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Historical Land-Cover Classification for Conservation and Management in Hawaiian Subalpine Drylands[1]

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Abstract: We used aerial photography from 1954 and airborne LiDAR and imaging spectroscopy from 2008 to infer changes in extent and location of tall-stature woody vegetation in 127 km^2 of subalpine dry forest on the island of Hawai'i (Pōhakuloa Training Area), and to identify 25.8 km^2 of intact woody vegetation for restoration and management. Total cover of woody vegetation was 54.7 km^2 in 1954 and 58.6 km^2 in 2008. Approximately 28.9 km^2 underwent woody vegetation change (22.7%) between 1954 and 2008. Increases in woody vegetation cover occurred in 16.4 km^2, and 12.5 km^2 represented reduction of woody vegetation cover (12.9% and 9.8% of the 127 km^2 study area, respectively). Our findings suggest that 3.9 km^2 (3.0%) experienced a net increase in woody vegetation cover between 1954 and 2008. Spatial patterns suggest that fires may be the primary driver of reductions in woody vegetation cover. Increases could be due to regeneration of dry forest trees or measurement errors associated with historical imagery. Areas remaining in woody vegetation cover over the 53-yr study interval can be targeted for restoration and management. We discuss challenges to integrating historical photography with contemporary conservation and management in Hawai'i and the Pacific and we outline additional studies that would help to improve estimates. The methods and analysis are general and could be applied to other dryland ecosystems with complex volcanic substrates in Hawai'i and the Pacific.

A CHALLENGE TO conservation and restoration projects is defining management objectives in the context of historical impacts. Whether current patterns represent natural or modified conditions is usually unknown in the absence of detailed records (White and Walker 1997). Even when long-term monitoring is available, it may be restricted to areas that are not representative of conditions on large landscapes. One way to acquire this information is through interpretation and analysis of historical aerial photography (Herwitz et al. 2000, St.-Onge et al. 2008). Linking historical records with advanced remotely sensed data, such as measurements from airborne LiDAR (Lefsky et al. 1999) or imaging spectroscopy (Ustin and Schaepman 2009), could help to interpret causes of contemporary patterns.

Pōhakuloa Training Area (PTA) is a 438 km^2 subalpine tropical dryland ecosystem on the island of Hawai'i (Figure 1). It is an

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active U.S. Army training installation and contains 15 species of federally listed threatened and endangered plants and the endangered honeycreeper, Palila (*Loxioides bailleui*) (Shaw and Castillo 1997, Pratt et al. 1998, Sakai et al. 2002). Although they were once extensive, clearing by Polynesians and European settlers, and introductions of exotic plant and animal species have reduced tropical dry forests in Hawai'i to <10% of their original extent (Bruegmann 1996). Because these forests were once the most diverse in the archipelago (Rock 1914), their decline is an important contributor to the loss of Hawaiian biota.

Introductions of exotic grasses have promoted conversion of dry forest to grasslands and an ongoing grass-fire cycle (D'Antonio and Vitousek 1992). Ungulates threaten to re-

