Tropical Forest Phenology and Satellite Vegetation Index Validation

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Abstract

Phenology, the study of life cycle events, is gaining importance globally as the onset of climate change is impacting the timing of forest and agriculture growth cycles. Phenological research often involves land surface phenology (LSP) analysis derived from satellite vegetation indices (VI's) such as those from Moderate Resolution Imaging Spectroradiometer (MODIS). Due to persistent cloud cover and atmospheric interference in tropical regions, satellite VI time series are subject to uncertainties and thus require near surface vegetation monitoring systems for ground-truthing. This study was designed to quantify the precision of MODIS phenological signatures using an above-canopy, down-looking digital camera installed on a flux tower in Hawai‘i Volcanoes National Park. Though static seasonality was predicted, quantitative measures derived from *in-situ* camera images illustrated moderate fluctuation in canopy greenness that was not detected by MODIS. These results indicate the limitations of MODIS for tropical locations and emphasize the need for continued *in-situ* phenology research.

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1 Introduction

Phenology, the study of plant and animal life cycle events as they correspond to seasonal patterns (Rathcke 1985), is becoming increasingly important for evaluating how nature responds to long term environmental change. The necessity for understanding forest phenology globally is gaining momentum as anthropogenic impacts associated with climate change are contributing to alterations in seasonal growth patterns (Fisher and Mustard 2007; Studer et al. 2007; Choi et al. 2011; Sonnentag et al. 2012). Significant changes in vegetation can have atmospheric and surface climate effects. Since functional aspects of most ecosystems, including survival and reproduction, rely on specific timing of vegetation growing periods, understanding alterations to green-up and senescence events is valuable at both local and broad scales (Studer et al. 2007; Sonnentag et al. 2012). Global vegetation phenology is often assessed using the following criteria: 1) day of year of greenness onset (green-up); 2) maximum greenness or maturity; 3) greenness decrease (senescence); and, 4) greenness minimum or dormancy (Zhang et al. 2003; Zhang, Friedl, and Schaaf 2006; Nagai et al. 2010). Changes in the timing of these four events can have cascading effects in forest and agricultural ecosystems that directly impact global carbon and water cycles (Ahrends et al. 2008; Hufkens et al. 2012).

Satellite remote sensing imagery and the output of vegetation indices (VI's) provides a means to analyze time-series vegetation changes and thus is a widely used tool in modern phenological studies (Zhang et al. 2003; Zhang, Friedl, and Schaaf 2006; Studer et al. 2007). Using VI's such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), allow for the calculation of green-up and senescence events by the maximum rate of VI growth and reduction, respectively. Similarly, the minimum and maximum VI values correspond to dormancy and maturity (Huete et al. 2002; Nagai et al. 2010).

The last decade has provided an increasing understanding of global vegetation growth patterns due to the capabilities of the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS) satellites. In temperate deciduous forests phenological activity is often decipherable due to clear visual evidence of seasonality. In contrast, due to their stable and steady state, tropical forests often show little deviation in their times series VI's (Huete and Saleska 2010). Compounding issues of less obvious seasonality, tropical regions are subject to extensive periods of cloud cover throughout the year and thus satellite remote sensing systems have higher uncertainties in their VI's for these regions. Furthermore, there are conflicting theories regarding photosynthetic activity in tropical forests during wet and dry seasons, as well as drought years. Some data from the Amazon indicates that drought and dry seasons increase photosynthetic activity due to increased levels of sunlight in tropical regions that are normally cloaked in cloud cover (Huete et al. 2006; Huete and Saleska 2010), whereas other studies illustrate the opposite effect in which tropical forest canopies undergo drying due to less available water (Huete and Saleska 2010). However, there are still uncertainties related to such data as cloud coverage, aerosols, and atmospheric interference give less creditability to temporal and spatial trends despite advancements in calibration of data (Zhang et al. 2003; Zhang, Friedl, and Schaaf 2006).

Given such uncertainties, ground-truthing and validation data sets are still considered necessary to give satellite outputs more credibility and often take the form of in-situ remote sensing techniques such as digital cameras mounted above forest canopies that record imagery unobstructed by cloud cover multiple times per day (Ahrends et al. 2008; Huete and Saleska 2010; Nagai et al. 2010; Sonnentag et al. 2012). Global site specific networks from the Phenological Eyes Network (PEN) and Phenocam have recently been introduced to reduce uncertainties in satellite remote sensing VI's by installing digital monitoring cameras in forests worldwide (Nagai et al. 2010). One of these networks' objectives is to improve our understanding of the relationships between canopy optical signals and phenological signals at the whole canopy level. Cameras have been installed throughout locations in Japan (Nagai et al 2010), mixed beech forests of Switzerland (Ahrends et al. 2008), and temperate deciduous and coniferous forests of the Eastern United States and Canada (Richardson et al. 2009; Sonnentag et al. 2012). Despite these efforts, few studies have focused on tropical areas. Although it is predicted that tropical phenology is mostly static, the importance of these forests as vital ecosystems lends weight to studies aimed at ground-truthing satellite data with potentially high atmospheric interference (Huete and Saleska 2010).

To address this paucity in tropical coverage, a study site equipped with an above-canopy, downward facing, hemispherical digital camera within Hawaiʻi Volcanoes National Park (HAVO) on the Big Island of Hawaiʻi is monitoring forest stands primarily composed of endemic ʻōhiʻa lehua (*Metrosideros polymorpha*). The Hawaiʻi Volcanoes, Thurston (HVT) site was chosen as a test site as it is an important stand of endemic forests. Hawaiʻi, like many island ecosystems, is subject to high risk of invasion and thus understanding phenological trends in these forests is important locally as well as to regional and global phenology studies. The HVT site is equipped with instrumentation that provides supplemental environmental variables such as net radiation, rainfall, temperature, and soil moisture. These variables allow for further understanding of *in-situ* seasonal dynamics that can be compared to digital camera and satellite VI outputs.

Given the lack of remote sensing based tropical phenology studies the overarching objective of this study was to fill gaps in knowledge regarding the ability of MODIS VI outputs to provide meaningful representations of seasonality in tropical forests around the world. It was hypothesized; 1) At the HVT site where slow growing evergreen *Metrosideros polymorpha* dominates the canopy, seasonality characterized by wet and dry seasons will show little variation in near surface camera VIs throughout the year and thus correlate with predictably static satellite remote sensing data; and, 2) despite recordable seasonal distinctions in environmental variables such as net radiation and rainfall, fluxes in forest canopy phenological signals will be too subtle to detect via remote sensing methods and thus have little correlation with environmental variables.

This study is an important step in forest phenology regardless of the result – should validation images contradict the optical signatures produced by MODIS satellites, the study will lend weight to the necessity for more site specific in-situ phenology studies; however should above canopy camera images support satellite VI output, more confidence can be awarded to the effectiveness of MODIS time series data in tropical phenology studies.

