HARMONIC ANALYSIS OF LONG-TERM MODIS TIME-SERIES DATA FOR VEGETATION DYNAMICS IN HAWAII

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ABSTRACT

Long-term MODIS vegetation index records were used to extract regularly-repeating seasonal and interannual greenness cycles in Hawaiian ecosystems using harmonic analysis. With two vegetation indices, NDVI and EVI, the MODIS system provided an opportunity to combine the two measures and create a hybrid approach to the leaf phenology study in a diversity of Hawaiian ecosystems. Despite data noise caused by variable meteorological conditions, the analysis effectively summarized the amplitudes and the frequencies of a series of sinusoidal harmonic terms based on 16-day vegetation index composite data. The amplitude of annual greenness quickly increased with mean annual precipitation (MAP) up to a 1000-1500mm range and declined rapidly thereafter. In wetter environments, where MAP was higher than 2000mm, NDVI values became saturated and EVI records showed that the amplitude of annual and biannual greenness cycles decreased gradually with MAP. MAP was also significantly correlated with the frequency of the first two predominant harmonics, the primary and the secondary harmonic terms. As MAP increased, the frequency of greenness cycles (or harmonic terms) increased. This pattern was observed among 12 land cover types selected from the Hawaii Gap Analysis Program's land cover map. These land cover types were categorized into three phenological groups based on their mean frequency of greenness cycles and MAP.

INTRODUCTION

One important research focus in tropical ecosystems is on the phenological patterns of the ecosystems and their link to long-term climate changes. Seasonal and long-term changes in photosynthetic activities rearrange spatiotemporal patterns of primary productivity, alter surface-atmosphere carbon exchange rates, and may function as a sensitive indicator of regional or global climate changes (Asner et al., 2000; Viña and Henebry, 2005). To understand and monitor the growth patterns of the tropical ecosystems, it is necessary to analyze and generalize the non-static leaf phenology of the landscape through time. Difficulties of data acquisition in cloud-prone areas have been overcome by availability of daily satellite coverage. The Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Index (VI) data products are designed to provide consistent vegetation conditions with moderate spatial resolutions (Justice et al., 1998). Time-series analysis of regularly sampled satellite data can help researchers extract a series of identifiable fluctuations from a highly variable but periodic phenomenon, such as the phenological development of vegetation, and summarize the phenomenon into simpler wave forms. Beginning in the mid 90's, harmonic analysis (also known as spectral analysis, Fourier analysis, and frequency analysis) has been successfully applied to high temporal resolution satellite data (Andres et al., 1994; Olsson and Eklundh, 1994; Verhoef et al., 1996, Azzali and Menenti, 2000; Jakubauskas et al., 2001; Moody and Johnson, 2001; Jakubauskas et al., 2002; Park, 2003). Harmonic analysis decomposes a time series into its constituent parts if the time series represents a periodic phenomenon. It transforms a complex time series to a sum of many sinusoidal functions, or harmonic terms (Davis, 1986). By using this mathematical approach, the phenological patterns of diverse biomes over a long-term period can be investigated and characterized based on remotely sensed vegetation indices. Knowing that the intensity and periodicity of photosynthetic activities are configured differently from place to place and that the Hawaiian environment consists of diverse ecosystems, characterization and generalization of their leaf phenology is a key to the understanding of vegetation dynamics of the environment. This paper describes, characterizes, and categorizes phenological patterns of a Hawaiian island's ecosystems using 7-year time-series MODIS VI data and harmonic analysis.

Using Vegetation Indices for Vegetation Dynamics

One set of biophysical variables formulated from remote sensing data is vegetation indices. These indices are defined as dimensionless, radiometric measures that indicate biophysical parameters of green vegetation, which includes leaf area index (LAI), percent green cover, biomass, chlorophyll content, and absorbed photosynthetically active radiation. LAI, in particular, is known as a key indicator of terrestrial plant biomass, and defined as projected leaf area per unit ground surface area (Bonan, 1993; Pierce and Running, 1988). Numerous studies have reported that remotely sensed vegetation indices could be used as a proxy indicator for biophysical variables even though the degrees of their correlations were different among various plant communities (Lee et al., 2004; Xavier et al., 2004; Turner et al., 1999). Although the Normalized Difference Vegetation Index (NDVI) has been widely used for vegetation monitoring, it may not be the optimal measure for photosynthetic activity of densely vegetated tropical forests. Researchers have reported that NDVI is more sensitive to chlorophyll content changes compared to canopy structural variations such as leaf area index (LAI), canopy type, and canopy architecture (Gao et al., 2000). The relationship between NDVI values and plants' photosynthetic capacity is not universal throughout different ecosystems, and NDVI is commonly saturated as LAI reaches 4 (Chen and Cihlar, 1996; Turner et al., 1999).

