Satellite Monitoring of Vegetation Phenology and Fire Fuel Conditions in Hawaiian Drylands

Andrew J. Elmore* and Gregory P. Asner
Department of Global Ecology, Carnegie Institution of Washington, Stanford, California

R. Flint Hughes
Institute of Pacific Islands Forestry, USDA Forest Service, Hilo, Hawaii

Received 3 March 2005; accepted 26 August 2005

ABSTRACT: Grass-fueled fires accelerate grassland expansion into dry Hawaiian woodlands by destroying native forests and by producing a disturbance regime that favors grass-dominated plant communities. Knowledge of grassland phenology is a key component of ecosystem assessments and fire management in Hawaii, but diverse topographic relief and poor field-sampling capabilities make ground studies impractical. Remote sensing offers the best approach for large-scale, spatially contiguous measurements of dryland vegetation phenology and fire fuel conditions. A 500-m spatial resolution, 8-day temporal resolution Terra Moderate Resolution Imaging Spectroradiometer (MODIS) satellite time series of photosynthetic vegetation (PV), nonphotosynthetic vegetation (NPV), and exposed substrate conditions was developed for the island of Hawaii between 2000 and 2004. The results compared favorably with similar measurements of drylands from higher-resolution aircraft data. The satellite time series was compared with available environmental data on precipitation, fire history, and grazing intensity. From these analyses, the temporal patterns of PV and its conversion to NPV and finally to bare substrate
were observed. An NPV buildup following fire of 7–8 yr was projected, and more heavily grazed lands were found to exhibit reduced NPV cover, most notably during the summer fire season. These results demonstrate the effects that land use and disturbance history have on fire conditions, and they support the concept that grazed lands managed to reduce litter buildup pose a lower risk of fire across ample geographic scales. Time series of satellite observations with modern analysis techniques can be used with environmental data to support a regional fire-monitoring program throughout Hawaii.

**KEYWORDS:** Hawaii; Wildfire; Remote sensing

1. Introduction

Grassland wildfire exerts a strong control on the structure and functioning of semiarid ecosystems and leads to large economic losses when fire spreads into regions of development (Dellasala et al. 2004). Fire is a defining characteristic of grasslands, helping to build complex mosaics of plant communities of various stages of succession (Harrison et al. 2003). Fire conditions are influenced by topography and weather, but fuel quantity is the principal ecosystem structural component that is required for fire. Furthermore, fuel quantity is the only fire component that can be modified by human land use, making it a key parameter for measurement in managed grasslands worldwide.

Grass-fueled fires are a particular problem in systems where grasses have invaded woodlands, such as in the Hawaiian Archipelago (D’Antonio and Vitousek 1992). Hawaii contains unique woodland ecosystems with a well-documented proliferation of exotic African grasses across its drier landscapes found on the leeward sides of the islands (Hughes et al. 1991). African grasses were introduced to Hawaii for grazing purposes and have expanded in geographic extent during the last century. They are now present in nearly all dry to mesic environments on Hawaii and have expanded similarly within many other tropical regions of the world (Parsons 1970). Following introduction, native forest conversion to grassland occurs when recruitment of native tree species cannot compete with invasive grasses under grazing pressure (Hughes et al. 1991). The steady decline of forest area and the increased dry grass biomass lead to higher fire frequency, speeding woodland, and forest destruction at larger geographic scales than occurs with grazing alone (D’Antonio and Vitousek 1992). In many areas of Hawaii, and on the northwest coast of the “Big Island” of Hawaii in particular, there has been a near total replacement of endemic forests by invasive grasses. As a result, grass-fueled fires have become a critical issue of public safety following several large fires near suburban and urban areas (NPS 1990).

Fire will continue to be a dominant component of these newly created Hawaiian grasslands; however, preservation of the remaining endemic forests requires some level of fire exclusion. Understanding the geographic distribution and phenology (i.e., timing of fuel development) of fire-prone grasses may be key to fighting fires and to performing precautionary treatments throughout Hawaii. Field-based techniques have identified useful options for reducing fire risk, including cattle grazing (Cabin et al. 2000) and controlled burns (NPS 1990). However, the effectiveness of these techniques requires detailed information on where the grass fuel load is accumulating, and its location relative to human settlements, endemic forests, and
prevailing winds. Furthermore, no broadscale studies have investigated the relationship between grazing and fire conditions in Hawaii, yet grazing has been identified as a possible method of fire control (Blackmore and Vitousek 2000). Grazing can reduce the risk of fire via at least two mechanisms: it reduces standing litter in grasslands (Heitschmidt et al. 1987; Shariff et al. 1994), and it can shift plant community composition toward less flammable grasses (Blackmore and Vitousek 2000).