2 Methods

2.1 Site Description

The HVT site is located within Hawaiʻi Volcanoes National Park (HAVO), a short distance from the Thurston Lava Tube. The HVT eddy covariance tower is located at 19°24’55”N, 155°14’55”W, at an elevation of 1219m in tropical montane cloud forest with average annual rainfall of 2500 mm. The canopy in this region of the national park is almost completely comprised of the endemic ʻōhiʻa lehua (*Metrosideros polymorpha*) with an understory dominated by the tree fern *Cibotium glaucum*. The steel flux tower is approximately 25 m high and along with the downward facing hemispherical digital camera is equipped with eddy covariance instrumentation for use in evapotranspiration, carbon exchange, and energy balance monitoring (Giambelluca et al. 2009).

M. polymorpha is a slow growing, broadleaf evergreen tree and shrub, growing on a variety of soils ranging from clay to barren lava flows. The size of *M. polymorpha* varies greatly as harsh conditions such as lava flows or bogs produce full grown shrubs only centimeters in height, while moist, well drained soils allow for dense forest stands as tall as 33 m (Friday and Herbert 2006). The HVT site falls within *M. polymorpha’s* optimal growing elevation and moisture conditions to produce a tall, dense closed canopy which provides habitat and critical food sources for many of Hawaiʻi’s endemic nectivorous and insectivorous forest birds (Friday and Herbert 2006).

2.2 MODIS Vegetation Indices

MODIS flies aboard the EOS Terra (AM) and Aqua (PM) spacecraft with 705-km sun synchronous orbits that provide full coverage of the earth every 1-2 days with a ±55° off-nadir field of view and swath width of 2,330 km (Zhang, Friedl, and Schaaf 2006). Spectral signatures collected by MODIS are used to determine and make judgments on atmospheric properties (cloud cover, aerosol optical depth, etc.), oceanic features (sea-surface temperatures, chlorophyll, etc.), and land ecosystem variables (VI’s, photosynthetically active radiation (PAR), land cover change, etc.) (Jensen 2007). MODIS delivers 36 spectral bands at resolutions ranging from 250m to1km and in continuing the mission of the Advanced Very High Resolution Radiometer (AVHRR), MODIS has increased effectiveness for terrestrial monitoring through improved atmospheric correction capabilities (Jensen 2007; Zhang et al. 2003; Zhang, Friedl, and Schaaf 2006). NASA provides a variety of products originating from their MODIS data sets which are available for public download and use in scientific research. These products are available via the REVERB website (http://reverb.echo.nasa.gov/reverb/) – users specify a region using the interactive map and select appropriate spatial extent, temporal range, instrumentation, and processing level using the available search options dialogue. Time series VI data for this study was produced using daily MODIS surface reflectance data from the AQUA sensor (MYD09GA) and 16 day VI composite data (MOD13Q1/A1 & MYD13Q1/A1). The prefixes MOD and MYD represent TERRA and AQUA platforms respectively, while the “13” indicates the VI product, and Q1 and A1 describe 250m and 500m spatial resolution respectively. Daily as well as VI products were reprojected, mosaicked, and screened for contaminated pixels using quality flags (Figure 1).

Following initial data processing, MODIS imagery was loaded into ENVI software and the region of interest (ROI) tool was used to select the pixel containing the latitude/longitude coordinates of the HVT tower on the Island of Hawai‘i. Time series VI's of NDVI and EVI were then extracted to represent a phenological metric for this site. NDVI and EVI were calculated as follows:

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \tag{1}$$

$$EVI = G\frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + C_1\rho_{red} - C_2\rho_{blue} + L}(1 + L) \tag{2}$$

VI's are radiometric measures designed to isolate the temporal and spatial distribution of green vegetation and photosynthetic activity (A. R. Huete et al. 2002; Jensen 2007); NDVI uses the red and near infrared bands ($\rho_{red,}$ ρ_{nir}) and is considered to be more sensitive to chlorophyll (A. R. Huete et al. 2002). EVI is derived by adding a gain factor (G) for scaling purposes, a soil adjustment factor (L), and coefficients ($C_{1\ \&\ 2}$) aimed at using the blue band (ρ_{blue}) of the visual spectrum to correct for atmospheric aerosol scattering in the red bands. Due to these adjustments and addition of the blue band, EVI is also considered to be more sensitive to environments with high biomass and variations in canopy structure, which characterizes the tropical local of the Hawaiian Islands (A. R. Huete et al. 2002; Jensen 2007). VI numerical values generally range from 0.2 - 0.8 (potential maximum at 1.0), with higher numbers illustrating more greenness in the vegetation canopy and lower values often indicating leafless canopies, bare soil, and even snow cover (Nagai et al. 2010). Tropical forests would predicatively illustrate consistently high VI values throughout all seasons.

To ensure the quality of VI time series a variety of methods were used for correction. Daily MODIS data were downloaded at the 2G processing level which applies algorithmic corrections for atmospheric gases and aerosols. These corrections are also applied at the higher level VI products. Although MODIS satellites have approximately daily global coverage, the presence of clouds limits the temporal accuracy of these daily observations and thus compositing methods are applied to find the best subset data (Jensen 2007; Nagai et al. 2010). MOD/MYD13 VI products use a 16 day compositing algorithm based on constrained view angle maximum value compositing (CV-MVC) techniques. Data is filtered for clouds and the two highest quality days within each 16 day window are chosen and the day with closest to nadir view angle and the highest VI value from the subset is selected to represent each period. Daily MYD09GA products were filtered using quality flags and then converted to monthly composites using both MVC (which removes the view angle constraint, but still chooses the highest VI value from the highest quality day) and mean compositing (meanc) methods. The meanc uses the mean VI value for all "quality" days within each month of the year (Vancutsem et al. 2007). After all processing was completed the MODIS data were represented as a time series to detect seasonal variation in canopy greenness.