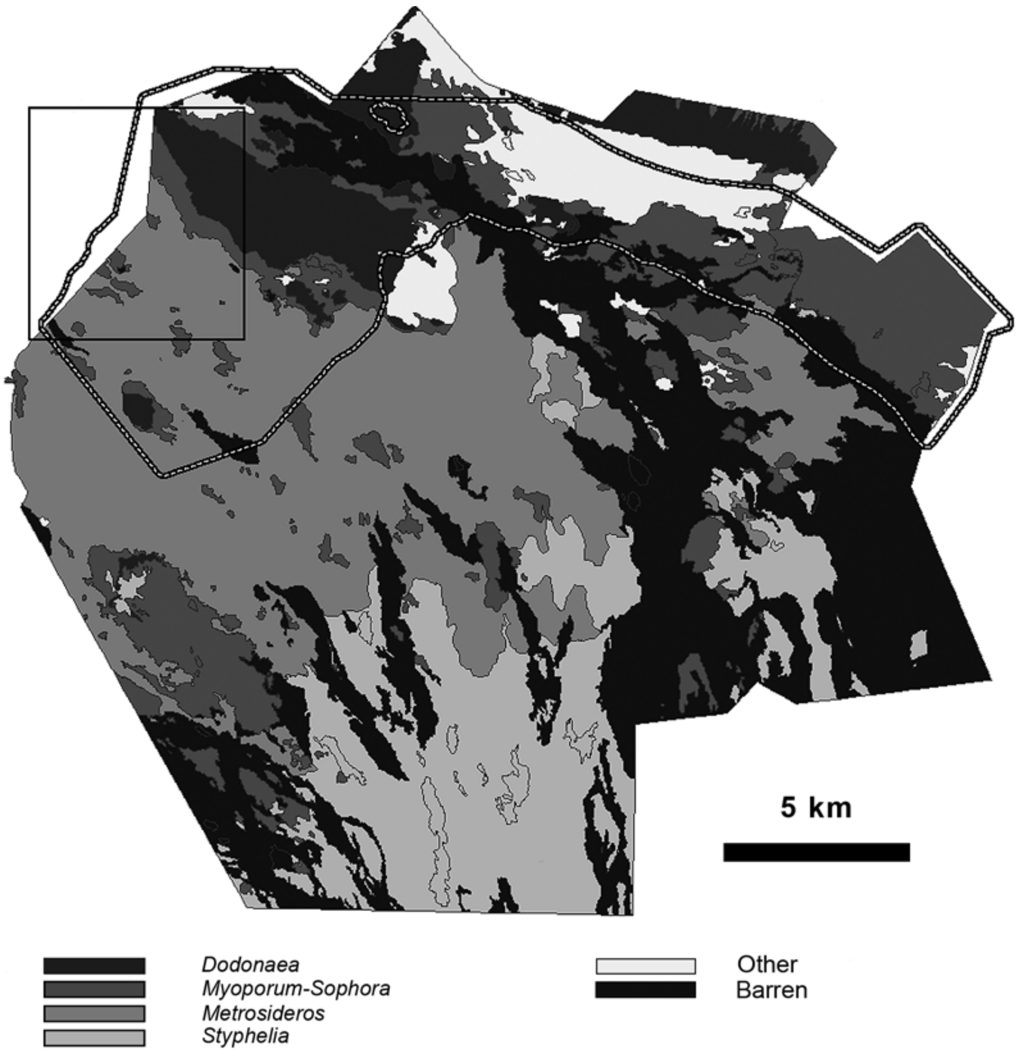

Figure 1. Pōhakuloa Training Area on the island of Hawai'i, showing dominant vegetation types (Shaw and Castillo 1997). The extent and dynamics of woody vegetation were analyzed using contemporary airborne remote sensing and historical aerial photography in the area outlined (black and white line, 127 km^2). The black box is shown in detail in Figure 3. The "Other" class includes *Chamaesyce* treeland, *Chenopodium* shrubland, disturbed areas, *Pennisetum* grassland, and *Eragrostis* grassland.

duce biological diversity of already impoverished communities through browsing (Cabin et al. 2000, Kellner et al. 2011). Like other dryland systems in Hawai'i, management at PTA emphasizes risk reduction of extensive fires, removal of feral ungulate populations, and restoration of native species (Cuddihy and Stone 1990, Smith and Tunizon 1992, Cabin et al. 2000, Kellner et al. 2011). However, a challenge to developing robust management plans is correctly interpreting contemporary patterns of vegetation structure and condition. Which areas are relatively intact native communities, and which have been produced by historic fires or other factors has not been clearly defined.

