ISPRS Journal of Photogrammetry and Remote Sensing 125 (2017) 174–183

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Assessing the impacts of canopy openness and flight parameters on detecting a sub-canopy tropical invasive plant using a small unmanned aerial system

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A R T I C L E I N F O

Article history:
Received 5 September 2016
Received in revised form 22 January 2017
Accepted 27 January 2017

Keywords:
Miconia calvescens
Hawai'i
Oblique
Canopy openness
UAS
Plant detection

A B S T R A C T

Small unmanned aerial systems (sUAS) have great potential to facilitate the early detection and management of invasive plants. Here we show how very high-resolution optical imagery, collected from small consumer-grade multirotor UAS platform at altitudes of 30–120 m above ground level (agl), can be used to detect individual miconia (*Miconia calvescens*) plants in a highly invaded tropical rainforest environment on the island of Hawai'i. The central aim of this research was to determine how overstory vegetation cover, imagery resolution, and camera look-angle impact the aerial detection of known individual miconia plants. For our finest resolution imagery (1.37 cm ground sampling distance collected at 30 m agl), we obtained a 100% detection rate for sub-canopy plants with above-crown openness values >40% and a 69% detection rate for those with >20% openness. We were unable to detect any plants with <10% above crown openness. Detection rates progressively declined with coarser spatial resolution imagery, ending in a 0% detection rate for the 120 m agl flights (ground sampling distance of 5.31 cm). The addition of forward-looking oblique imagery improved detection rates for plants below overstory vegetation, though this effect decreased with increasing flight altitude. While dense overstory canopy cover, limited flight times, and visual line of sight regulations present formidable obstacles for detecting miconia and other invasive plant species, we show that sUAS platforms carrying optical sensors can be an effective component of an integrated management plan within challenging subcanopy forest environments.

1. Introduction

A key strategy in the fight against invasive weeds, early detection of nascent alien plant populations has long been a focus of applied remote sensing research (see Bradley, 2014; Huang and Asner, 2009; Lass et al., 2005 for reviews of this topic). One aspect that has proven particularly challenging is the detection of subcanopy species of concern within forest environments. When areas with dense canopy cover are observed from above, subcanopy species are often partially or fully obscured by the overstory vegetation layer, making their detection difficult (Anderson et al., 1996; Bradley, 2014). Researchers have attempted a variety of solutions for detecting understory species, including phenological (Tuanmu et al., 2010; Wilfong et al., 2009) and imaging spectroscopy (Asner et al., 2008; Barbosa et al., 2016; Peerbhay et al., 2016) approaches, as well as using microwave and lidar to penetrate forest canopies and detect understory exotic plant species (Ghulam et al., 2014; Singh et al., 2015). While these efforts have shown great promise, phenological approaches developed for deciduous temperate species are of limited value in the tropics, and most researchers and land managers working in this part of the world do not have access to expensive and specialized instrumentation. A different solution may lie in the use of very fine spatial resolution visible imagery collected from inexpensive small unmanned aerial systems (sUAS). sUAS, defined as low altitude, short-endurance systems weighing <5 kg (Watts et al., 2012), can be used to capture very high resolution spatial data on-demand from low flight altitudes (Crommelinck et al., 2016; Puliti et al., 2015; Salamí et al.,

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http://dx.doi.org/10.1016/j.isprsjprs.2017.01.018
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2014). Though limited in flight time and payload capacity in comparison to manned airplanes and helicopters, sUAS platforms have lower operational costs, carry much lower risks of loss of life and property, and can fly within previously inaccessible areas such as sheer ravines or forest interiors (Chisholm et al., 2013; Ogden, 2013). As a result, many of the constraints previously associated with generating high resolution aerial imagery over an area of interest (e.g., scheduling conflicts, fuel costs, platform availability, accessibility) have been removed or simplified, making it easier to quickly collect imagery with a very fine ground sampling interval (<0.05 m). Specific regulations concerning sUAS flight operations, which may include maintaining visible line-of-sight and other airspace and licensing requirements, provide a new set of constraints and vary by country (ICAO, 2015).sUAS are beginning to be used as a new means of surveying for invasive species, often incorporating image segmentation and machine learning algorithms (Dvorák et al., 2015; Michez et al., 2016; Müllerová et al., 2016; Peña et al., 2015). Most of these efforts have been limited to non-forested and agricultural landscapes. In Hawai'i and other locations with native forests under threat from invasive species, work is needed to determine how well these new sUAS platforms can detect subcanopy invasive species in forest settings with multiple vegetation canopy layers. The purpose of this study was to quantify the impacts of flight altitude, camera look angle, and overstory vegetation canopy cover on the ability of a sUAS platform to detect known individual miconia (*Miconia calvescens* DC.) plants within a highly invaded tropical rainforest on eastern Hawai'i Island. Our original hypotheses were that miconia plants <1 m would be undetectable from the air in this forested setting and that there would be a clearly defined maximum degree of overstory canopy cover beyond which miconia plants would be undetectable. We hypothesized that the addition of oblique photos, in combination with images taken in the traditional nadir orientation, would improve detection results as the angled look direction would better allow us to detect plants beneath the overstory vegetation canopy layer. We were also interested in determining an optimal flight altitude for detecting miconia plants, balancing the need to survey large areas against the minimum resolution required to identify individual plants. The results of this study are broadly applicable to detecting other understory species of interest via sUAS or other platforms.