Fire conditions vary greatly in time and space: fuels require time to accumulate, and topography and microclimate influence the condition of fuels. Therefore, any investigation of fire occurrence, hazard, or behavior requires observational measurements over broad spatial scales and through time. Remotely sensed measurements meet these requirements and are particularly useful for investigations of wildfire history (Hicke et al. 2003), fuel load production (Roberts et al. 2003), and the impact of land use on fuel load (Bachelet et al. 2000). Combined with other spatial analyses and predictive modeling, remotely sensed measurements of fuel quantity can be used to estimate fire risk (Ambrosia et al. 1998).

We compiled and tested a time series of National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data for quantifying photosynthetic vegetation (PV), nonphotosynthetic vegetation (NPV), and bare substrate fractional cover in Hawaiian dryland ecosystems. A second objective was to uncover relationships between these satellite measurements and existing environmental and land-use data. This latter objective was intended to prototype an operational fire-monitoring program that must eventually also include fire risk assessment and modeling. Our work also provides a more detailed understanding of how the invasive grass/fire cycle operates at regional scales on the dry leeward slopes of Hawaii.

2. Site description

Hawaii is a volcanic island archipelago containing strong climatic gradients leading to a diversity of ecosystem types ranging from tropical rain forests to desert environments (Figure 1). We focused on the dry lowland and submontane areas located on the leeward side of the Hawaii Island. This region is roughly 700 km² and receives between 250 and 1500 mm of precipitation annually. Most rainfall occurs in the winter months between January and March.

Substrates in the study region are derived from one of four volcanoes: Mauna Kea, Mauna Loa, Hualalai, or Kohala. Flow ages range from 1.5 millions of years ago (MYA) to less than 200 yr and are dark black basaltic lava flows, a‘a and pahoehoe. Soil development varies widely with almost no soil on young flows or on flows located in the very low precipitation zone without substantial vegetation cover. Well-developed soils occur on old flows where precipitation is high and vegetation is abundant. In either case, organic matter adheres to mineral material and forms dark, well-aggregated soils with high soil organic matter content (Sherman and Ikawa 1968), which is therefore often similar in color (visible light) to the basaltic parent material. The term “substrate” will be used in this paper to refer to both young basaltic flows (rock surfaces) and well-developed soil surfaces.

Plant communities of the arid to mesic environments on the leeward side of Hawaii were once defined by a small number of native tree species. These include
Metrosideros polymorpha (ohia) and Acacia Koa (koa). However, African grasses were introduced to Hawaii for grazing purposes following European contact in 1778, and these grasses have largely replaced native vegetation. Pennisetum clandestinum (kikuyu grass), P. setaceum (fountain grass), and Melinis minutiflora (molasses grass) are among the common invading species across the dry portions of Hawaii. Since introduction, these grasses have expanded in extent and now exist in monospecific stands in many areas (Figure 2).

3. Methods

3.1. Spectral mixture analysis

Spectral mixture analysis (SMA) (Adams et al. 1986) was used to estimate three ecosystem structural properties: PV, NPV, and the fraction of exposed substrate.
This technique assumes that the remotely sensed surface reflectance can be modeled as the linear combination of three end-member reflectance spectra (i.e., PV, NPV, and substrate; Figure 3). End-member spectra (either laboratory, reference, or image pixel spectra) are selected to represent the physical scene components of interest, but they also must adequately explain the majority of scene spectral variance. End-member selection is discussed in detail below.