PTA contains 24 unique vegetation communities and substrates from numerous volcanic eruptions (Rhodes and Lockwood 1995, Shaw and Castillo 1997). Volcanic substrates include both pāhoehoe and 'a'ā types of lava and volcanic cinder cones. Three vegetation communities account for 52% of the PTA landscape. *Metrosideros polymorpha* woodlands are common on Mauna Loa substrates <3,000 yr old (Stemmermann and Ihsle 1993). They are intact native communities and sometimes support understory with *Dodonaea viscosa* and *Styphelia tameiameiae*. *Dodonaea viscosa* shrublands are on Pleistocene Mauna Loa and Mauna Kea substrates that support widespread exotic plant species, including *Pennisetum setaceum* and *Senecio madagascariensis*. Short-stature tree communities dominated by the endemic tree species *Myoporum sandwicense* and *Sophora chrysophylla* are on intermediate-aged substrates from Mauna Loa and Mauna Kea Volcanoes.

Here, we quantitatively compared archival aerial photography (1954) and contemporary airborne remote sensing (2008) to assess changes in the extent of woody vegetation over time. Our analysis integrates visual interpretation of historical woody vegetation cover from aerial photos with contemporary measurements from airborne LiDAR and imaging spectroscopy to infer the frequency, location, and extent of woody vegetation changes in a 127 km^2 subset of PTA. We performed this analysis to improve understanding of the recent disturbance history of this dryland ecosystem and to identify areas that remained in woody vegetation during the previous 54 yr, which can serve as targets for restoration and management.

MATERIALS AND METHODS

Historical Aerial Photography

Black-and-white aerial photos were acquired in October 1954 by the United States Navy from a fixed-wing aircraft at approximately 1:52,000 and 1:42,000 scale. Original photographs were digitized at 1,000 and 1,200 dots per inch, respectively. We resampled these images to 1.5 m resolution, and the study area encompassed 23 individual photographs. Due to variable solar illumination among photographs, we processed each digitized photo using Adobe Photoshop Elements version 3.1 to improve the consistency of visual interpretation and image analysis. We eliminated areas near edges with strong geometric distortion and darkening, and manually adjusted image brightness and contrast to improve apparent visual consistency. We processed all images to generate a single image mosaic, which we georeferenced using ENVI 4.3 and a 2.2 m LiDAR digital terrain model (DTM, see next section). Overall root mean squared error (RMSE) was 5.5 m.

Contemporary High-Resolution Surface Cover Mapping

The Carnegie Airborne Observatory (CAO) is an integrated airborne remote sensing and analysis system developed to acquire spatially detailed and extensive measurements of structural and biochemical properties of vegetation (Asner et al. 2007). In this analysis, it combined the airborne visible and infrared imaging spectrometer (AVIRIS) with a LiDAR sensor and 3-D navigation technology (i.e., the CAO Beta system [Asner et al. 2007]). We used height measurements from LiDAR to quantify vertical and horizontal vegetation structure, and reflectance observations from the imaging spectrometer to estimate the fractional cover of photosynthetic vegetation, nonphotosynthetic vegetation, and barren volcanic substrate using methods detailed by

Asner and Heidebrecht (2002) and Asner et al. (2005).

Airborne data were collected on 7 January 2008, which is 53 yr after collection of aerial photography. The LiDAR system was configured to record the locations of up to four reflecting surfaces for every emitted laser pulse at 1.1 m laser spot spacing. Horizontal and vertical accuracy of the LiDAR system is discussed in detail in Asner et al. (2007). Laser ranges were combined with navigation information to determine the vertical and horizontal locations of reflecting surfaces. To estimate canopy height aboveground, LiDAR elevation measurements were processed to identify which laser pulses were likely to have penetrated vegetation and reached the ground surface. These points were then used to interpolate a raster digital terrain model (DTM) for the ground surface. The remaining points were used to interpolate a digital surface model (DSM) for the vegetation canopy. Subtraction of the DTM from the DSM produced a model of canopy height aboveground (digital canopy model, DCM). The elevation models were generated at 2.2 m resolution, and all subsequent analyses were performed directly on the elevation models.