2. Materials and methods

2.1. Miconia calvescens

Miconia, a highly invasive understory alien tree species from Central and South America, presents a well-documented threat to native tropical ecosystems across the globe due to its fecundity, long-lived seeds, and ability to grow in extreme low light conditions and shade out native species (Meyer, 1994, 1998). Miconia trees can grow up to 15 m tall, with large characteristic leaves up to 1 m in length that have deep purple undersides (inset photo, Fig. 1), and can produce dense monotypic stands in both disturbed and intact rainforest habitat (Csurhes, 1998; Meyer, 2010). The crown size of an individual Miconia plant can vary from <1 m^2 for seedlings to >5 m^2 for mature plants. Currently infested areas include rainforests in Australia, French Polynesia, Hawai'i, New Caledonia, and Sri Lanka (Brooks and Jeffery, 2010; Lowe et al., 2000; Medeiros and Loope, 1997; Meyer, 1996, 2010) with the potential to spread well beyond these areas (González-Muñoz et al., 2015). Decades of intensive miconia eradication efforts across the Pacific have largely been unsuccessful, in part because of difficulties with detection (Leary et al., 2014; Meyer, 2014; Meyer et al., 2011).

2.2. Study site

The study site for this work is located at 19.4719°, −154.9554°, approximately one mile south by southwest of the town of Pāhoa on the Island of Hawai'i (Fig. 1). The 0.8 ha site is oriented as a ~160 × 50 m rectangle, flanked by a service road on the southern edge. Situated at an elevation of 237 m on an early successional lava flow ranging between 400 and 750 years old (Sherrod et al., 2007), the area has a 3% slope to the northeast and receives an annual rainfall of 3261 ± 104 mm (Giambelluca et al., 2013). Formerly cleared of native forest and used to grow sugarcane between 1897 and 1984, the land has been fallow and colonized by fast growing invasive grasses and tree species since the closure of Puna Sugar LTD in the mid-1980s (HSPAPA, 1992).

The vegetation canopy is now comprised of invasive tree species including Albizia (*Falcataria moluccana*), Common and Strawberry Guava (*Psidium cattleyanum* and *guajava*), Strangling Banyan (*Ficus* sp.), Trumpet Tree (*Cecropia obtusifolia*), Octopus Tree (*Schefflera actinophylla*), Bingabing (*Macaranga mappa*), and Princess Flower (*Tibouchina heteromalla*). Invasive liana species are also present, including Stink Vine (*Paederia foetida*) and Passion Flower (*Passiflora* spp.). Understory vegetation species are dominated by two fern species, Uluhe (Dicranopteris linearis) and Hā pu'u (*Cibotium glaucum*). Miconia was first identified in the area in 2006 and a four-year control effort immediately followed (Big Island Invasive Species Committee, unpublished data). During this period, 566 miconia plants were removed within the study area (172 mature, 394 immature) through mechanical and chemical means. Organized control efforts ended in 2010.

2.3. Data collection

2.3.1. sUAS flights

A consumer-grade Inspire-1 multirotor sUAS platform (DJI Inc., Shenzhen, China) was used to carry a DJI FC350 camera (20 mm lens with a f/2.8 focus, 94 degree FOV, Sony EXMOR 1/2.3-inch CMOS), mounted on a Zenmuse X3 gimbal during a series of flights over the study area on July 28 and August 5, 2016. sUAS flights were conducted between 11 a.m. and 3 p.m. under environmental lighting conditions ranging from full sun to partly cloudy. Flight operations were conducted manually at a forward velocity of 3 m/s and between 30 and 120 m above ground level (agl) to produce imagery datasets with varying ground sampling distance (GSD) (Table 1). It was impossible to safely fly lower than 30 m due to the tree canopy, which reached heights of 25 m within the study area and >30 m outside. Each flight took two to seven minutes and consisted of multiple flight paths (re-flown in opposite directions), parallel to the road bounding the study area (Fig. 1) and spaced between 12 and 30 m apart, depending on altitude, to achieve the desired overlap. For each flight, photos were automatically triggered in transit from a nadir position every 10 m along the flight path, resulting in image sets with an average overlap of 85% or greater, as suggested by Dandois et al. (2015). The exception to this was a portion of the 30 m agl flight which, out of prudence given the proximity of the surrounding tree canopy, followed a slightly modified flight path that produced 15% fewer photos than recommended for 85% overlap, while still covering the study area. For the 60 m agl flight, uncertainty regarding the operation of the camera during the initial flight (which was indeed operating properly) caused us to re-fly the mission, resulting in more than twice as many photos for that flight altitude. For each flight, following the collection of the nadir photos the platform returned to the starting position and the area was re-flown with the camera in a forward oblique (~45 degree) position. This resulted in two sets of photos that were processed and analyzed for each flight altitude - nadir alone and nadir plus oblique