SMA proceeds with the formation of the following system of equations for each pixel in the image:

$$
\rho_b = F_{PV} \rho_{PV,b} + F_{NPV} \rho_{NPV,b} + F_S \rho_S + E_b,
$$

where $b$ varies for each band in the dataset, $F_{PV}$ is the fractional cover of photosynthetic vegetation, $F_{NPV}$ is the fractional cover of nonphotosynthetic vegetation, and $F_S$ is the fraction of exposed substrate. The end-member spectra ($\rho_{PV}$, $\rho_{NPV}$, and $\rho_S$) are each multiplied by their respective fractional cover and summed along with $E_b$, the residual error for band $b$. Therefore, the number of equations in the system is instrument dependent: for MODIS satellite data with seven spectral bands, Equation (1) is expanded to seven equations ($b = 1$ through $b = 7$). This system of equations is solved for the end-member fractions, $F_{PV}$, $F_{NPV}$, and $F_S$.

The end-member fractions are further constrained to sum to one:

$$
F_{PV} + F_{NPV} + F_S = 1.
$$

Figure 2. Photograph of a *Pennisetum setaceum* (fountain grass) meadow with scattered trees in the background taken at Pu‘uwa‘awa‘a Ranch (region B in Figure 1).
A root-mean-squared error (rmse) can be calculated from the individual band residuals as an estimate of model fit across the entire wavelength range used:

\[
\text{rmse} = \sqrt{\frac{1}{B} \sum_{b=1}^{B} (E_b)^2},
\]

where \(B\) is the total number of bands or wavelengths used in the analysis. Note that Equation (2) constrains the sum of the fractions to equal unity; however, there is no constraint that the fractions must be between 0.0 and 1.0.

Estimates of ecosystem properties from both multispectral and hyperspectral data have been shown to return values comparable to field and laboratory measurements (Garcia-haro et al. 1996; Smith et al. 1990). This is particularly true for estimates of PV fraction (Elmore et al. 2000), but accuracy is also often high for the measurement of NPV fraction (Asner and Lobell 2000).

Figure 3. Image end members chosen for linear spectral mixture analysis of MODIS data. Spectra were selected from large, apparently homogeneous surfaces identified in the image data: photosynthetic vegetation, a forest canopy near the town of Kailua; nonphotosynthetic vegetation, a grassland canopy in midsummer from a region south of the town of Waimea (Figure 1); and exposed substrate, a young lava flow on the northwestern side of the island.
3.2. MODIS data and processing

MODIS sensor data were acquired from the Earth Observing System Data Gateway via the World Wide Web for the period spanning 26 February 2000 to 27 December 2003. Surface reflectance 8-day L3 Global data at 500-m resolution (v004) were selected for analysis. Two MODIS tiles were mosaicked (horizontal: 03; vertical: 06 and 07) and cropped to the region occupied by the Hawaiian Islands. These data were then projected to universal transverse Mercator (UTM) zone 5, WGS-84.

Image end-member spectra were chosen to represent PV, NPV, and substrate surfaces for spectral mixture analysis. In most environments, a 500-m MODIS pixel cannot be found that consists of just one end member. However, in Hawaii we found very unique opportunities that were not readily available in previous studies. For the green vegetation end member, a tropical forest was selected. For the NPV end member, a grassland location was selected from midsummer when the grasses are typically dry and effectively cover the ground. For the substrate end member, a young lava flow was selected that had not been colonized by more than sparse plant cover. In particular, this single substrate end member was made possible by the fact that the different lava flows and organic matter soils are both very dark, greatly simplifying this study in Hawaii. We arrived at this set of end members by iteratively selecting end-member spectra, performing SMA, and assessing the results. Ideal end-member selection will result in end-member fractions between 0.0 and 1.0, and low rmse (Elmore et al. 2000). The use of laboratory reference end members with SMA is in some cases more desirable than image end members. However, when chosen carefully image end members are inherently an excellent representation of scene variance, and when compared against reference end members, image end members simply result in a different scaling. This technique also allows us to place less emphasis on atmospheric correction, which would not be the case if reference end members were used (Tompkins et al. 1997).

