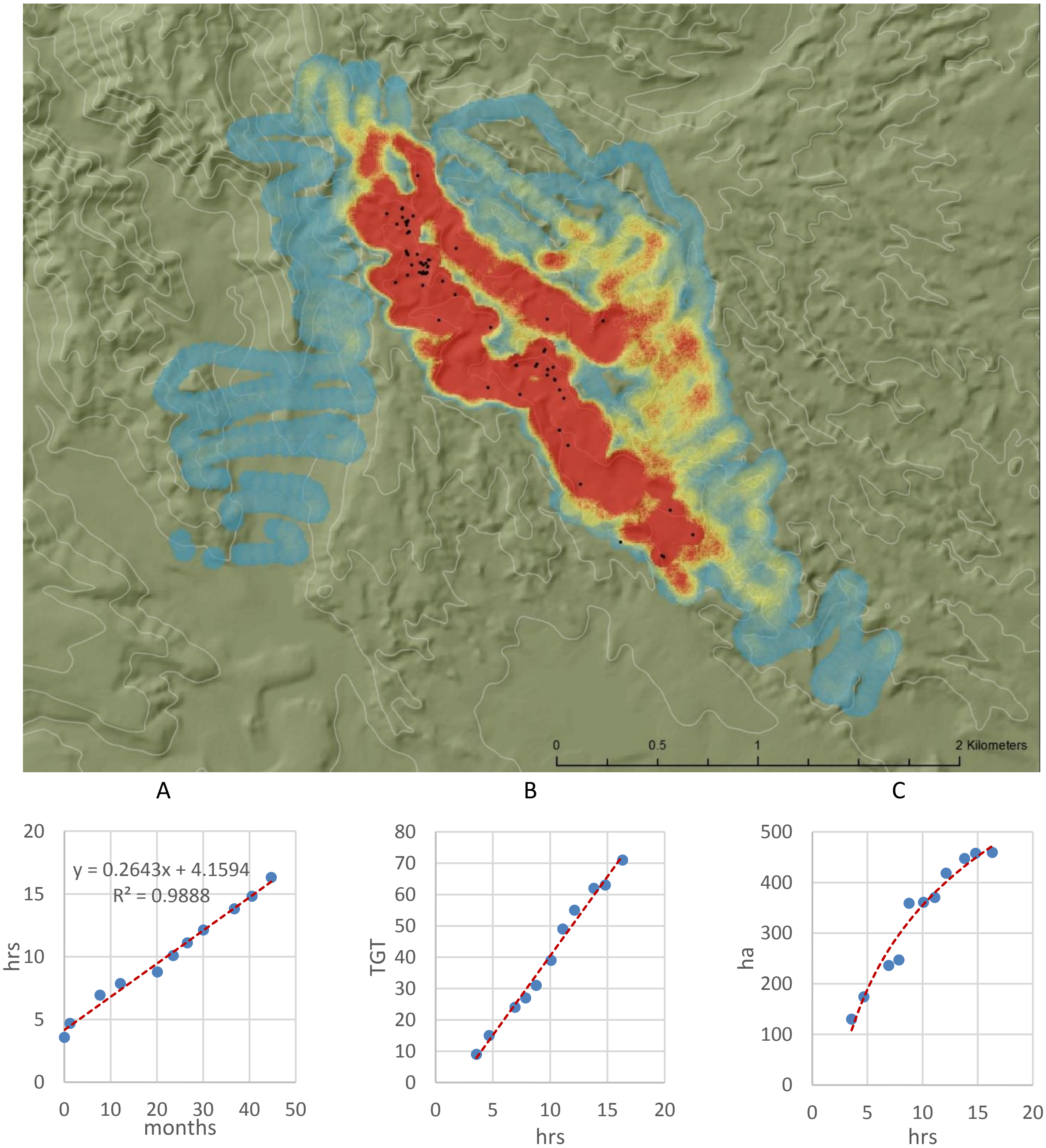

Figure 8. Wailua Game Management Area (Kauai) cumulative metrics for flight time inputs (A) with targets treated (B) and area searched (C) outputs from 2012-2015. The raster depicts the discrepancy of flight time allocated between surveillance of known target locations (red) and reconnaissance of surrounding areas (blue). Black points are locations of targets acquired.

These projections are highly dynamic and prone to adjustments as new data is added, serving as caution in reliability of this current rendition. With only four points to show, dating back only to 2014, the Oahu projections are not as developed as those presented for Maui (EMW) and Kauai (Wailua) with longer histories. Regarding these more developed projections, the two forces dictating these decay patterns are the intensity of interventions being imposed