Classification of Land-Cover Types Using Historical Photography

We used object-based classification to distinguish four land-cover types: grasses and forbs, tall-stature woody vegetation, short-stature woody vegetation, and lava and exposed soil (Table 1). We applied a multiresolution segmentation using Definiens eCognition version 5.0. The segmentation parameters were 20, 0.8, and 0.7 for the scale factor, color, and compactness, respectively. We then aggregated these objects and classified image segments using a nearest-neighbor classification. Training sites were identified that described each class using field surveys and a contemporary vegetation map (Figure 1) (Shaw and Castillo 1997).

Evaluation of Land-Cover Classifications

We evaluated land-cover classifications from historical photography by comparing results with contemporary airborne remote sensing, field surveys, and vegetation maps (Shaw and Castillo 1997). We classified contemporary airborne remote sensing data into the same four land-cover classes (Table 1) by using a DCM and fractions of photosynthetic vegetation, nonphotosynthetic vegetation, and barren substrate. We also conducted field studies to determine whether classifications using historical photography and contemporary remotely sensed data accurately identified features on the ground. We visited sites in the field that were well distributed throughout the western side of the PTA landscape in November and December 2008. At each site, we traveled by four-wheel drive and compared classification results with conditions on the ground using a hand-held tablet personal computer with a global positioning system. We used features that were identifiable in the field and within imagery (such as individual trees or shrubs) to ensure that we were in the correct location in the field before determining whether classifications were accurate.

TABLE 1

Land-Cover Classifications Applied to Historical Aerial Photography

Land-Cover Class	Description
Grass/forb	Short-stature herbaceous vegetation cover representing grasses and forbs
Tall woody	Tall-stature woody vegetation typically exclusively *M. polymorpha* but occasionally *S. chrysophylla* and *M. sandwicense*
Short woody	Short-stature woody vegetation dominated by *S. chrysophylla* and *M. sandwicense*
Barren	Barren volcanic substrate

Historical Change in Woody Vegetation

Assessment of land-cover classifications in the field using historical aerial photography indicated that they did not accurately distinguish the four land-cover classes. The only features that were consistently represented in digitized historical photos were shadows cast by large isolated objects (trees and shrubs). We therefore processed imagery from historical photos and contemporary LiDAR to generate binary classifications of tree presence and absence based on apparent shadows and used these classifications to determine the extent and change in woody vegetation cover. Binary images for each historical photo were created by identifying a threshold that distinguished shadows from nonshadow objects. Visual examination indicated that the threshold was 90. Therefore, we assigned all pixels $\leq$90 a value of 0 and all pixels >90 a value of 1. Although these analyses were performed on the 1.5 m images, we aggregated pixels to summarize woody vegetation cover within units of 20 by 20 m. This aggregation was selected to produce a size that would minimize small geometric offsets between images while retaining spatial detail. We then subtracted the 2008 aggregations from the 1954 aggregations to produce a map of woody vegetation change.

RESULTS

Field assessment of land cover classifications using historical aerial photography indicated that classification maps were not accurate (Figure 2, Table 2). Grasses could not be distinguished from *Myoporum-Sophora* dry forest using historical imagery, and field studies indicated that *Myoporum-Sophora* dry forest was not consistently distinguishable from tall-stature tree communities dominated by the tree species *M. polymorpha*. We therefore focused on changes in the extent of woody vegetation using binary classifications of tree presence (Figure 3).

Total cover of woody vegetation was 54.7 km^2 in 1954 and 58.6 km^2 in 2008. Approximately 28.9 km^2 underwent woody vegetation change (22.7%) between 1954 and 2008. Increases in woody vegetation cover occurred in 16.4 km^2, and 12.5 km^2 represented reduction of woody vegetation cover (12.9% and 9.8% of the 127 km^2 study area, respectively). Our findings suggest that 3.9 km^2 (3.0%) experienced a net increase in woody vegetation cover between 1954 and 2008.