The asymmetric, unimodal distribution of the rmse images allowed us to identify portions of images that were compromised by clouds and data errors (Figure 4). Since a cloud end member was not used in the SMA, cloud-compromised pixels reported high band residuals, and therefore high rmse values similar to data with sensor errors. Since the rmse is an overall measure of SMA model fit, it is desirable to exclude pixels with a high rmse regardless of the underlying reasons (clouds, data errors, etc.). A threshold rmse of 0.18 (units of reflectance) was found to accurately separate cloud-compromised and usable pixels. This rmse value was selected by comparing rmse values for all pixels with the MODIS quality assurance bit and with raw image reflectance data. This approach resulted in greater apparent accuracy than a similar method utilizing the MODIS quality assurance bit alone to identify usable data. After the threshold rmse value was identified, we looked through the MODIS time series for each pixel, identified periods of high rmse, and filled these periods with data using linear interpolation from the most recent (before and after) low-rmse acquisitions in the time series.

The resulting MODIS time series were continuous and generally remained between 0.0 and 1.0 through time for each pixel. To reduce the impact of high-frequency variation in end-member fractions through time, we applied a three-element low-pass digital filter to each pixel time series to smooth the data. This
3.3. Comparison of results to other studies and analysis with environmental data

Field validation of 500 m × 500 m MODIS pixels was viewed as impractical. Therefore, we utilized a scaling approach and validated the MODIS results against a previously field-validated Advanced Visible Infrared Imaging Spectrometer (AVIRIS)-based dataset created by Asner et al. (Asner et al. 2005). Portions of Asner et al. (Asner et al. 2005) pertinent to this paper will be reviewed here. On 16 October 2001, 10 AVIRIS flight lines were acquired over arid and semiarid environments on Hawaii at 10-m spatial resolution. These data were geometrically registered and atmospherically corrected to reflectance before performing an analysis of PV, NPV, and substrate fractional cover. These canopy structural components were made using AutoMCU, which is an automated approach based on spectral mixture analysis. AutoMCU has been documented in numerous publications to be a highly accurate method for the measurement of plant tissues and

Figure 4. A histogram of rmse for SMA of MODIS data for Hawaii. End members were selected to reduce the width of the peak distribution centered on about 0.05 reflectance units. Clouds were assumed to compromise pixels with an rmse greater than 0.18 reflectance units.
substrate cover despite wide variability in the spectral properties of these materials (Asner and Lobell 2000; Asner and Heidebrecht 2002). Coincident with these over flights, field measurements were made at 20 locations, selected for homogeneity. At each location, point-line transect analyses and top-of-canopy digital photography (Agricultural Digital Camera, Tetracam Inc., Chatsworth, California) were used to measure the fractional cover of PV, NPV, and exposed substrate. Results showed that the AutoMCU results using AVIRIS data were highly correlated with field-based measurements [PV, $r^2 = 0.93$ ($p < 0.05$); NPV, $r^2 = 0.89$ ($p < 0.05$); substrate, $r^2 = 0.92$ ($p < 0.01$)] (Asner et al. 2005).

A statistical comparison was performed between the AVIRIS-based (data provided by Asner et al. 2005) and the MODIS-based measurements of PV, NPV, and substrate at 41 sites representing dryland environments on the leeward slopes of Hawaii. The 41 sites were each 2.25 km$^2$ in size and the site centers were stratified such that one site was placed every arc second of longitude, thus spread evenly across the MODIS image in all areas that overlapped with the aircraft data. The north–south position of each site was chosen to be the most homogenous location within each region of common longitude. Homogeneity was estimated using the standard deviation of the photosynthetic vegetation fractional cover derived by MODIS. At each site we extracted the average of 9 MODIS pixels and the average of 22 500 AVIRIS pixels and compared these values using linear regression.

Precipitation plays an important role in determining the productivity of grasslands through inputs to soil moisture and through the release of nutrients (Burke et al. 1998). To investigate the influence of precipitation timing on PV, NPV, and substrate cover in the MODIS time series, we acquired and processed monthly precipitation data from the National Oceanic Atmospheric Administration for 23 sites across the dry side of Hawaii. Land-cover values (PV, NPV, and substrate) were extracted and averaged from the nine MODIS pixels centered on each of the 23 sites. These monthly precipitation time series (February 2000 through December 2002) were compared against the MODIS land-cover time series using linear regression. Precipitation data from 2003 were not available at the time of this data analysis.