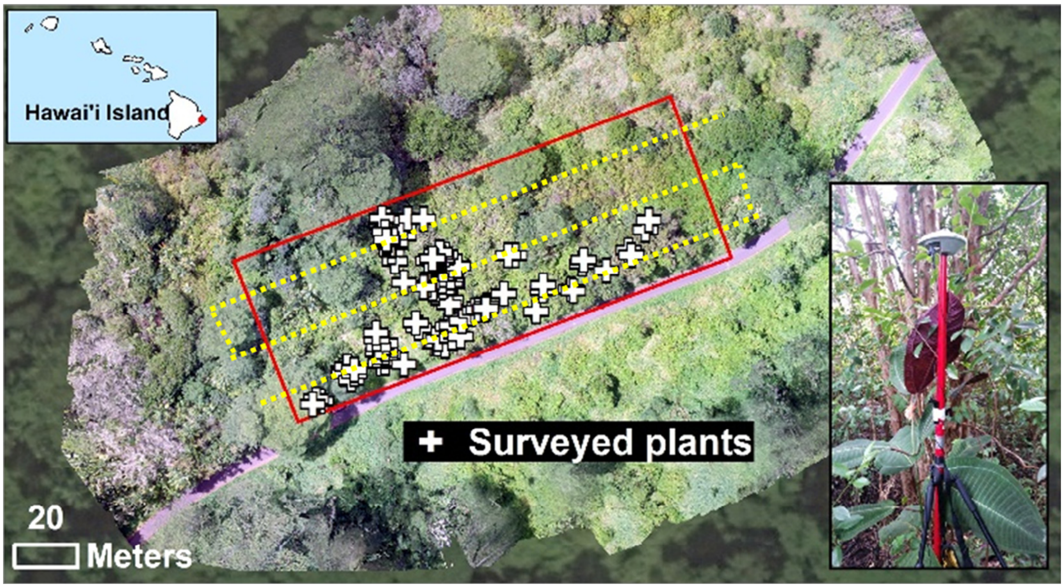

Fig. 1. 0.8 ha study site (red rectangle) south of Pāhoa on the Big Island of Hawai'i showing the 108 surveyed miconia plant locations, sUAS-derived orthomosaic of study area overlain on 2016 WorldView 2 satellite image. Yellow dashed line shows example sUAS flight path. (upper left) Locator map for study site on Hawai'i Island. (inset photo) Example surveyed miconia plant showing characteristic leaf shape and purple underside. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Imagery datasets included in the study.

Flight altitude (agl) (m)	Number of photos collected		Nadir Mean GSD (cm)	Nadir photo Mean footprint (m^2)	RMS error (m)	
	Total (Nadir & Oblique)	Nadir photos (min. # required for 85% overlap)			Nadir	Nadir & Oblique
30	287	156 (184)	1.37	2524	0.027	0.047
40	248	144 (114)	1.69	3728	0.031	0.04
50	179	90 (73)	2.17	5867	0.04	0.043
60	386	254 (46)	2.6	8490	0.029	0.046
80	172	105 (35)	3.54	15,461	0.03	0.036
100	151	84 (18)	4.37	23,968	0.041	0.064
120	124	72 (16)	5.31	33,496	0.045	0.049

(Table 1). Maximum slant line distances within the study area for the oblique imagery ranged from 100 m (30 m agl imagery) to >235 m (120 m agl imagery). All flights were conducted following Federal Aviation Administration (FAA) operating rules under the University of Hawaii at Hilo's Blanket Area Public Agency Certificate of Authorization 2015-WSA-172-COA.

2.3.2. Ground control points

Prior to the sUAS flights, six ground control points (GCPs) in the form of white crosses were deployed across the 0.8 ha study area and their three dimensional coordinates (WGS84, UTM Zone 5N) determined with a Trimble GeoXH 6000 handheld differential GPS connected to a Zephyr 2 external antenna mounted on a tripod. GCPs were occupied for 20 min each (1 s interval) and the resulting GPS data post-processed with the nearest operational base station. Based on the differential correction report, 94.6% of the corrected logged positions had an estimated accuracy of 5–15 cm. Five of the GCPs were used for image registration, with one held out as a check point to independently assess positional error.

2.3.3. Miconia plant field measurements

In order to quantify our effective detection rates, 247 individual miconia plants were located and tagged across the study site via a field campaign prior to the sUAS flights. Of these, a subset of 108 plants were surveyed with the differential GPS system described above (3 min occupation, average positional accuracy of <1.0 m for 92% of the corrected logged positions) and their crown height measured using an extendable survey pole. Plants <0.5 m in height were not included in the study. To determine the degree of obstruction above each miconia plant from overstory vegetation, a Canon EOS 5D camera with a Canon EF 15 mm 1:2.8 fisheye lens (180 degree diagonal angle of view) was mounted to an extendable pole and raised ~10 cm above the top of the miconia plant crown (Fig. 2). Photos were captured using an infrared remote trigger and brought into WinSCANOPY software package (Regent Instruments Inc., Canada) for analysis to determine canopy openness (Jarčuška et al., 2010).

2.4. Data processing and analysis

An overview of the data collection and analysis workflow is shown in Fig. 3. The sUAS-derived photos and GCP coordinates were brought into Pix4Dmapper Pro software (Lausanne, Switzerland) for processing via Structure-from-Motion (SfM) to generate an orthomosaic, digital surface model, and three-dimensional georeferenced point cloud for each flight (Westoby et al., 2012). Default settings were used for all processing steps. Based on the software-generated report, root mean squared positional errors for the ground control points were <7 cm for all flights. The mean

Fig. 2. (Left) Collecting photos of the vegetation canopy cover directly above the miconia plant crown using a fisheye lens camera mounted on an adjustable height survey pole. (Center) Example raw photos from miconia plants #60, 36, and #58, (Right) resulting sky cover classified images following processing in WinSCANOPY software (calculated openness values of 42%, 45%, and 6% from top to bottom).