Although some areas of the landscape may have experienced regrowth of woody vegetation during the 53 yr interval, visual assessments and field studies suggested that LiDAR data were capable of detecting trees and shrubs that were obscured within historical aerial photos, so that some apparent regrowth could be attributable to improved detection of small trees and shrubs using LiDAR. In addition, the crown area of trees detected by LiDAR was larger than the area of the same trees estimated using historical imagery (data not shown). Analysis of reductions in

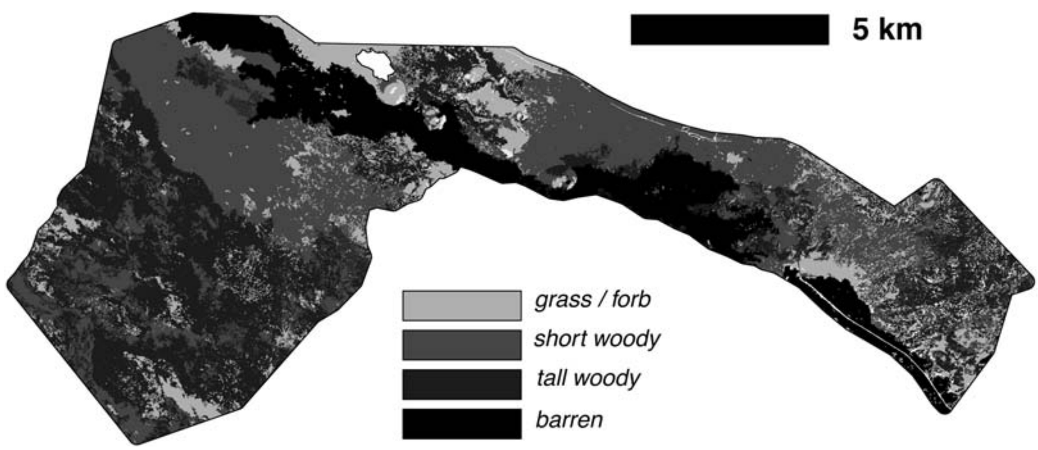

FIGURE 2. Classification of historical aerial photography to distinguish grasses and forbs, tall-stature woody vegetation, short-stature woody vegetation, and barren volcanic substrate.

TABLE 2

Comparison of Land-Cover Classifications from Historical Aerial Photography (Columns) and Contemporary Composition (Rows) from Shaw and Castillo (1997)

Vegetation Communities	Grass/Forb	Tall Woody	Short Woody	Barren
Dodonaea	26.6 (5.37)	5.7 (5.60)	44.1 (29.68)	0.9 (0.33)
Metrosideros	17.2 (3.47)	49.1 (48.20)	20.1 (13.50)	0.3 (0.11)
Myoporum-Sophora	46.4 (9.37)	43.8 (42.97)	32.6 (21.95)	18.6 (6.79)
Barren	9.1 (1.84)	1.4 (1.37)	3.2 (2.13)	80.2 (29.36)
Styphelia	0.6 (0.13)	0.0 (0.00)	0.1 (0.07)	0.0 (0.00)

Note: Numbers are the percentage of pixels in each historical land-cover class that were represented by the contemporary community type, followed by the area (in square kilometers). For example, 18.6% of the area in barren land cover in historical photography was *Myoporum-Sophora* in Shaw and Castillo (1997), which represents 6.79 km^2.