Our work from other projects in Hawaii has built a substantial base of knowledge pertaining to land-use history, land-cover characteristics, and location of one recent large wildfire. We know the Kohala rangelands (region A in Figure 1) to be a large region of grassland dominated by mosaics of PV, NPV, and soil. Precipitation data from this region included one large event in the fall/winter of 2001, making this region a good site to study land-cover response to precipitation. We extracted and averaged MODIS land-cover data from a 25-km$^2$ region for analysis including comparison with precipitation data.

Similarly, we used our knowledge of the Pu‘uwa‘awa‘a Ranch to aid in the analysis of the MODIS time series in an area of recent wildfire and in areas of known grazing intensity (region B in Figure 1). In 1999, a large wild fire burned across the lower portion of the Pu‘uwa‘awa‘a Ranch. The fire was controlled on its southern boundary by a highway and therefore provides an ideal location for a time series analysis of fire recovery. We selected two areas, each 1 km$^2$ (four MODIS pixels), one immediately above and another immediately below the highway at Pu‘uwa‘awa‘a Ranch. We then analyzed the time series of PV, NPV, and substrate reported by MODIS for evidence of fire recovery in the burned pixels.
Second, we identified pixels representing grazed land and pixels representing less grazed land. The grazing intensity in these lands was influenced by the proximity of water and supplemental feeding over the past 20–30 yr (M. Kato, ranch manager, 2003, personal communication).

4. Results

MODIS results exhibited recognizable patterns of photosynthetic vegetation, non-photosynthetic vegetation, and exposed substrate across Hawaii (Figure 5). Young lava flows on the high volcanic peaks of Mauna Loa and Mauna Kea were identifiable as nearly bare substrate surfaces. The eastern side (north of Hilo) and western side (Kona coast) are closed canopy tropical forests, and in the MODIS data photosynthetic vegetation and some substrate dominated these regions. Most importantly for this paper, mosaics of nonphotosynthetic vegetation and soil dominate the northwestern side of the island. Low precipitation in this region (Figure 1) dictates low PV and high NPV, both of which are apparent in the MODIS SMA results (Figure 5).

Figure 5. MODIS SMA and 10 m × 10 m aircraft-based SMA results for Hawaii on 16 Oct 2001. The aircraft results were obtained using the NASA AVIRIS, as detailed by Asner et al. (Asner et al. 2005).
Linear regression of SMA fractional cover measurements from MODIS and aircraft-based data (Asner et al. 2005) demonstrate the capability of MODIS data to retrieve values correlated with high-resolution data for PV ($r^2 = 0.83$), NPV ($r^2 = 0.88$), and bare substrate ($r^2 = 0.86$) (Figure 6). However, the slope of the regression between these data (for all three variables) was consistently in the range of 0.6–0.7. This indicated that MODIS data do not accurately produce the same values as the high-resolution aircraft data across the entire range of environments. MODIS underestimated cover values at the higher range of cover and overestimated values at the lower range of cover. Despite the lower accuracy of the MODIS results compared to results from AVIRIS, MODIS did have high internal

![Figure 6](image-url)

Figure 6. A statistical comparison of forty-one 2.25-km² regions common to the MODIS satellite and AVIRIS (Asner et al. 2005) results presented in Figure 4.
precision and thus captured the overall fractional variability of the dryland ecosystems. This facilitated use of these data in subsequent regional-scale studies of phenology, climate, and fuel load interactions.

4.1. Analysis with environmental data

The available precipitation record between March 2000 and January 2003 for 23 sites on the northern side of the island allowed an analysis of the relationship between PV, NPV, and exposed substrate with precipitation. We noted a weak correlation between PV and precipitation at most sites, with only six sites reporting significant relationships varying from $r^2 = 0.1$ and $r^2 = 0.6$ ($p < 0.05$). These six sites were located in regions dominated by introduced grasses. The highest correlations between PV fraction and precipitation were retrieved from the Kohala on the northern end of the island. Here, grazed lands appear to be more productive during wet years such as the winter of 2001/02 (apparent from Figure 7). Not surprisingly, nonvegetated sites located at high elevations (e.g., the summit of the Hualalai Volcano), or in areas heavily disturbed by land use (e.g., Kona coast) did not exhibit strong relationships between PV and precipitation.