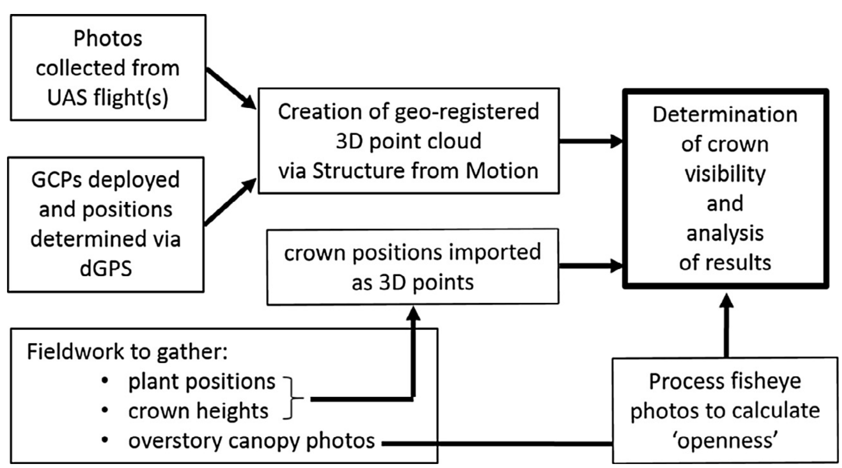

Fig. 3. Workflow for data collection, processing, and analysis.

footprint of nadir imagery (Table 1) was determined by geo-referencing three raw images collected at each flight altitude (image-to-image registration with the orthomosaic) and calculating their average area.

Following the generation of the three-dimensional canopy models, the individual crown coordinates for the surveyed miconia plants were brought into the 'raycloud' environment of Pix4dmapper Pro for assessment of their detectability for each of the different flights (Fig. 4). The raycloud environment (a linked visualization of the generated point cloud and contributing raw photos) was chosen for the detection analysis over a more traditional orthomosaic due to challenges in generating very high resolution orthomosaics in natural forest environments and the loss of pertinent 3D information. For each known miconia crown, all possible photos that contained that 3D position were visually assessed for positive detection of the plant. Positive detections were recorded when the three-dimensional position 'bulls-eye' of the targeted plant fell directly on a visible miconia leaf within at least one raw image containing that position (Fig. 4, right side). In the case of dense infestations where many individual plants of varying heights were located in close proximity to one another, positive detections were only marked for the tallest plants in order to minimize double-counting. In all cases where the positive identification of an individual miconia plant was in doubt, it was marked as 'not detected'. The known miconia detections for each flight were independently assessed by 2–3 different analysts familiar

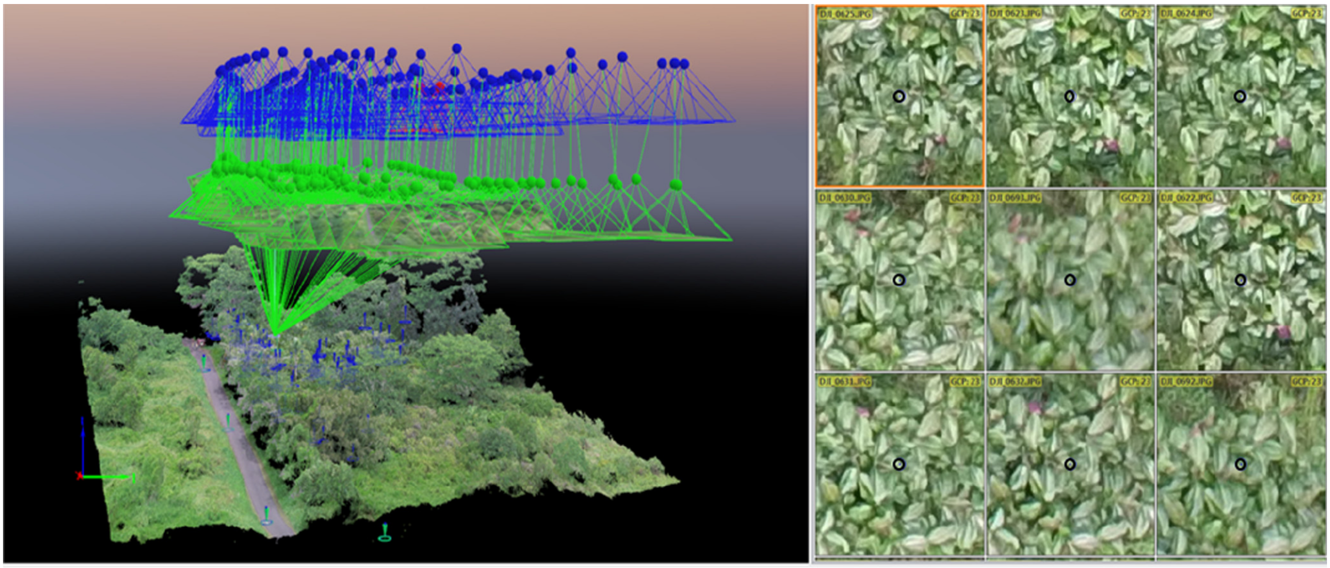

Fig. 4. (Left) Three-dimensional 'raycloud' of study area. sUAS photo locations (colored spheres-blue for initial, green for calibrated, red for uncalibrated) taken from 50 m flight altitude. Green 'rays' connecting a targeted miconia plant crown position with raw photos that include that location (a subset of the contributing raw photos, with small 'bulls-eye' targets in the center of each image, is shown on right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with sUAS imagery and invasive species. Analyst assessment time for the 108 known miconia plants took between 60 and 90 min per set of flight images. Other miconia plants within the study area that were not included in the ground survey, though present and identifiable in our imagery, were not evaluated as we were solely interested in determining detection rates using known plants.