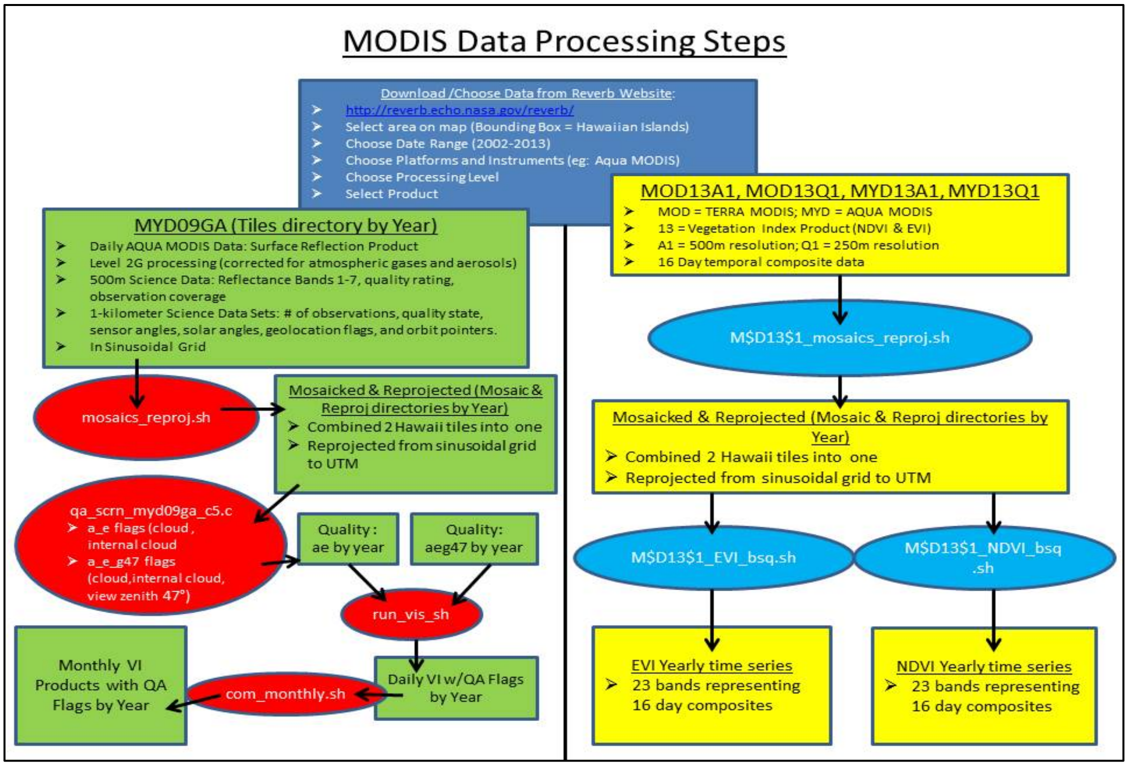

Figure 1: MODIS processing workflows

2.3 *In situ*, Top of Canopy, Downward Facing Digital Cameras

A downward facing, top of canopy camera (Nikon Coolpix 4500) fitted with 180° fish eye lens was installed at approximately 23m at HVT. The camera joins a world-wide network as part of PEN. The HVT camera has been recording images hourly from 6:00 to 18:00 local time from April 6th 2012 to July 26th 2013 and then subsetted into a group with images between 10:00-14:00. This subsetting is designed to optimize sun angle illumination effects as early morning and late afternoon times produce long shadows that may have significant effects on the canopy's optical signal. This time period also corresponds to the range of overpass times associated with the MODIS satellites. Technical issues in the field including power loss and overheating caused shutdowns of the camera for 187 of the 478 days (gaps in image collection during the following periods: 4/14/2012, 5/22/12 – 6/6/12, 6/13/12 – 7/18/12, 7/21/12 – 7/30/12, 11/13/12 – 11/16/12, 11/25/12, 12/3/12 – 1/15/13, 2/11/13 – 2/27/13, 4/15/13 – 6/6/13).

Images were analyzed both visually and quantitatively. Simple visual representation of seasonality was recorded through animations of time series data using Photoshop. Furthermore, images were analyzed by extracting the red-green-blue (RGB) digital numbers (DNs) to produce a VI for use in phenology studies. Specifically, both Excess Green (ExG) or the Green Chromatic Coordinate (Gcc) are types of VIs which rely on the visible bands of light (R, G, B) to produce a quantitative measure of canopy greenness that can be compared daily or seasonally (Ahrends et al. 2008; Richardson et al. 2009; Hufkens et al. 2012; Sonnentag et al. 2012). Both indices are designed to diminish the effects of RGB brightness shifts based on scene illumination (Sonnentag et al. 2012).

$$Excess\ Green: ExG = 2G - (R + B) \quad (3)$$

$$Green\ Chromatic\ Coordinate: G_{cc} = \frac{G}{(R+G+B)} \quad (4)$$

2.3.1 ROIs

A sample image from the camera data set was used to create three ROIs drawn as rings radiating out from nadir (Figure 2). The hemispherical fish-eye lens creates distortion at an image's edges as the pixels are elongated and thus the ROIs were used to test whether this distortion would affect the optical signal. Each ROI was drawn with gaps so as not to include the tower and a water spot that developed on the protective dome of the camera's waterproof casing during early months of the study. Though this water spot was cleaned the gap in the ROIs was used for all images to maintain consistency. Both ExG and Gcc were extracted from each ROI by averaging the DNs within each ROI for each image (Ross Bryant, USDA, MATLAB code). Previous studies have used ROIs to distinguish between different regions of a heterogeneous temperate forest in order to understand variations in species growth patterns (Richardson et al. 2009; Hufkens et al. 2012). However, the canopy at the HVT site is a homogenous *M. polymorpha* dominated forest where these effects are less relevant. Spearman rank correlation was used to test for similarities (significant p-value < 0.05) in the time series of each ROI to determine if a mean VI value could be used across the image.

2.3.2 Image Illumination Classification

To understand how illumination differences in near-surface camera VI's that arise due to environmental noise such as cloud cover and precipitation affect phenological signals, I used a combination of image classification and moving average techniques. Photos were categorized into a Visual Image Classification (VIC) by labeling each of the hourly images as "sunny" (1), "overcast" (2), and "cloudy" (3). This classification was made by inspecting each image for clouds, raindrops, brightness, and overall clarity. The overcast designation was made for days with high clouds and muted grey tones, while cloudy days included precipitation on the camera dome, and low cloud cover with darker illumination. The VICs were then used to find a subset of data considered to be sunny days by filtering days that had an average VIC of 1.2 or less. This meant each day needed to have 4 out of 5 "sunny" images during the 10:00 to 14:00 interval in order to fit subsetting criteria (labeled *.sun, n = 83). A second subset was created by using only the midday times of 11:00 to 13:00 and only "sunny" days in which all three images had VIC = 1 (labeled *.midday.sun, n = 74). Using midday images eliminates the potential for shadows created at 10:00 and 14:00 at different times of the year (observed through visual inspection). Sunny days provide the most consistent visual illumination and color balance (Hufkens et al. 2012), whereas cloudy days often enhanced the vibrancy of canopy greenness, and overcast days were highly variable in their visual effects on greenness, but most often created muted colors (Figure 2).

Given the perpetual greenness in Hawai‘i the goal was to understand if VI time series would have responses to changes in season or if the optical signal would be flat.

Once illumination conditions were accounted for, time series for camera VIs were created to visualize phenological fluctuations. These times series were plotted for daily data, 16-day composites, and monthly composites. In each of these times series the data was presented unfiltered and using the sunny day filters. The 16 day composites were designed to match the MOD/MYD13 data sets so trend comparisons and correlations could be made. The sunny day filtering was used as a method to match MODIS quality filtration applied to all the satellite data sets and to further reduce the effects of changing illumination.

2.3.3 Solar Zenith Angle Effects

Different locations on the globe have unique positioning in relation to the angle of the sun and its illumination – the angle between directly overhead and the sun's center is labeled the solar zenith angle (SZA). In order to test the effects of SZA, 32 days with sunny images for all times of day (10-14) were selected throughout the study period. SZA changes seasonally as the sun is higher in the sky during summer months and thus creates varying illumination conditions throughout the year. Solar noon (the local time when the sun is at its highest position in the sky) occurred anywhere from 12:08 to 12:35 throughout the year. ExG means of each of the 32 sunny days at each hour were compared using analysis of variance (ANOVA) with Bonferroni adjustment to test if significant differences (p-value <0.05) in VI values were apparent between each observed hour.