With the advent of MODIS, a new vegetation index, the Enhanced Vegetation Index (EVI), was developed to optimize the sensor's signals for surface greenness with improved sensitivity to ground biomass. It was designed in a way that the aerosol influence on the red band reflectance is minimized (Kaufman and Tanré, 1992). EVI is known as a better vegetation index because it is not saturated by higher LAIs, which is common in tropical forests. NDVI and EVI, the two vegetation indices available from MODIS, were used in this study because Hawaiian islands support diverse ecosystems from dry shrubland to tropical rainforest.

Harmonic Analysis of Time-Series Data

Harmonic analysis reduces a complex raw curve, such as a time-series NDVI, to a series of sinusoidal waves, terms, or harmonics. Each of these curves represents a periodic, repeating pattern of a phenomenon with a unique set of height, wavelength, and phase angle. Since the amplitude of a term corresponds to the magnitude of surface green-up, the phenological pattern of a place over a multi-year period can be evaluated. A more in-depth mathematical definition of harmonic analysis is described by Jakubauskas et al. (2001). Each term designates the frequency, or the number of cycles completed by a wave form over the defined study period (seven years in this case). In other words, the most variance of a row crop's NDVI time-series may be represented by the 7th term because it completes seven wave forms over the 7-year period with its peak in midsummer each year.

Although some of these studies used long-term vegetation index data for harmonic analysis, there has been no comprehensive analysis of continuous multi-year harmonic terms for a vegetation dynamics study, especially in tropical environments. These previous studies were conducted with 1 km or coarser AVHRR NDVI time-series data, which are often too coarse to characterize landscape dynamics in complex tropical ecosystems. With the two MODIS-based vegetation indices and their finer spatial resolution, interannual variability and its linkage to long-term precipitation change can be better investigated.

METHODS

Study Area

The study was conducted on the Island of Hawaii, the youngest and the largest island of the Hawaiian archipelago (Figure 1). Annual mean precipitation (MAP) varies enormously, ranging from below 200 mm/yr in the western leeward side to more than 7,000 mm/yr in the eastern windward side of the island. Seasonally, the rainfall regime is dry in summers (May-September) with steady trade winds and wet in winters (October-April) when trade winds are less frequent and storm development is more common. This pattern of rainfall is much stronger in dry areas compared to wet areas (Giambelluca and Sanderson, 1995). Most of Hawaii's coastal areas have annual temperatures of 23-24 °C, and the annual variation in mean monthly temperatures is no more than 5 °C. However, there is a significant temperature variation with elevation (Giambelluca and Schroeder, 1998; Nullet and Sanderson, 1993). The rainfall and temperature variations along with the mosaic of diverse substrates have resulted in wide gradients of soil and ecosystem development. As a result, the island supports 25 out of the 35 global life zones classified by Holdridge (1947).

Sample Site Description

Ground-based LAI values were collected from August 2006 to July 2007 at five different sites across the island (Figure 1). LAI was measured with a Li-Cor LAI 2000 plant canopy analyzer. The five field sites represent different biomes, elevations, and climatic regimes, and they have minimum human-induced disturbance. The sites include Hilo Forest Reserve (HR), Ōlaʻa Rainforest Reserve (OL), Mauna Kea forest (MK), Mauna Loa koa forest (ML), and Puʻu Waʻawaʻa dry forest (PU). Main characteristics of these sites are summarized in Table 1.