Fisheye photos of the sky directly above each surveyed miconia plant were processed within WinSCANOPY software to estimate the visibility of miconia crowns when seen from the air (Fig. 2). We chose to use openness, defined as the fraction of open sky unobstructed by vegetation above the lens in three dimensional space and the complement of canopy closure (openness = 1 – canopy closure), as the canopy parameter for this study because openness is a three-dimensional measure of the open sky cover (Jennings et al., 1999) and we were interested in the impacts of including oblique imagery on detection rates. Ground-based, wide-angle digital photography has been shown to be a simple and accurate technique for estimating canopy openness/closure in forest environments (Paletto and Tosi, 2009). Gap fraction, a measure of canopy cover, was not chosen for this analysis as it only considers two-dimensional space. Optimal thresholds for partitioning image pixels between sky and canopy cover were determined manually for each of the fisheye photos, and openness results were reproducible to within 3%.

3. Results

Within our study area and using the protocols described above, the highest overall successful detection rate we obtained for known miconia plants was 40.7% (44 out of 108 surveyed miconia plants positively identified) for the 30 m agl flight that included both nadir and oblique images (Fig. 5). The addition of oblique photos improved detection rates at each flight altitude, although this effect generally decreased as flight altitude increased. Detection rates were inversely related to flight altitude and the corresponding GSD of the imagery. Beyond a flight altitude of 100 m (GSD of 4.37 cm), it was difficult to positively identify and discriminate individual miconia from other plants with any degree of confidence without *a priori* knowledge of their existence (Fig. 6).

We also examined the relationship between detection rates and canopy openness and plant crown height for each of the different flight altitudes (Fig. 7). Miconia plants beneath very dense overstory vegetation (openness between 0 and 10%, n = 32) were undetectable at all flight altitudes. For plants with higher openness values, detection rates were negatively related to imagery GSD and flight altitude. For the 30 m and 40 m image datasets, all known plants with openness >40% were detected. For the 50 m imagery, >50% openness was required to achieve 100% detection success, and this threshold increased to >70% openness for the 100 m flight imagery (grey shading in Fig. 7 depicts detection success for targeted plants, binned in 10% openness increments). The minimum plant crown height detected was also related to imagery GSD and flight altitude, rising from 0.7 m at 30 m agl to 2.2 m at 100 m agl.

4. Discussion

For ecosystems under threat from invasive species, effective management requires early detection of nascent populations and continual monitoring. These are resource-intensive endeavors, requiring both aerial and ground-based operations, and make up a significant portion of the $2B annual U.S. federal budget dedicated to invasive species activities (US NISC, 2013). New tools that can improve detection rates and reduce costs are therefore of great interest. Our results show that an inexpensive consumer-grade sUAS platform can be used to successfully detect individual invasive miconia plants, including plants <1 m tall and with >10% above-crown canopy openness values. Similar to other studies using high-resolution visible imagery for the detection of subcanopy targets, we found that the amount of above-crown openness is a key determinant for success (Van Andel et al., 2015; Wilson and Ference, 2001). We also found that plant detection rates decreased with increasing flight altitudes and GSD, corroborating previous work from precision agriculture (Peña et al., 2015; Torres-Sánchez et al., 2013). The addition of oblique images improved detection rates by allowing us to "see under" the canopy (Fig. 8), though that effect decreases with increasing flight altitude. Other studies have also shown oblique sUAS imagery to be useful

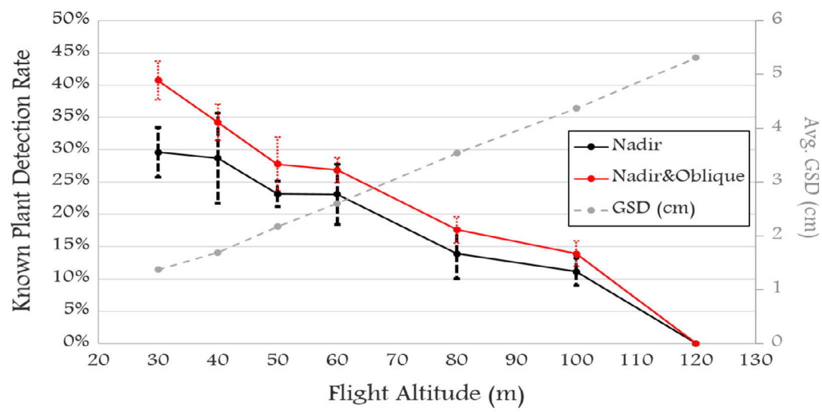

Fig. 5. Relationship between flight altitude, image GSD, and detection success for known miconia plants. Error bars depict standard deviation from multiple analyst detection assessments.