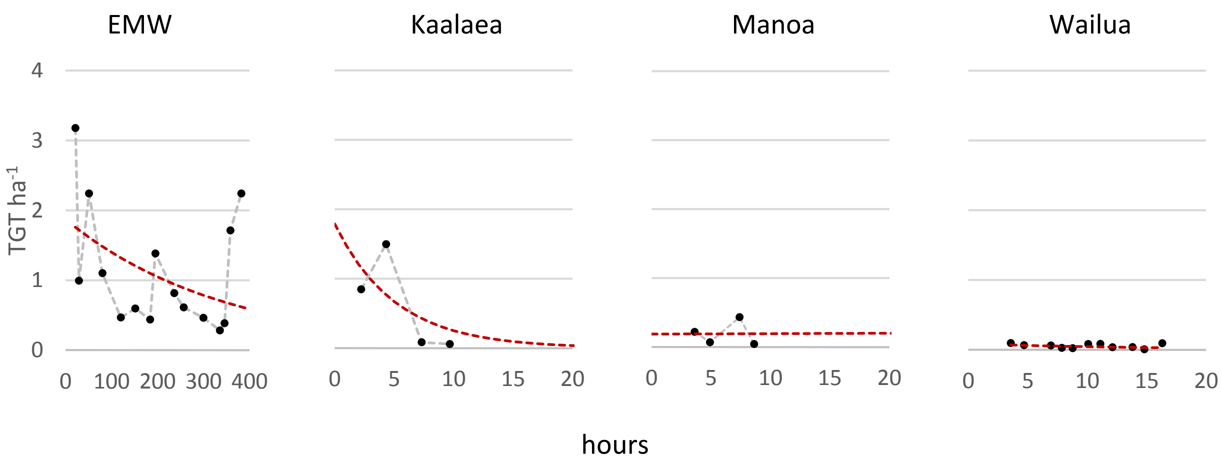

Figure 9. Target densities encountered for each of the management areas over accumulated operational flight time with fitted exponential decay projections.

and the biological response of miconia. Interesting to note the incipiency of miconia in the EMW is more than 20x greater with a decay rate that is 1/10th of the Wailua interventions, yet the entire EMW population is projected to reach 99.9% depletion thirty years before Wailua. The difference in these timelines, is a direct result of the different invention schedules. Thus, when plotted against a calendar timeline the decay function for the EMW is now at 3% versus only 1% for Wailua. The notion that the decay function is a constant to completion would be a misconception, i.e., maintaining a high frequency of interventions will become less optimal as target detection becomes less frequent (Burnett et al 2007). It is more realistic that as EMW densities approach the densities observed in Wailua, interventions will likewise decelerate. If that were the case, we could speculate on a timeline composite that transitions to a decelerated schedule when reaching a lower density threshold that ultimately extends the timeline to reaching extinction (Fig. 10). For instance, if accounting for a transition from 3% down to 1% decay (per month) at the target density where Wailua started, this would extend timeline for depleting (99.9%) the EMW from 24 years, as described above, to 68 years (i.e., year 2080).

As suggested above, 97% of targets are being treated within known locations. The oscillating spikes in target density are apparent in Figs. 9 and 10. Miconia is highly fecund with apomictic seeds known to have exceptional viability in the soil and a physiological dormancy that promotes an asynchronous germination pattern (Fernando 2013, Meyer 1996). The residuals of the best fit function are a determinant of the actual decay rate and may be interpreted as biological recruitment events from the latent seed banks within these known target locations. Thus, the amplitudes of the residuals (i.e., lack of fit) may serve as measure of seed bank viability, where over time we should observe a damping effect as an indicator of seed bank exhaustion that may ultimately provide better projections to the point of extinction.

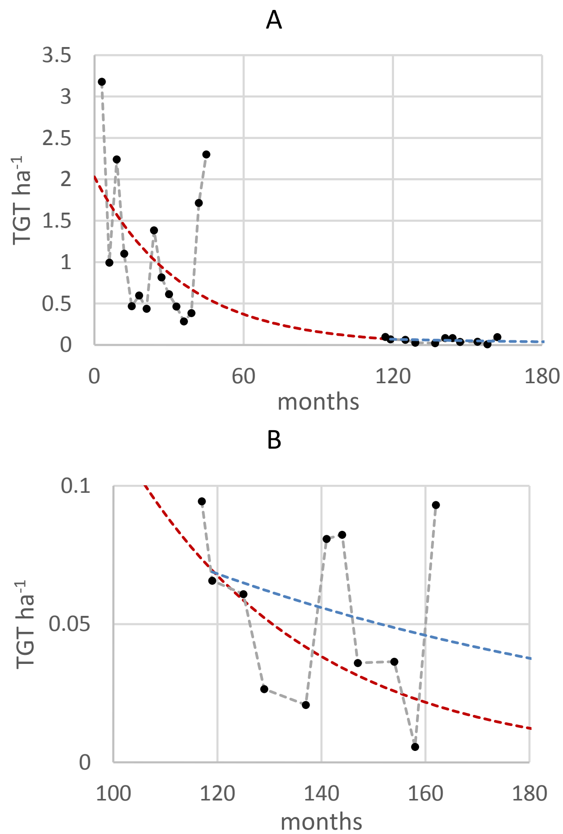

Figure 10. A composite of decay functions for EMW (red) and Wailua (blue) as a rendition of a timeline speculating the point of extinction based on a deceleration of intervention frequency from current efforts imposed in EMW to Wailua (A). Close up of the transition to the Wailua decay function. Note target density values for EMW and Wailua superimposed for reference.

Conclusions

This project is driven by innovation, new knowledge and performance. New technologies are building robust data sets, being deployed in decision-support analytics with outcomes in performance expressed with improved reliability. Our latest figures present a reality check on the commitment to provide effective, long-term watershed protection against miconia. Future work needs to focus on cost effectiveness and optimization for meeting these long-term goals.

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