MODIS, Land Cover and Climate Data

MODIS vegetation index 16-day composite data (Feb. 2000-Jul. 2007) were obtained from USGS Earth Resources Observation ad Science (EROS) Data Center. These vegetation index products provide consistent spatial and inter-annual comparisons of global vegetation conditions, by which monitoring of the Earth's terrestrial photosynthetic activity is available. The MODIS Reprojection Tool software program was used to convert the original sinusoidal projection to UTM (zone 5), and two tiles (03/06 and 03/07) were stitched together to cover the entire island. Raw EVI and NDVI data were filtered and smoothed out with a 3-by-3 kernel using a focal median function. The Hawaii Gap Analysis Program (GAP)'s land cover map was obtained from the National GAP Project website (www.gap.idaho.edu/products/hawaii). The raw data contained 37 land over types, but it was generalized to 12 classes. Monthly rainfall data (2000-2007) were obtained from the National Climatic Data Center (www.ncdc.noaa.gov). To represent the rainfall amount at the sampling sites, the closest weather station was selected for each site. However, no weather stations were available in the proximate area of the HR site. Weather conditions are so variable on the mountain slope where the HR site is located and it is not reasonable to use meteorological data collected from great distances. Therefore, meteorological data for the site were not collected. Spatially continuous MAP data (1971-2000) were downloaded from the PRISM group's website (prism.oregonstate.edu). The data were constructed based on the PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system (Daly et al., 1994).

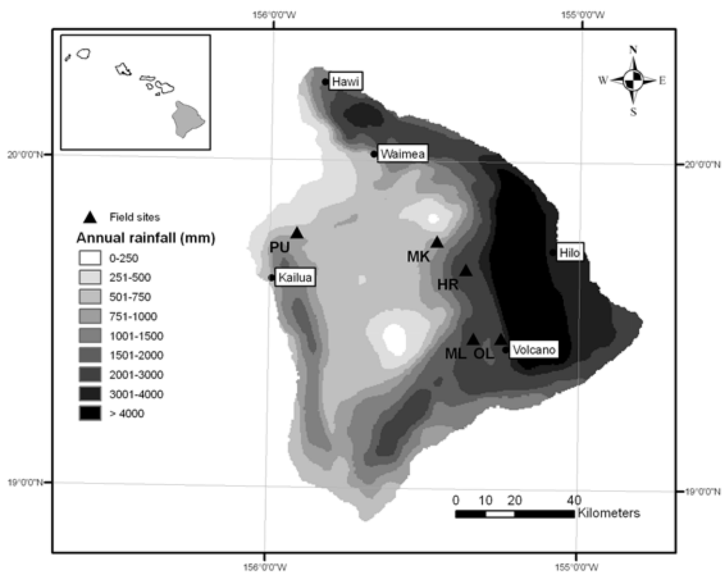

Figure 1. Study area. Mean annual precipitation (1971-2000) is represented with five sample site locations.

Table 1. Field site description.

Site	Land cover	Elevation	Annual precipitation	Mean LAI
HR	Ōhiʻa	1710 m	2682 mm	2.40
OL	Ōhiʻa /hapuʻu pulu	1200 m	2620 mm	4.30
PU	Dry forest	625 m	666 mm	1.45
MK	Mamane	2820 m	626 mm	0.56
ML	Koa forest	1450 m	1487 mm	2.37

Harmonic Analysis

For harmonic analysis, the *Fourier Machine* software (Jakubauskas and Kastens, 2000) was used. The variance of a harmonic is determined by the magnitude of its amplitude, and the variance of the *k*th harmonic is given as:

$$s_k^2 \text{ (variance of the } k\text{th harmonic)} = \frac{A_k^{\,2}}{2}, \quad \text{where } A_k \text{ is the amplitude of the } k\text{th harmonic.}$$

Since the sum of harmonics equals the original time-series, the harmonic with the largest variance is considered as the dominant periodic component. For example, if an annual cycle is dominant in the seven-year VI time-series, the variance of the 7th harmonic (7 complete cycles during the 7 years) will be peaked. The first two highest variances were selected for each pixel, and the sum of these variances was averaged for pixels that were in the same NDVI class and converted to percent variance against the total variance of all harmonic terms considered. The mean percent variance for each NDVI class was calculated with an increment of 0.1. This calculation indicated how the dominance of the major harmonics changed in representing the periodicity of greenness as NDVI increased. If NDVI was saturated in wet, dense forests, the NDVI percent variance of a dominant harmonic became smaller than the EVI percent variance of that harmonic because the saturation significantly reduced seasonal and interannual amplitude of NDVI harmonics. For those pixels whose NDVI percent variance was smaller than their EVI percent variance, NDVI-based harmonic analysis was replaced by EVI-based one to avoid the saturation problem.