2.4 Environmental Variables

The University of Hawaiʻi at Mānoa Geography department manages a series of flux towers and weather stations that record environmental variables around the Hawaiian Islands and provides calibrated data for rainfall, temperature, net radiation and soil moisture at the HVT site (Dr. Giambelluca lab, personal correspondence). Each of the variables were recorded at the site using the following instrumentation: 1) Temperature (°C) – Vaisala model HMP45C; 2) Rainfall (mm) – Texas Electronics model TE525, dynamically calibrated based on the rainfall rate in mm/30min; 3) Net Radiation (W m^{-2}) – Rebs Q7.1, Kipp and Zonen CNRI, and Hukseflux NR01; and, 4) Soil moisture – Campbell SC615, 30 cm water content reflectometer placed at 4 cm horizontal, 6-36 cm vertical and 19-49cm vertical. At the HVT site the soil is approximately 10-20 cm deep with layers of cinder and rock getting larger with depth. Environmental variables were averaged daily, into 16 day composites, and monthly. The calibrated environmental variables were evaluated in Spearman Rank correlation analysis to assess if such data provided potential explanatory information for trends in the remote sensing data.

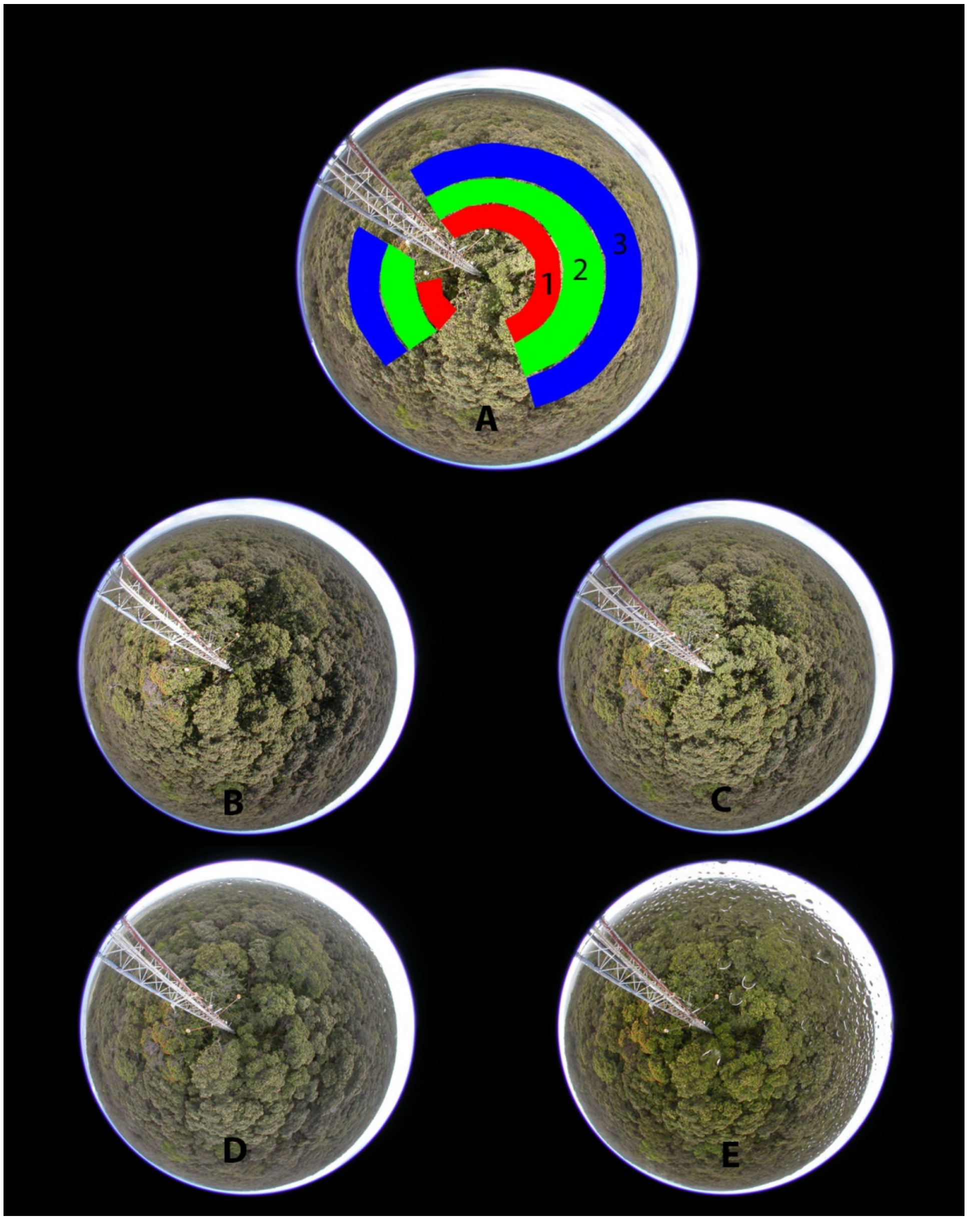

Figure 2: HVT photographic images illustrating ROI's and illumination conditions: A) ROI's radiating out from the center of each image were designed to test the effect of pixel distortion as VIs were recorded moving out from nadir (represented as 1,2,3 color bands in image). The gap in the ROIs is designed to keep out pixels containing the tower as well avoid a water spot that developed on the protective cover during the first months of the study; B) 10AM sunny day image – shows large shadows at this time of day which effect VIs; C) 12PM sunny day image with consistent illumination conditions; D) Overcast illumination condition shows muted color conditions; E) Cloud/Rain illumination conditions show a more vibrant green.

3 Results

3.1 In-situ Near-Surface Digital Imagery

3.1.1 Region of Interest Effects

The purpose of dividing the scene of each camera image into ROIs was to assess the view angle effects of pixel distortion as the scene moves out from nadir. Results of ROI effects showed that although the inner ring produced higher VI values than the outer rings, the overall trend was nearly identical (Figure 2; all Spearman rank correlations > 0.88, all p-value < 0.05) . Given the similarity in ROIs, all data were analyzed by averaging VIs across all three ROI to produce daily VI values for the scene (the three ROI together do not extend to the edge of the image so as not include the most distorted pixels and the horizon).