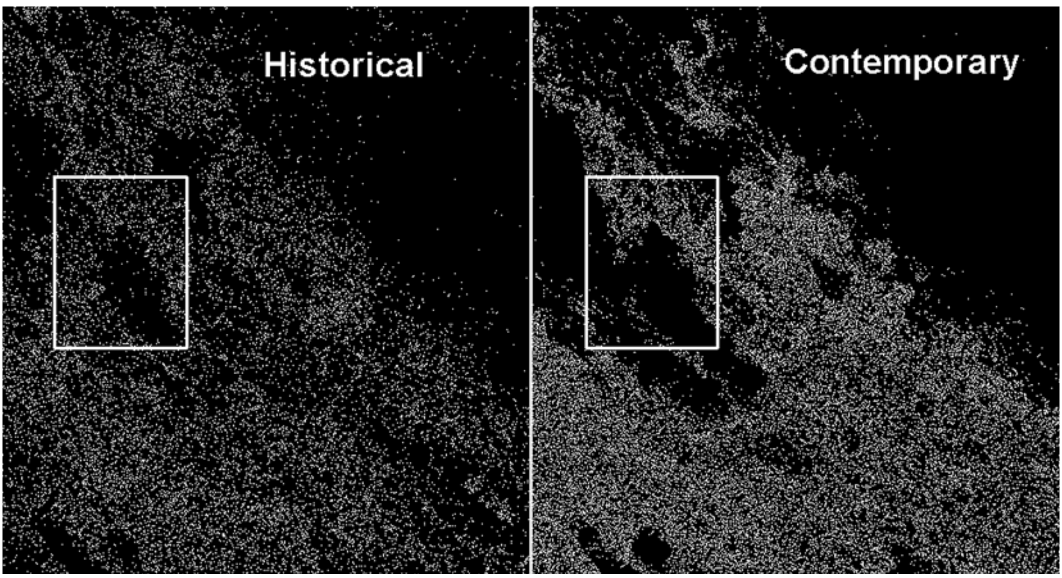

Figure 3. Comparison of locations of tall-stature woody vegetation (individual trees) using contemporary LiDAR remote sensing (2008) and historical aerial photography (1954). The data are shown as binary values, where white indicates tree presence, and black indicates tree absence. The box indicates areas of confirmed reduction in woody vegetation cover.

vegetation cover is conservative with respect to these sources of uncertainty.

Some areas now dominated by shrubs formerly contained taller, arboreal canopies. This is apparent for a 36 km^2 sample based on a visual examination of Plate I, which indicates spatial correspondence between areas of net reduction in woody vegetation cover and communities represented by the tree species *M. sandwicense*, *S. chrysophylla*, and *M. polymorpha*. Few changes were detected in shrubland communities currently dominated by *D. viscosa*.

DISCUSSION

We used a combination of historical aerial photography and contemporary airborne remote sensing to quantify changes in the spatial extent of woody vegetation in a subalpine tropical dry forest landscape on the island of Hawai'i. Our results suggest that 9.8% of the landscape (12.5 km^2) experienced a net reduction in woody vegetation cover between 1954 and 2008. Visual examination of the spatial patterns of vegetation changes suggests that most changes occurred in contiguous patches that are consistent with the known fire history of this landscape. However, attributing causes to specific changes will require further study, such as paleoecological investigations using isotopes to quantify changes in vegetation cover or the frequency of charcoal in soils (Chadwick et al. 2007).

Unlike the positive, regenerative role that natural wildfires play in many continental systems, contemporary fires in Hawai'i are a largely destructive force. They can convert forests into grasslands dominated by exotic plant species (Hughes et al. 1991). The majority of native Hawaiian trees and shrubs have evolved in isolation from the influence of frequent and widespread fire, and therefore lack adaptations to recurring fires and are unable to recover from fire-induced destruction of seed banks and plants (Mueller-Dombois 1981). Similarly, Aplet et al. (1998) demonstrated that repeated occurrence of grass-fueled fires in dry forest ecosystems on the leeward side of Hawai'i have nearly eliminated woody vegetation and facilitated the establishment of alien grasslands dominated by *P. setaceum*. Knowledge gained from a landscape and historical perspective, as provided in this study, can guide restoration and protection efforts toward areas that have been or remain forested, and are thus likely to have high potential for restoration and management based on their protection from grass-fueled fires. Reestablishment of forests may reduce the threat and spread of fire in dryland systems (Funk and McDaniel 2010). Because tree canopies reduce air temperatures, wind speed, and available light but increase relative humidity and soil moisture (Loik and Holl 1999), restoration of tree canopies in grasslands could reduce fuel loads and facilitate establishment and persistence of tree seedlings.