RESULTS AND DISCUSSION

Comparison of LAI, NDVI and EVI

The annual mean LAI at the five field sites was well correlated with the vegetation indices (Figure 2). For sparsely vegetation sites, however, EVI was not as responsive as NDVI to LAI. Since EVI was designed to better respond to high LAI, EVI change at sites with low LAIs (0-2) was marginal but its sensitivity to LAI change increased significantly at sites with high LAIs. For this reason, lower EVI values for HR, MK, and PU sites did not reveal any apparent seasonal patterns. The peak of the percent variance of a harmonic indicates how much that harmonic stands out as a major repeating cycle. Those harmonics that had higher frequencies than four per year were considered unrealistic and excluded from further analysis. The percent variance of the two highest peaks rapidly increased as NDVI increased, but it dropped quickly after an NDVI range of 0.5-0.6. Beginning from a 0.6-0.7 range, on the other hand, the percent variance of EVI became greater than that of NDVI, where the percent variance of EVI became greater than that of NDVI. Therefore, NDVI is more effective than EVI in detecting leaf phenology for sparse/open-canopy vegetation, while EVI outperforms NDVI for dense vegetation. As expected, the relationship between NDVI and EVI showed that NDVI became saturated and leveled off instantly after 0.6.

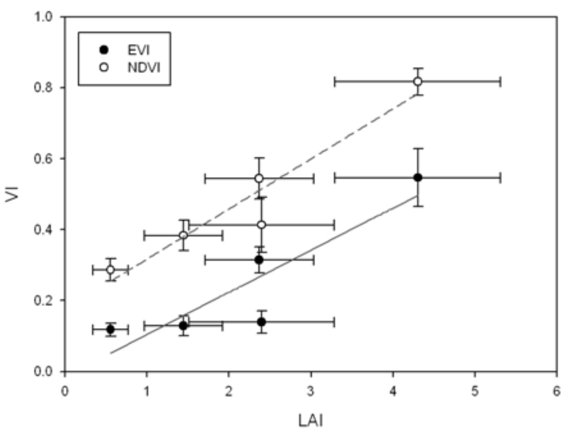

Figure 2. Correlations between NDVI and EVI and the annual mean LAI measurements at the five field sites (r = 0.96 for NDVI and r = 0.90 for EVI).

Phenological Characteristics

There were several notable outcomes in the long-term time-series signals. Firstly, the wettest site, OL, had a pattern clearly opposite to the other sites. The OL site had summer-low/winter-high greenness cycles, while the others, except the HR site, had a summer-high/winter-low pattern. This pattern is in large part correlated with the climatic pattern of the region (dry summers and wet winters). Knowing that temperature remains relatively constant over the year, it is believed that photosynthesis in the rainforest ecosystem is inhibited by too much rainfall or limited sun hours in the winter. If the greenness pattern of the OL site is compared with monthly rainfall records, most of the EVI peaks are associated with low precipitation while low EVI's are with high rainfall (Figure 3-a). Similar results were observed with recent data collected from wet tropical forests in Maui (Schuur, 2003). The study revealed that forest productivity in the wet environment decreased with precipitation over 2000 mm.

Secondly, the two mid-altitude windward sites, OL and ML, had weaker seasonal signals until 2003 and stronger signals thereafter, while the PU site located on the leeward side had an almost reversed pattern. The absence of typical summer-low/winter-high rainfall regime in 2001 and 2003 might have disturbed the growth pattern of these two wet ecosystems (Figure 3-a and b). For the PU site, no significant greenness amplitude was observed in the two wettest years, 2004 and 2005, during the study period. (Figure 3-c). Finally, a long-term, low-frequency cycle was only observed at the leeward location, PU, while high-frequency patterns were dominant at the four windward sites. It is obvious that the dry site had the smallest annual rainfall variation each year, but it had enormous seasonal greenness fluctuations (2000-2003). Knowing that rainfall amount was relatively small and its variation was not significant, it is difficult to explain what might have caused the greenness change. Excluding this outlier, the amplitude of annual harmonics of the sites agreed well with the annual variance of LAI collected during the field survey from 2006 to 2007 (r = 0.89). On the opposite end, the HR site did not show any apparent seasonal pattern throughout the study period. Being located below the temperature inversion layer with estimated mean annual rainfall of 2682 mm, the site is constantly under cloudy and rainy conditions. The unpredictable condition is well represented in Figure 3-e with significant noisy greenness signals.