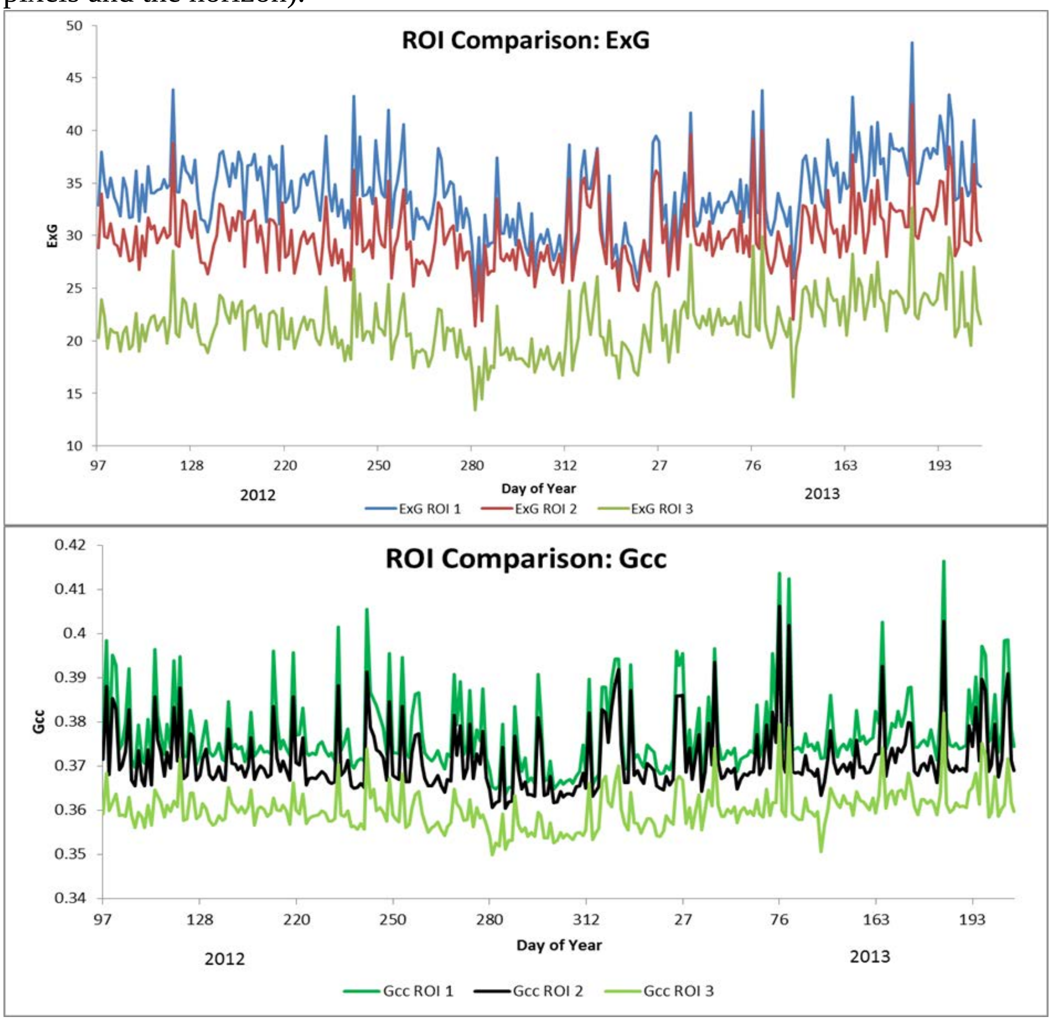

Figure 3: Comparison of Digital Camera VIs based ROI – Both ExG and Gcc show differences in values based on each ROI, but exhibit almost perfectly correlated trends over time. Based on this result it was reasonable to average VIs across ROIs to determine a mean value for each image.

3.1.2 Illumination Effects & Near-Surface VIs

Near surface VI results were displayed in time series to compare trends in daily, 16 day, and monthly means based on varying illumination classifications. Daily data showed that cloudy and overcast days were highly variable in the VIs. However, despite this noise, when unfiltered days were composited into 16 day and monthly periods, the trends exhibited were similar to filtered data (Table 1 and Figure 3) However, characterizing illumination conditions is still an important aspect of using near-surface digital cameras in an attempt to ground-truth satellite derived VIs. Visual inspection of images showed clear effects of cloudy days on the VIs and though unfiltered data produced mean VI values similar to the sunny filtered data, this may not always be the case as cloud contaminated data is most likely producing inaccurate VIs. Additionally, SZA ANOVA analysis indicated that there were significant differences between times of day and pairwise t-tests showed that the 10:00 hour was significantly different from all other hours (p-value < 0.05 for all comparisons). This was further confirmed in visual analysis in which many 10:00 images were cloaked in shadows resulting from a non-overhead sun angle.

Gcc was more affected by illumination conditions, as unfiltered daily means showed more variability than ExG (Figure 4). Although changes in ExG were subtle in comparison to trends seen in temperate forests a seasonal greenness pattern was observable during the study period (Figure 4). Maximum green was registered in June during 2012 and 2013 and the most significant decline in greenness was shown between September and October 2012. While there was a slight spike in greenness during November, VI values remained at their lowest through the winter months until a consistent rise began again between January and February. Thus, near surface image VIs when averaged and filtered showed subtle changes in greenness and exhibited some seasonal patterns.

Table 1: Range of ExG values across filtering criteria and mean composite length – unfiltered data has a much broader range for daily data, however as the ExG VI is averaged over 16 day and monthly periods the effect of cloudy and overcast days is diminished. When data are filtered for only midday images labeled as sunny, they VI values show a slight increase.

	Daily		16Day		Monthly	
	Min	Max	Min	Max	Min	Max
ExG.unfiltered	19.68	41.2	25.21	31.63	25.27	31.34
ExG.sunny	23.84	34.36	24.42	31.83	24.95	31.52
ExG.midday.sunny	25.05	35.32	25.41	34.72	26.29	33.61