Since the highest degree of correspondence between precipitation and PV fraction was identified in the Kohala region (region A in Figure 1), we directed our analysis of the MODIS time series to this area (Figure 7). Photosynthetic vegetation cover responded to annual inputs of winter precipitation beginning in No-

![Central Kohala Precipitation, PV, NPV, Soil Elevation: 350-450m](image)

**Figure 7.** MODIS time series of PV, NPV, exposed substrate, and monthly precipitation from the Kohala Mountain rangelands (region A in Figure 1).
November or December of each year and typically lasting into the spring of the following year. The relationship between these PV “peaks” and the NPV and substrate time series is shown in Figure 7, but also in a calculation of the seasonal cycle (averaged for 2000–04) (Figure 8). Seasonal increases in PV fraction were associated with a decrease in NPV and substrate fraction as the new growth covered dead plant litter from the previous year and covered exposed substrate. Coincident with the annual PV peak, NPV began to increase and reached a maximum shortly after PV cover had declined. Likewise, bare substrate increases lagged behind NPV increases and peaked much later, often just prior to fall-season precipitation of the following year.

In an attempt to measure rates of phenological change in the Kohala region, we calculated the correlation between PV and NPV, and NPV and substrate, at different time lags (Figure 9). For the PV and NPV seasonal cycles (both from Figure 8), as the lag was increased and the PV cycle “caught up” with the NPV cycle, the correlation coefficient increased. The highest correlation between PV and NPV was measured when the PV time series was advanced 18–19 time steps, which corresponds with a peak offset of 144–152 days. This indicated that, on average in the Kohala region, peak PV cover and peak NPV cover were separated by 5 months. The same calculations were performed for the transition from NPV to

![Figure 8. Average seasonal PV, NPV, and soil cycles for the Kohala time series presented in Figure 7 (2000–04).](image-url)
exposed substrate; here the time lag was calculated at 104 days, or roughly 3.5 months (Figure 9).

4.2. Analyses with land use and disturbance

The burn scar at Pu’uwa’awa’a Ranch (Figure 5) resulted from a wildfire that occurred less than one year prior to the start of the MODIS time series. The MODIS results from this scar and from an unburned location less than 1 km away demonstrated the utility of the MODIS time series for the evaluation of fire conditions (Figure 10). Photosynthetic vegetation measurements between March 2000 and December 2003 were similar for the burned and unburned sites. Non-photosynthetic vegetation, however, was notably higher at the unburned site, reaching 80% cover during the dry summer months of 2000. The fraction of exposed substrate was above 70% for 2 yr following the burn, and its seasonal variability was less than that of bare substrate at the unburned site. Through the 3-yr period of analysis, the burned site gradually began to resemble the unburned site. The maximum NPV difference between the sites (during summer months) converged at a rate of just over 6% NPV cover per year.

Figure 9. Correlation of the annual MODIS time series from the Kohala region (Figure 7) for PV and NPV, and NPV and substrate at different lags (e.g., for PV and NPV, the PV time series was advanced relative to the NPV series and at each step the correlation between the two series was calculated).
The MODIS time series analysis at Pu‘uwa‘a Ranch also allowed an analysis of PV, NPV, and bare substrate differences between two sites, one grazed and another less grazed (Figure 11). Photosynthetic vegetation cover was very similar at each site, suggesting that precipitation was very similar at these two sites over the period of analysis. However, peak PV cover values at the more heavily grazed site (<45% PV) were slightly lower than in the less grazed area (<55% PV). Grazing resulted in lower NPV cover (25%–75% NPV versus 25%–90% at the less grazed site). The largest differences in NPV cover occurred during the summer fire season.

Figure 10. MODIS time series of PV, NPV, and substrate from a region burned in a 1999 fire and an otherwise similar region left unburned due to a highway that served as a firebreak.
5. Discussion

The measurement of PV, NPV, and substrate fractions from remotely sensed data are important tools for fire monitoring and modeling (Roberts et al. 1998; Roberts et al. 2003) and for more basic goals of ecosystem analysis (Facelli and Pickett 1991). We compared MODIS-derived values of these structural components to the extensive field- and aircraft-based studies of Asner et al. (Asner et al. 2005). The good correlation between MODIS and aircraft-based estimates of NPV was su-
prising. Difficulties in separating NPV from bare substrates with multispectral data are widely recognized in the literature (Asner 2004). However, we can identify several site-specific issues in Hawaiian ecosystems that greatly reduced this obstacle. The low spatial resolution (500 m) of the MODIS data results in pixels that average together much of the landscape variability observed in higher-resolution data. This result is consistent with previous sensor comparisons across different spatial scales (Hansen et al. 2003). It may be possible to generalize and say that low-resolution data are inherently less complex than high-resolution data, and therefore the same spectral resolution is not required to make reasonably accurate measurements.