Fig. 6. Representative imagery of miconia plant #23, collected from the ground and at the different flight altitudes used in this study. Image GSD (in cm) corresponding to each flight altitude is also reported.

for detecting individual trees, although in an urban context (Lin et al., 2015).

Miconia's characteristic leaf shape, deep central vein, and purple underside provide a strong contrast with other vegetation species, allowing it to be readily identified under semi-open sky conditions in the highest resolution imagery. Our highest resolution imagery (30 m agl, 1.37 cm GSD) was extremely effective when above-crown openness was high, achieving a 100% detection rate for plants with above-crown openness values >40%, and a 69% detection rate for plants with above-crown openness values >20%. These numbers may be slightly conservative, as the 30 m dataset did not reach the recommended minimum image overlap (Dandois et al., 2015) across the entire study area due to the proximity of the vegetation canopy at that flight altitude. For the specific case of miconia, which takes four or more years of growth to reach a fruiting stage and develops most rapidly under partial and full sun conditions (Meyer, 1998), these initial results may be adequate to support a proposed "juvenilization" management approach targeting mature trees to prevent the distribution of fruit (Meyer et al., 2011). For example, an accelerated miconia intervention strategy in the East Maui Watershed has employed manned helicopter sweeps with herbicide ballistic technology (HBT) on a 60–90 day repeat interval (Leary et al., 2014). Despite the high frequency of intervention efforts, new mature targets continue to intermittently appear based on visual observations from repeat helicopter surveys. Low-cost repeated sUAS operations could economically complement and inform these types of intervention efforts by generating spatial imagery and target coordinates prior to manned operations, though plants under very dense canopy closure will invariably be missed.

While problematic, our present inability to detect plants under very dense overstory vegetation does not mean that this technique is without value. Miconia can serve as the dominant canopy (particularly as monotypic cohort patches) in Hawaiian and other rainforest settings (Meyer, 2010), and gap-phase regeneration is a known driver of seed germination for pioneer species including Melastomataceae (Ellison et al., 1993; Pearson et al., 2002). The ability to generate very high-resolution imagery over areas at-risk of invasion by alien species holds great potential for assisting with their control, but effectively integrating sUAS into invasive species management programs will require overcoming a number of existing limitations.