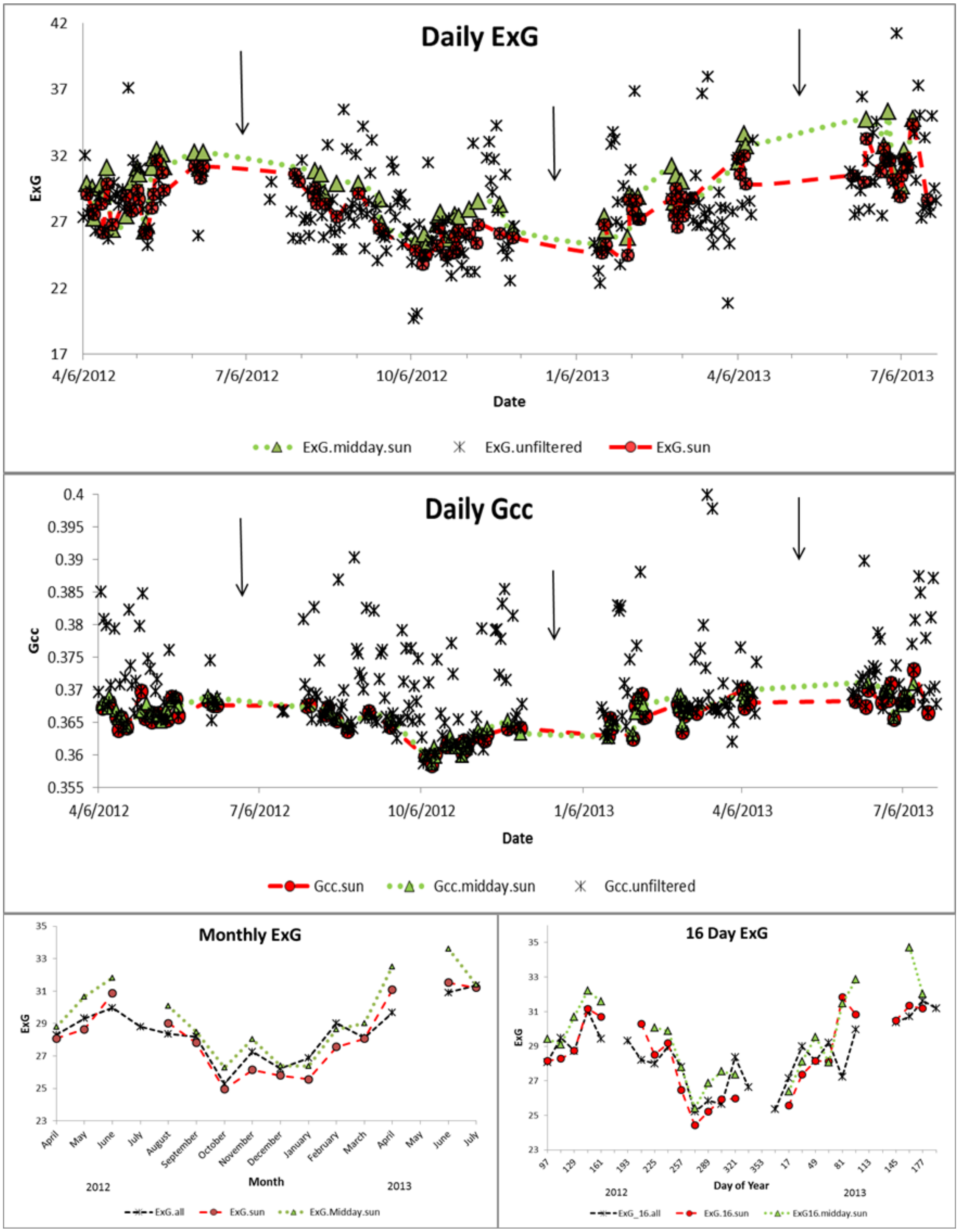

Figure 4: Time Series of camera VIs – Daily ExG and Gcc show high variation in unfiltered data, but when composited into 16 day and monthly periods, unfiltered and filtered ExG values follow similar trends (arrows represent gaps in which the camera was offline due to technical issues in the field).

3.2 MODIS & Near-Surface Digital Imagery VIs

MODIS data contains a great deal of noise in both 16 day and monthly composites for NDVI and EVI. Using MOD13Q1 (250m, TERRA) data as a test case for quality control, results indicate ample atmospheric influences that create this noise. Of the 16 day composites from 2012 to 2013, 19 of 32 days were flagged as having “marginal” (but “useful”) data quality and 13 had “good”, “use with confidence” flags. Using visual analysis of false color composites (R, NIR, B) of the 19 marginal days, 7 days showed cloud contaminated pixels in and around the pixel of interest containing the HVT tower. This result illustrates that even with 16 day compositing periods, VI signals in tropical cloud forests are subject to a high degree of cloud and atmospheric conditions that may influence optical signals. Given this scenario it is difficult to discern a seasonal pattern from MODIS satellite 16 day VI outputs at the HVT site without further visual screening.

Direct comparisons between MODIS and near surface camera VIs are imperfect as issues of scale are evident. Although MODIS offers high temporal coverage the 250m and 500m spatial resolutions are much wider than the camera field of view (approximately 100m). At the HVT site the one MODIS product that correlated well with near surface measurements of greenness was the monthly “meanc” composite of EVI. However, 16 day products and monthly “mvc” and NDVI values had little correlation or showed negative correlations with camera VIs (Table 2 and Figure 4). The noise in the satellite VIs relative to the near-surface images further illustrates the difficulties in using satellite remote sensing outputs in tropical locations with persistent cloud cover.

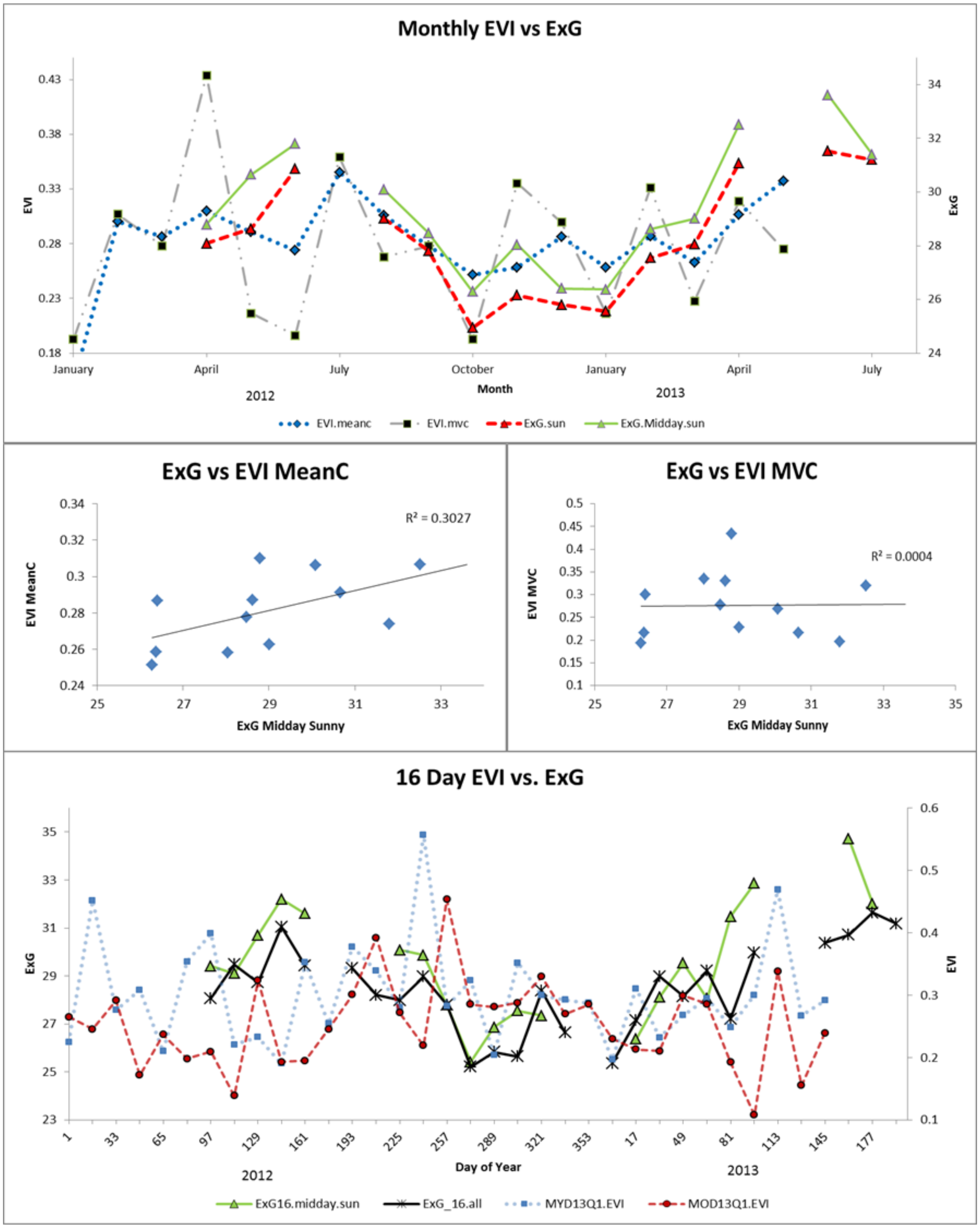

Figure 5: Comparisons of near-surface ExG VI to MODIS EVI – In almost all compositing methods MODIS data exhibited a great deal of noise in which seasonal trends in VIs were difficult to discern. The top panel, as well as the scatter plots, indicates MODIS EVI using "meanc" filtering criteria was the only VI to show some correlation with ExG VI from near-surface cameras. 16 day MODIS composites appeared noisy across the board (bottom panel).