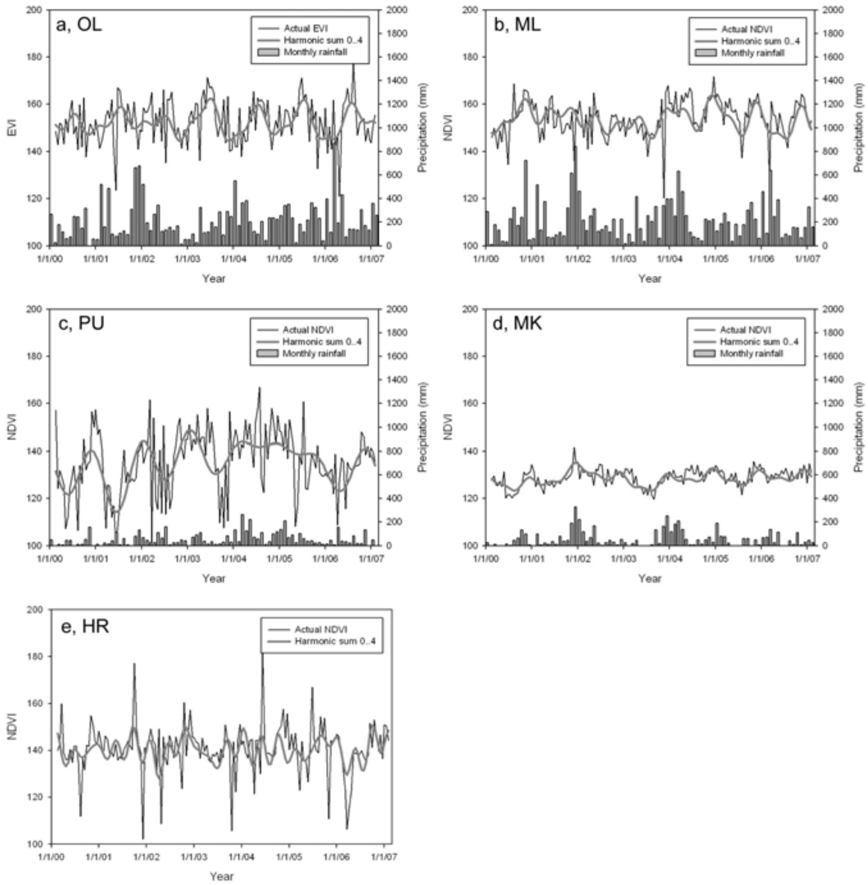

Figure 3. Rescaled (0 – 200) vegetation index values are superimposed with the partial sum of the first four major harmonics. Monthly rainfall records from the closest weather stations are compared with the curves. No weather station is available for the HR site.

Vegetation Dynamics-Land Cover Relations

The first two harmonics that had the most VI variance, the primary and the secondary harmonics, were extracted for each pixel based on their variance magnitude. Each of these two dominant harmonic terms was categorized into one of five different periods, which included multiyear (1st to 5th terms), annual (6th to 8th terms), subannual (9th to 12th terms), biannual (13th to 15th terms), and frequent (16th to 32nd terms) periods. These five greenness periods were cross-tabulated with 12 land cover types from the generalized Hawaii GAP land cover map (Table 2).

Table 2. Twelve land cover types selected from a generalized Hawaii GAP map. Mean annual precipitation and land area of each class are provided.

Land cover	MAP (mm)	Area (ha)	% cover	Land cover	MAP (mm)	Area (ha)	% cover
alien mixed forest	2682.1	31918.8	3.06	mixed forest	3136.7	637.5	0.06
closed koa-ōhiʻa	3579.2	43487.5	4.17	open koa-mamane	720.3	9568.75	0.92
closed ōhiʻa	3260.1	80487.5	7.72	open koa-ōhiʻa	2162.7	27356.3	2.62
grassland	1325.7	225888	21.67	open ōhiʻa	3304.3	89756.3	8.61
koa	2080.8	262.5	0.03	shrubland	1449.5	169106	16.22
mamane	868.6	12925	1.24	wetland	2754.2	1068.75	0.10

The frequency of leaf phenology cycles was lower in dry areas, but it increased with MAP. The two harmonic terms had a similar pattern, but the secondary harmonics represented higher frequencies of greenness cycles compared to the primary harmonics. Based on the frequency of leaf phenology-MAP relation as illustrated in Figure 4, three natural groupings were found among the 12 land cover types. The first group included open koa-mamane, mamane, grassland, and shrubland, and it was dominated by multiyear- and annual cycles. The second phenological group included koa forest, open koa-ōhiʻa forest, and alien mixed forest. Signals of multiyear periods were diminished for the primary and secondary harmonics, but the mean frequency of the harmonics was close to annual cycles. The final group include closed ōhiʻa forest, open ōhiʻa forest, mixed forest, closed koa-ōhiʻa forest, and wetland. These land cover types typically had biannual or more frequent greenness cycles. Judging from the frequencies of the primary harmonics and precipitation regime of the ecosystems, we can characterize the three different groups of leaf phenology types as ‘dry, long-term,’ ‘humid, annual,’ and ‘perhumid, biannual’ patterns.