Unique Hawaiian ecosystem features combine with the advantages of low-resolution data to further strengthen measurements of ecosystem structure from MODIS data. At the 500-m pixel scale, Hawaiian soils (all being derived from basaltic lava flows) achieve a uniformly dark and featureless appearance, almost independent of age. Substrate variability becomes significant only at higher spatial resolutions (perhaps <100 m per pixel) when individual substrate types (e.g., individual lava flows and within-flow variation between a’a and pahoehoe lava) can be identified. In contrast, dry grass litter is the primary form of NPV and this material is 5–6 times more reflective across the entire shortwave spectrum than are the dark substrate surfaces found in this unique Hawaiian setting (Figure 3).

Because the MODIS results were better constrained between 0 and 1 than were the AVIRIS results, a nonunity slope resulted (Figure 6). This may be a result of the lower resolution and thus lower substrate variability inherent to the MODIS data; however, it could also be due to the method used to choose end-member spectra. As described in Asner et al. (Asner et al. 2005), the AutoMCU approach utilizes reference end-member bundles. The applicability of these end-member spectra will vary with the accuracy of the reflectance retrieval, which in itself varies by pixel. In the case for MODIS, we utilized image end members that are not sensitive to atmospheric correction. Atmospheric correction of multispectral data amounts to a linear transformation of the data, and therefore analyses that are linear transformations of the data [such as linear SMA (LSMA)] are invariant under these calibration procedures. Therefore, for multispectral data the advantage is that reflectance retrieval is not necessary and image end members can be found that correctly represent the edges of the mixing space (Small 2004), leading to end-member fractions that are well constrained between 0 and 1.

The strong correlation between MODIS estimates and AVIRIS-based results (provided by Asner et al. 2005) suggests that MODIS data and LSMA can result in quantitative measurements of ecosystem structure for use with a variety of earth science applications. However, considerable variability was observed in the MODIS time series that did not appear to be directly attributable to precipitation or land use (Figure 7). Bidirectional reflectance distribution function (BRDF) effects due to non-Lambertian surfaces and the widely varying sun angles and sensor look angles between MODIS overpasses are likely responsible for the majority of this high-frequency variance in the MODIS time series. We investigated this problem by comparing substrate fraction and sun angle throughout the period of study for several locations throughout the study area (data not presented) and found that for some regions exposed substrate fraction was correlated with sun angle ($P < 0.05$). These areas were limited to the summits of each volcano where
exposed substrate was high and low sun angles resulted in considerable shading. One potential solution to this issue would be to modify the analysis to utilize the BRDF-corrected product (Schaaf et al. 2002). This solution, however, has three drawbacks: 1) reduced spatial resolution to 1 km per pixel, 2) reduced temporal resolution to 16 days, and 3) uncertainties in the future of the BRDF product. Therefore, for our continued monitoring of NPV conditions in Hawaii, we suggest using the 8-day surface reflectance product and giving more weight to broad features and annual changes in fractional cover rather than month-to-month variability. Another solution would be to use the MODIS daily product and restrict the analysis to nadir or near-nadir acquisitions; however, the frequency of cloud cover in Hawaii will likely limit this option.