Although our original objective was to quantify vegetation changes in both woody and nonwoody communities during a period of increased fire frequency and size in Hawai'i (Larosa et al. 2008), a number of challenges restricted our analysis to tall-stature woody vegetation. Next we discuss the nature of these limitations and suggest additional studies that would help to improve the estimates reported here or eliminate sources of uncertainty.

Problems directly related to historical aerial imagery were the most serious limitations. First, the historical photos are a crude brightness metric. This means that dark objects appear to be black in the images, and light objects appear to be white. Intermediately illuminated objects take on shades of grey. This is inherently limiting, because the relationship between brightness and vegetation cover is complex. Woody vegetation, such as individual tree canopies, appeared as dark objects within historical photos. However, photosynthetic grasses were bright and closely matched with barren soil, so that simple thresholds could not be used to distinguish vegetated from nonvegetated parts of the image. In addition, the 1954 aerial photography was acquired when the sun angle and camera orientation caused inconsistent illumination within photos. This presented challenges to a comprehensive and internally consistent analysis. Analyses of spatial variability could be used in cases where there are complex associations between vegetation and brightness, but highly variable lava substrates at PTA, which range in color from light red to deep black depending on substrate age and oxidation of iron, and in shape from smooth pāhoehoe to rough 'a'ā boulders, confounded this approach.

Using shadows as a proxy for woody vegetation cover improved classification accuracy within tall-stature *M. polymorpha* woodlands, but the approach was prone to uncertainty in other woody communities. Crowns within *Myoporum-Sophora* dry forests are typically <5 m in height and appeared to cast larger shadows than *M. polymorpha*. Because differences in shadow sizes were restricted to historical imagery, this created potential for overestimation of the frequency of woody vegetation loss in *Myoporum-Sophora* dry forests relative to *M. polymorpha* woodlands. In addition, substrates associated with *M.*

sandwicense and *S. chrysophylla*, which are older substrates with substantial soil development in comparison with *M. polymorpha* woodlands (Stemmermann and Ihsle 1993), were sometimes difficult to distinguish from vegetation.

Contemporary classifications based on fractions of photosynthetic vegetation and nonphotosynthetic vegetation also produced poor accuracy. Field checks confirmed that there was substantial overlap between classes, primarily because grasslands were photosynthetic at the time of image acquisition, so that signals associated with grasses and woody vegetation were not consistently expressed in fractions of photosynthetic and nonphotosynthetic vegetation. Because dry landscapes in Hawai'i have strong seasonal and interannual patterns in vegetation phenology (Elmore et al. 2005, Kellner et al. 2011), future efforts should attempt to minimize differences in phenology between dates of image acquisition if the objective is a direct comparison of vegetation structure or cover.

Finally, the short stature of shrublands at PTA created challenges for LiDAR estimation of vegetation height in those areas. The configuration of the LiDAR system at the time of data acquisition prevented detection of inbound pulses <2 m apart. Because large areas of the landscape at PTA contain shrub vegetation that is <2 m in height, this effectively meant that it was impossible for the sensor to receive a ground return and vegetation return for a single laser pulse in those areas of the landscape. Combined with the fact that shrub canopies lack complex heterogeneity of taller forests or isolated trees, it is possible that laser returns from shrub canopies could have been misclassified during data processing as ground returns, leading to an underestimation of vegetation cover based on LiDAR data. Therefore, the use of LiDAR data was the most effective for woody classification in tall-stature *M. polymorpha* communities, similar to the use of aerial photography.

The results of this study have shown how historical and contemporary remotely sensed data can be integrated to characterize changes in the extent of tall-stature woody vegetation in a tropical dry forest landscape. These findings suggest a 3.9 km^2 (3.0%) net increase in the extent of tall-stature woody vegetation. More important, they indicate that 25.8 km^2 of the landscape remains in woody vegetation cover. These areas can be targets for conservation or restoration activity. Further studies should assess in detail the nature of LiDAR sampling within short-stature woody communities and should target image acquisition during intervals when phenology patterns will be distinct among classes of interest.