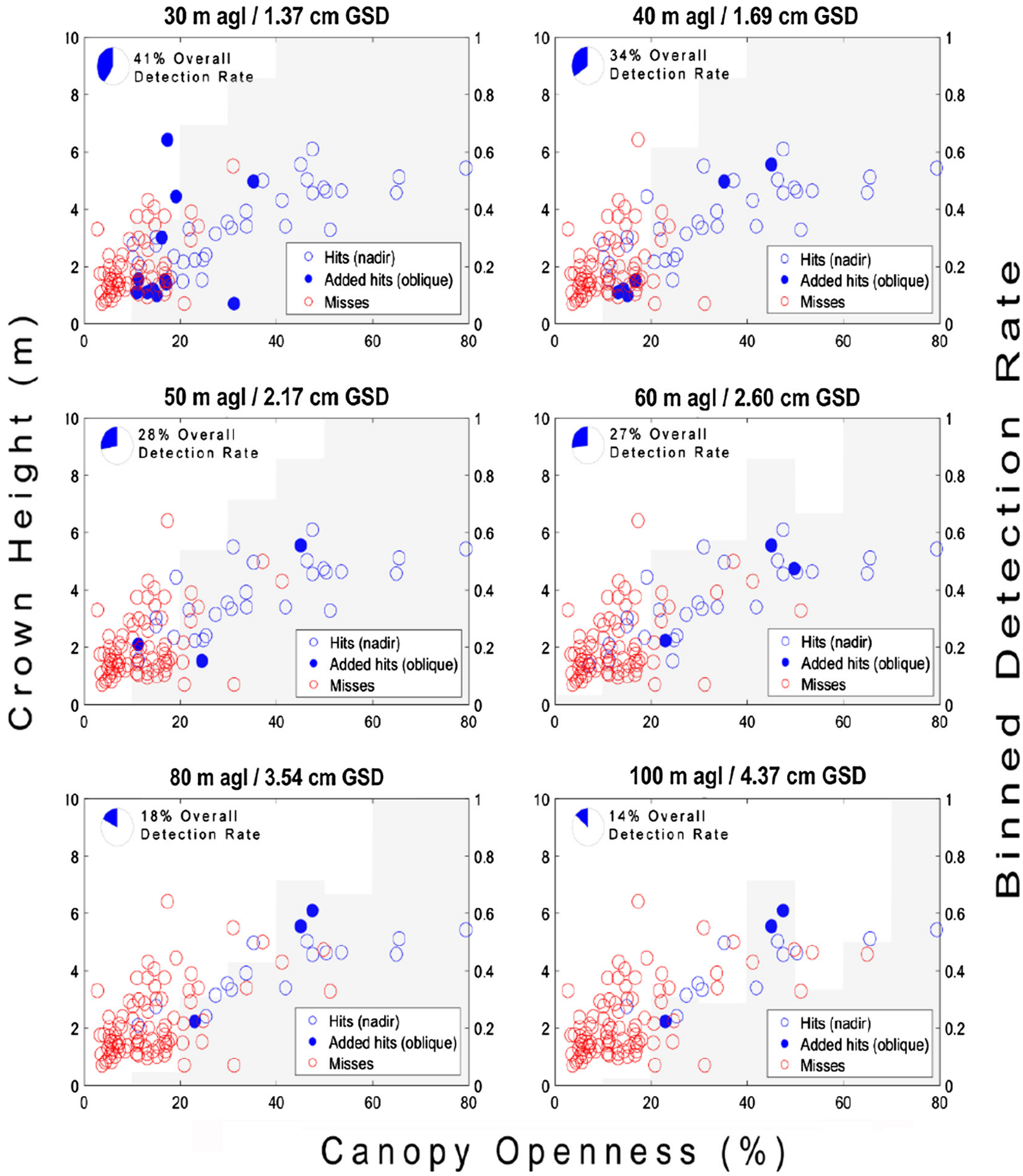

Fig. 7. Percent openness and miconia plant crown height detection plots for the different sUAS flights. Open blue circles are positive detection 'hits' within the nadir images, filled blue circles are additional positive 'hits' from the oblique photos at that same altitude, and open red circles are misses. Grey shading represents binned detection rates based on 10% openness increments (0–10%, 10–20%, etc.). Pie charts indicate overall known plant detection rate using all images at that altitude. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Two of the most important of these are limited flight times and regulatory visual line-of-sight requirements. For the DJI Inspire-1 multirotor platform used in this study, maximum flight times are 16–18 min. Depending on the altitude, airspeed, and other flight conditions, this translates into nadir coverage areas of roughly 20–30 ha per battery, which is sufficient for small areas but inadequate for monitoring large forest parcels. Oblique imagery collection requires additional flight time, at least for UAS platforms with a single camera. Advances in UAS battery and fuel technology are progressing rapidly (Bole et al., 2014; Kaya et al., 2016; Lee et al., 2015), but short flight times will likely constrain the use of inexpensive sUAS platforms for the near future.

Another operational aspect that must be considered, at least in the United States and other countries with strict UAS airspace regulations, is the visual line-of-sight requirement. Currently, the United States requires an exemption from the Federal Aviation Administration for flight plans that include 'extended' or beyond line-of-sight operations (USDOT, 2016). In dense forest environments without access to adequate vantage points, this presents a greater limitation on acquiring imagery than any technological obstacle. Fortunately, beyond line-of-sight UAS operations are becoming more common and easier to obtain (Atkins, 2014; Naftel, 2009; Stevenson et al., 2015).

For this work we focused on determining the environmental and operational parameters that impact our ability to detect individual miconia plants, using a set of known plant locations within a heavily invaded tropical forest environment. To our knowledge, this is the first attempt to quantify these parameters for a subcanopy invasive species using a sUAS platform carrying a RGB camera. Similar trials could be conducted for other invasive plant species and environments, and the results would vary based on the phenological and morphological characteristics of the target