3.3 Remote Sensing and Tower Environmental Variables

Across both the filtered and unfiltered ExG outputs there were correlations between the VI and net radiation (Figure 6). One area of note is during October 2012 in which there was a low point in precipitation (52 mm), a high in sunny days (based on visual image inspection, n=11), and a large spike in net radiation. After the most significant drop in VI between September and October, there was a spike evident in November for ExG, Gcc, and meanc EVI (Figure 5). Most other environmental variables showed little to no correlation with camera or satellite VIs (Table 2).

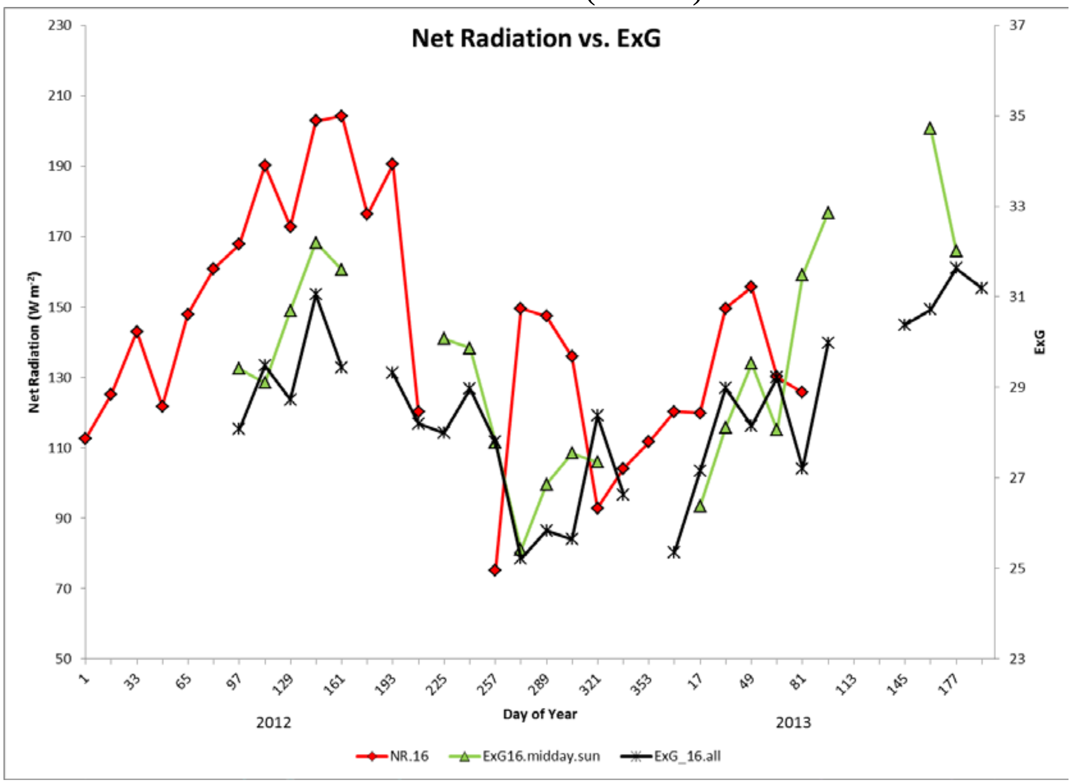

Figure 6: Time Series comparison of filtered ExG and Net Raditaion at HVT

Table 2: Results of correlation analysis (Spearman Rank) – This correlation matrix shows all variables from Near-Surface Cameras, MODIS VI, and environmental variables represented in 16 day composites (NR = Net Radiation; SM = Soil Moisture; *significant at $p < 0.05$). There is almost no significant correlation between in-situ camera VIs and MODIS VIs with the exception of a few negative correlations.

	ExG_16.all	ExG.16.sun	ExG16.midday.sun	Gcc_16.all	Gcc.16.sun	Gcc16.midday.sun	MOD13A1.EVI	MOD13Q1.EVI	MYD13A1.EVI	MYD13Q1.EVI	MOD13A1.NDVI	MOD13Q1.NDVI	MYD13A1.NDVI	MYD13Q1.NDVI	Rain	Temp	NR	SM1	SM2	SM3
ExG_16.all	1																			
ExG.16.sun	***0.7**	1																		
ExG16.midday.sun	***0.74**	***0.96**	1																	
Gcc_16.all	***0.63**	0.31	0.24	1																
Gcc.16.sun	***0.71**	***0.95**	***0.9**	0.33	1															
Gcc16.midday.sun	***0.72**	***0.9**	***0.92**	0.31	***0.95**	1														
MOD13A1.EVI	-0.19	-0.1	-0.13	0.09	-0.03	0.05	1													
MOD13Q1.EVI	-0.31	***-0.49**	***-0.53**	-0.22	***-0.47**	***-0.54**	***0.47**	1												
MYD13A1.EVI	0.01	0.02	0.03	-0.02	-0.09	-0.01	0.13	0.14	1											
MYD13Q1.EVI	0	-0.06	-0.12	0.03	-0.07	-0.15	0.01	0.16	***0.64**	1										
MOD13A1.NDVI	0.15	-0.16	-0.2	0.17	-0.05	-0.18	-0.12	0.12	***-0.4**	-0.11	1									
MOD13Q1.NDVI	0.05	-0.1	-0.15	-0.1	-0.1	-0.28	-0.29	0.26	-0.14	0.19	***0.76**	1								
MYD13A1.NDVI	0.11	0.36	0.3	-0.02	0.32	0.35	-0.15	***-0.37**	0.04	-0.33	-0.07	0	1							
MYD13Q1.NDVI	0.1	0.16	0.11	-0.19	0.29	0.27	-0.29	-0.34	-0.29	***-0.51**	0.14	0.02	***0.74**	1						
Rain	0.25	0.34	0.44	0.14	0.42	0.46	***-0.38**	***-0.43**	-0.01	-0.1	-0.08	-0.1	0.05	-0.07	1					
Temp	-0.26	-0.14	-0.22	-0.36	-0.31	***-0.52**	0.19	0.38	0.23	0.15	0.02	0.32	-0.01	-0.22	***-0.48**	1				
NR	***0.58**	0.44	***0.64**	-0.13	0.35	0.48	-0.04	-0.33	0.05	-0.03	-0.02	-0.05	-0.03	0.07	0.14	-0.16	1			
SM1	0.26	0.32	0.38	0.26	0.34	0.4	-0.12	-0.3	0.14	-0.16	-0.14	-0.2	0.21	-0.04	***0.82**	***-0.39**	0.2	1		
SM2	0.22	0.31	0.39	0.35	0.31	0.43	-0.27	***-0.4**	0.01	-0.12	-0.1	-0.18	0.18	-0.05	***0.89**	***-0.59**	0.06	***0.87**	1	
SM3	0.23	0.41	0.46	0.28	0.44	***0.52**	-0.24	***-0.44**	-0.02	-0.16	-0.1	-0.29	0.15	0.01	***0.88**	***-0.67**	0.12	***0.86**	***0.96**	1