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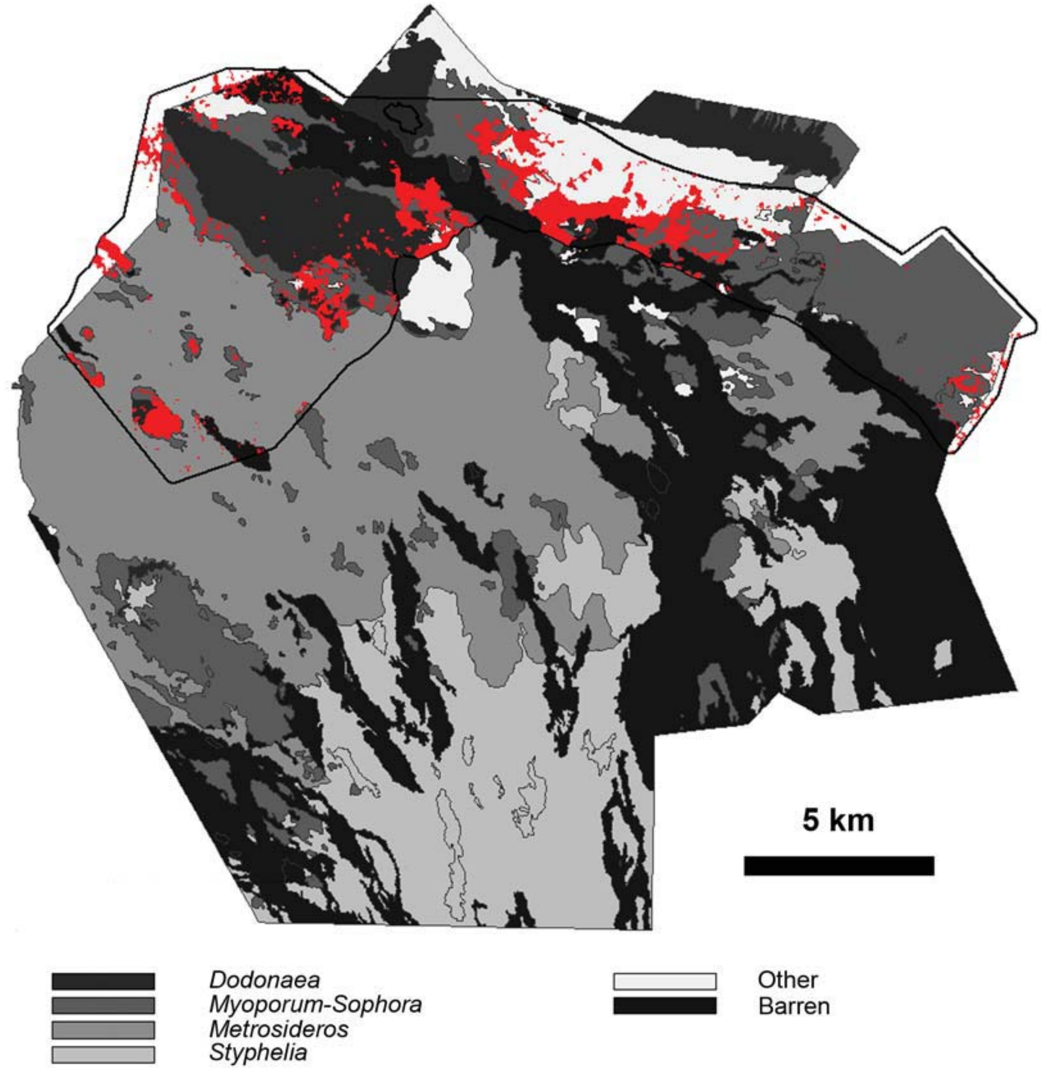

PLATE 1. Net reduction in woody vegetation cover between 1954 and 2008 (red areas). Many apparent changes were associated with short-stature woody vegetation and could be spurious. Field studies indicate that spurious changes were restricted to short-stature woody vegetation dominated by the tree species *S. chrysophylla* and *M. sandwicense*.

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