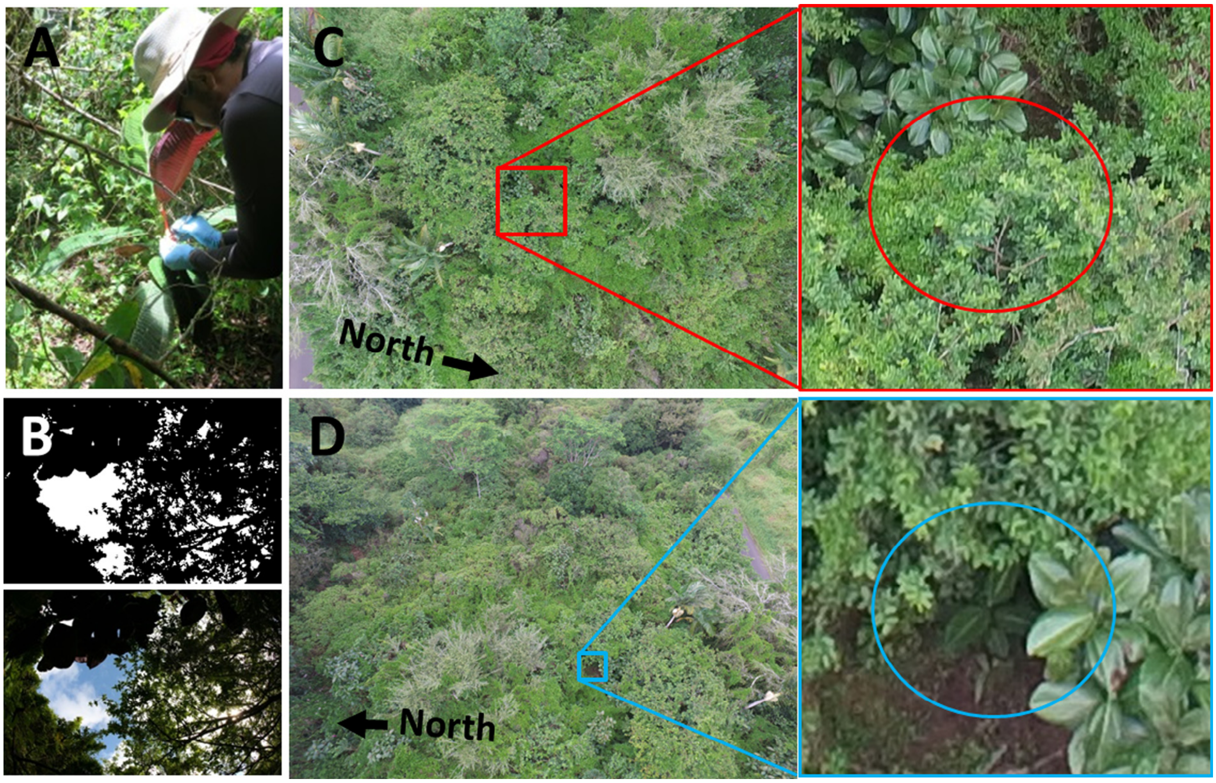

Fig. 8. Improved detection ability using oblique imagery. (A) Field survey to mark 1.1 m tall miconia plant #85. (B) Fisheye sky cover photos above plant #85 (top, classified; bottom, raw) showing 13.14% openness. (C) Nadir photo over plant #85 (30 m agl), inset close-up of #85 location shows overstory canopy and no visible miconia plant. (D) Oblique photo of same (30 m agl), inset shows clearly visible plant.

species and the contrast with surrounding vegetation types (Huang and Asner, 2009; Hung and Sukkarieh, 2015; Torres-Sánchez et al., 2013). While we endeavored to ensure the work reported here is accurate, possible sources of error that may influence our results include positional error in the surveyed plant locations, misidentification of plants in locations with multiple miconia in close proximity, mislabeling of plants during the fieldwork component, and the problem of *a priori* knowledge for analysts repeatedly evaluating the same area with different sets of imagery. While important to acknowledge, we believe that the combined errors likely affect only a small number of plants in our study and should not affect the overall findings.

We believe the true value of this work will lie in combining our findings with robust plant detection algorithms and more capable UAS platforms and instrumentation, to produce automated detection systems that can continually survey and monitor meaningful expanses (100 s–10,000 s ha) of threatened forest ecosystems. Computer vision algorithms, including machine learning and object-based image analysis, are making it possible to rapidly and autonomously detect targets within imagery (Hu et al., 2015; Krizhevsky et al., 2012; Penatti et al., 2015; Reyes et al., 2015), although the high noise environments of tropical forests present distinct challenges that still need to be overcome. With continued improvements in sensor resolution and miniaturization, battery capacity, and detection algorithms, sUAS deployed over areas of interest could greatly improve detection rates while reducing operational costs by decreasing reliance on manned helicopter and ground-based surveys. Incorporating lidar or other instrumentation able to penetrate the canopy layer to these platforms, along with aerially-deployed herbicide applicators such as HBT (Leary et al., 2013; Rodriguez et al., 2015), would further improve their efficacy.

Along with the sUAS-derived imagery itself, which has been the focus of this study, the ability to generate three dimensional digital aerial photogrammetric point clouds via SfM provides additional capabilities that can improve our ability to characterize forest structure and detect sub-canopy plants. While sUAS-derived photogrammetric point clouds are not as comprehensive as those generated from lidar instruments, they have been used to measure a variety of forestry metrics, such as vegetation height, stem volume, and canopy cover (Fraser et al., 2016; Puliti et al., 2015; Wallace et al., 2016). sUAS-derived estimates of canopy closure, in particular, could be used to provide a means of attaching a confidence measure to the positive and negative detections across a forested environment (i.e., more confidence should be assigned to a 'no detections' result within an area of high canopy openness than within an area of moderate or low canopy openness). This type of analysis and supporting information, while not explored here, could allow managers to determine if certain areas may require additional resources and monitoring and allow them to more efficiently allocate their limited resources.

5. Conclusions

Early detection of invasive species via remote sensing is of major interest for ecological and economic reasons, but even with specialized instrumentation, detecting subcanopy vegetation species has proven difficult. Our results demonstrate that an inexpensive, consumer-grade small UAS platform can detect an invasive species -- miconia -- in a complex tropical forest subcanopy setting under certain threshold conditions. The ability to generate imagery on-demand with a ground GSD <2 cm made it possible to detect individual miconia plants under heavy overstory vegetation cover

(>10% openness), and the inclusion of oblique images improved detection rates by >10% for the highest resolution imagery dataset. Overall detection rates were negatively related to flight altitude, and no miconia plants were confidently detected using imagery with a GSD >5 cm or under canopy cover with <10% openness. We believe that sUAS technology can provide a safer and more economical alternative to manned aerial surveillance (Ogden, 2013), especially in remote and challenging tropical environments. To our knowledge, this is the first study that has systematically assessed the impacts of flight altitude, camera look angle, and canopy openness above targeted plant crown on invasive plant detection rates using a sUAS platform.

Acknowledgments

Funding: this work was supported in part from a grant provided by the Hawaii Invasive Species Council. The authors would like to acknowledge the following for their field assistance and help with this project: Arthur Cunningham, Jamison Domingsil, Rose Hart, Heather Kimball, Keely Roth, the Fall 2015 GEOG385 students, and the BIISC Early Detection Team. The authors would also like to thank two anonymous reviewers and Dr. James Leary, Roberto Rodriguez, and Sharon Dansereau for their editorial comments and input.

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