4 Discussion

Hypothesized results centered on the idea that tropical forests show no seasonality and thus would be described by flat VI signals. However, the use of near-surface digital cameras at the HVT site indicated the contrary, as subtle changes to canopy greenness were evident and showed some correlation with net radiation. Despite in-situ evidence of seasonality, the MODIS VI signatures showed little correlation to near-surface camera VIs and were affected by complications related to cloud contamination. In relation to the overall objective of the study, these results indicate that use of moderate resolution satellite imagery for phenological purposes may be unreliable in Hawaii's tropical montane cloud forests where atmospheric interference is prevalent. Therefore, it is important that ground-truthing and *in-situ* studies continue.

4.1 Near Surface Camera ROIs and Illumination

The ROI results at HVT suggest it is safe to average across the canopy as the correlated trends illustrate the high degree of homogeneity present in the forest at this site. However, given the changes in values off nadir (applies to downward facing, hemispherical fields of view), a heterogeneous forest would possibly need a scaling factor applied to the VI results for different regions of the forest. For instance previous studies from the PEN and Phenocam network use a landscape with elevation gradients and mixed tree canopies (Richardson et al. 2009) and thus for VIs to be comparable controlling for pixel quality on the outer thirds of the image may be advantageous. Hufkens et al. (2012) notes a similar strategy by choosing only pieces of the canopy in the foreground of their straight ahead field of view.

Despite results of illumination classification indicating that unfiltered camera data means are similar to filtered means, careful consideration should still be given to visual image classification as cloudy conditions can have dramatic effects on the appearance and optical signal of greenness. Given the year round potential for high levels of cloud cover and precipitation in the tropics thorough screening for illumination effects may be more important than temperate locations. Temperate locations with canopies that experience dormancy will have more predictable near zero values during cloudy winter months and mostly sunny conditions during peeks of greenness and thus lend to using 90^{th} percentile moving average techniques for filtering, but given the potential for year round clouds in the tropics the percentile technique may include noisy data and thus filtering should aim to remove inadequate images. Restricting image use to midday images (11:00 – 13:00) can also remove the potential for shadow effects that were observed on some of the 10:00 and 14:00 images at the HVT site. The SZA analysis indicated significant differences in VIs at 10:00 as compared to the other hours and thus lends further weight to using midday images associated with more overhead sun lit conditions.

4.2 Seasonal Trends and MODIS validation

Though seasonal changes in greenness were subtle, the camera VIs indicated a clear phenological cycle in which greenness decreased and remained at its lowest levels between October 2012 and January 2013. The most significant decrease in greenness following September was reinforced both by visual inspection, which revealed not a single day during August or September with a VIC of 1 (sunny for all times of day), and also a significant drop in net radiation during those months. There was a slight spike in ExG during November which followed a large increase of net radiation during the drought month of October and further illustrated some of the correlation between the two variables. This result would be consistent with other tropical studies (Huete et al. 2006) that have predicted that tropical forests are light limited rather than moisture limited and their greenness responses are thus reacting to available sunlight for increased photosynthetic activity. Given the relatively modest time frame of this study it wouldn't be prudent to conclude that net radiation is explaining all changes to canopy greenness, but the trends should be continually monitored on site to lend to any future predictive explanatory possibilities.

Temperate forests ranged in the ExG index from 0-70 (deciduous red maple and birch forests, Bartlett forest), 0-25 in mixed higher elevation forests (Richardson et al. 2009), and 24-34 at HVT. The lack of a dormancy period at HVT explains the smaller changes in VI values. However, the existence of these subtle trends challenges the hypothesis which predicts a flat optical signal across seasons in tropical locations. The onset of more extreme climate change threatens to have large effects on phenological cycles and thus it is important to continue monitoring these trends, as Hawaii's montane cloud forests are important components to a threatened set of native natural resources that have large influences on ground water recharge, nutrient storage cycles, local climatic conditions, and provide habitat for native species (Giambelluca et al. 2009). The PEN camera shows the capabilities to be a useful monitoring device in understanding seasonal and environmental drivers of change to a tropical forest's photosynthetic activity measured through camera VIs.

Previous studies have shown that while there may be slight differences in specific onset dates, quality screened satellite data and near surface VIs can show high levels of correlation (Choi et al. 2011). However, for this study MODIS VI output proves difficult to trust as an indicator of seasonality in the tropics. Despite level 2G screening for atmospheric effects and the use of quality assessment flags, satellite data contains noise across most indices for the pixel at the HVT site. The 16 day MOD13 products all had erratic signals that made it difficult to recognize a seasonal trend. NDVI performed relatively poorly across all filtering and compositing techniques. EVI, as expected, given its use of further atmospheric corrections in its algorithm, performed slightly better as an indicator of the phenological trends reported in near surface camera VIs. However, this correlation only existed in "meanc" screened monthly composites based on daily MYD09GA products. This result indicates a need for more thorough screening of pixels for tropical locations as the MOD13 products include days that may have some cloud contamination even after quality assessments and compositing. Issues of scale both spatially and temporally must also be noted as Hawaii's landscape has quick changes in elevation, vegetation, and climate regimes that make the 250m and 500m spatial scale potentially coarse. While the 250m and 500m meter pixels that contain the HVT site appear relatively homogeneous based on aerial imagery the VI outputs are not consistent with ground observations and do not exhibit clear seasonal trends. Additionally, MODIS's advantage in temporal coverage is lost due to the lack of clear days, where even 16 day composites may not contain valuable observation days (despite near daily coverage) – this lends to a loss of detail in phenology studies where the date of greenness onset is important for understanding potential seasonal changes across time. Thus, the more frequent nature of near surface camera images is a valuable tool for more pin-point phenological analysis and for detecting the more subtle seasonal activity of a tropical forest.

4.3 Conclusions

Results from this study illustrate previously reported ambiguity in tropical forest phenology studies as the year round presence of cloud cover and precipitation make it difficult to distinguish the overall greenness cycle of the forest based on satellite remote sensing techniques. However, the use of near surface digital cameras to record visual spectrum optical signals and extract greenness indices proved useful in visualizing subtle seasonal changes in the forest's photosynthetic activity. There is also evidence that the phenological changes to canopy greenness are responding to available light in the form of net radiation. Based on this analysis it is recommended that phenology studies in tropical cloud forests use caution in relying on MODIS VI outputs to understand seasonal trends and that further near surface digital image studies are needed to a) understand subtle changes in canopy optical signals and b) to continue an effort to ground truth satellite remote sensing outputs.

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