The analysis of PV time series with the precipitation record from 23 sites on the northwestern side of Hawaii indicated that many land-use practices reduce the sensitivity of the vegetation to precipitation. In the Kohala area, grasslands were more sensitive to precipitation than other regions. This is likely due to the lack of development in the Kohala rangeland area and thus to the predominance of herbaceous vegetation, but also to the existence of one large precipitation event spanning the winter of 2001/02. During this event, PV fraction and precipitation were highly correlated. Thereafter, we observed the transition from PV to NPV, and the loss of NPV to expose substrate surfaces. To our knowledge, this cycle has not been previously observed in remote sensing data. Our analysis of this cycle in grasslands throughout the northwestern side of Hawaii demonstrated this robust feature of the MODIS time series. It might be expected that the time lag between PV production and conversion to NPV and then to substrate would vary from location to location due to the effects of microclimate and land use. A further analysis of the constraints on conversion between these ecosystem structural parameters would be possible given extensive environmental data on grazing intensity, precipitation, temperature, wind speed, etc. These data could conceivably result in improved models describing the cycling of carbon in grasslands.

Large quantities of NPV biomass accumulating in Hawaiian grasslands lead to wildfires (D’Antonio and Vitousek 1992). One of these fires provided a chance to observe conditions of land that could burn if ignited (the unburned area in Figure 10). We assumed this area could burn because it was located near a climatologically similar area that did burn. The fractional cover of NPV in the unburned area was significantly higher, peaking at almost 80% cover during the summer months, compared with NPV cover on the burned area at about 30%. The observed development of NPV over time following the burn was illustrative of how quickly these sites become capable of carrying fire. We calculated a period to convergence of roughly 7–8 yr. This is remarkably similar to the fire return interval of 8 yr for ungrazed lands in the vicinity of Pu’uwa’awa’a Ranch (M. Castillo, 2003, personal communication). However, using only the PV data, the two sites were indistinguishable after just the 4-yr period analyzed here. Therefore, studies that utilize only measures of green vegetation (e.g., the normalized difference vegetation index) for analysis of fuel load miss this important component of the fire hazard (Wessman et al. 1997).

In field studies, grazing has been identified as an effective method for the reduction of NPV and fire conditions (Blackmore and Vitousek 2000), and the MODIS time series of NPV from Pu’uwa’awa’a Ranch support this notion. The
differences were small, but more heavily grazed lands exhibited less NPV and more exposed substrate. The fact that grazing reduces plant litter and exposes more soil is also well documented in field studies (Heitschmidt et al. 1987; Shariff et al. 1994). Therefore, the satellite results further highlight the interaction of precipitation, fire history, and grazing management in controlling the phenology and flammability of these Hawaiian grasslands. MODIS time series clearly provide a powerful tool to monitor these processes in an era of changing climatic and land-use conditions.

6. Conclusions

We used spectral mixture analysis to estimate the fractional cover of photosynthetic vegetation, nonphotosynthetic vegetation, and exposed substrate in time series of MODIS 500-m multispectral data of Hawaii Island. We then compared these results to measurements of the same ecosystem structural parameters derived from field- and aircraft-based data and assessed the application of the MODIS data for ecosystem monitoring and analysis in the Hawaiian Islands. Our results offer the following conclusions and considerations.

1) MODIS measurements of PV, NPV, and exposed substrate were correlated with high-resolution aircraft-based measurements and therefore represent a promising technique for the monitoring and analysis of grassland phenology and response to land use.

2) The MODIS results were used to examine the phenology of introduced grasses in the Kohala Mountains, Hawaii. Cycles of growth, senescence, and physical decomposition between PV, NPV, and exposed substrate were observed to follow consistent patterns across the landscape, suggesting that these data could be applied to studies of carbon cycling within grasslands.

3) Comparison of two sites with different wildfire histories revealed the impact of wildfire and the rate of accumulation of NPV following fire. Wildfire reduced the NPV cover by 50% during the subsequent summer fire season. NPV at the burned site will converge with the nonburned site in 8 yr.

4) Grazing has been observed in field studies to reduce the accumulation of NPV. The MODIS data demonstrated this pattern as well, with more heavily grazed lands exhibiting 20%–25% lower NPV cover than less grazed lands.

5) Generally the MODIS results represented temporal and spatial patterns of PV, NPV, and exposed substrate that support its use as an instrument for ecosystem monitoring and analysis. The diverse environments of Hawaii, combined with a globally significant set of land-use issues, support the further development and analysis of remote sensing time series of ecosystem structure.

Acknowledgments. We thank David Lobell and many others at the Carnegie Institution of Washington for helpful comments. Support from the USDA Forest Service to G. Asner and R. F. Hughes is gratefully acknowledged.
References