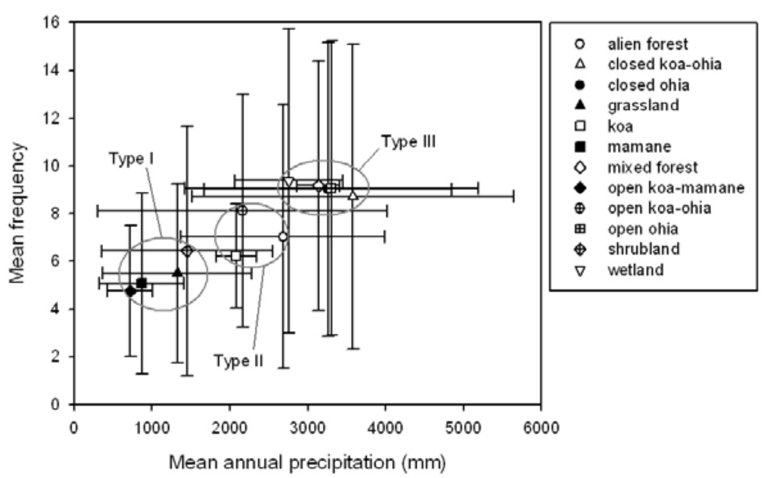

Figure 4. The relationship between MAP and frequencies of harmonics for individual ecosystems. Three natural breaks were found among the 12 land cover types. Type I = ‘arid, long-term,’ type II = ‘humid, annual,’ and Type III = ‘perhumid, biannual’ patterns.

Vegetation dynamics are land cover-dependent. However, climatic conditions play a significant role as well. Since rainfall is a much stronger control factor compared to temperature in the tropics (Schuur, 2003), the leaf phenology of the land surface was strongly correlated with rainfall amount. The percent variance of the primary and the secondary harmonics were further analyzed in relation to MAP. The NDVI percent variance of the two major harmonic terms combined increased rapidly with MAP until 1500 mm, but it decreased thereafter. The relative significance of the major harmonic terms for EVI was lower than NDVI in dry areas, but it surpassed NDVI if MAP was greater than 2000 mm. Thus, greenness periodicity could not be effectively detected by NDVI in very wet environments (MAP > 2000 mm) because the index became saturated in densely vegetated areas, where NDVI values were typically higher than 0.6. NDVI rapidly increased with MAP, reaching 0.6 when MAP was greater than 2000 mm, and the NDVI percent variance of the two major harmonics became smaller than the EVI one in wetter conditions due to NDVI saturation. Therefore, it is believed that the prevailing periodicity of vegetation greenness is much clearer and detected by NDVI records in drier (MAP <2000 mm) areas, but EVI becomes a better indicator of leaf phenology in wetter (MAP >2000 mm) environment.

CONCLUSIONS

Study results suggested that the greenness of Hawaiian ecosystems constantly fluctuated and the frequencies of their phenological cycles were strongly correlated with MAP. Although individual ecosystems were found under a broad range of precipitation, harmonic analysis showed that ecosystems in wetter environments, in general, had more frequent greenness cycles than those in drier areas. The periodicity of greenness and its magnitude were most prominent in areas with MAP of 1000 to 1500 mm, and it was dominated by annual and longer-term frequencies of dry biomes, especially grassland and shrubland. EVI was a better indicator than NDVI for dense vegetation, but it should not replace NDVI in regions, where a wide array of ecosystems exists, such as the Hawaiian islands. NDVI better represented greenness changes compared to EVI in dry to temperate environments, where their greenness fluctuations were not effectively captured by EVI. The greenness of multi-layered, dense rainforests in perhumid conditions was negatively influenced by very high rainfall amounts. It is believed that productivity of dense rainforests is limited by solar hours in the region. Knowledge of long-term vegetation dynamics in relation to rainfall can provide pivotal information about habitat quality evaluation, impacts of climate change on terrestrial ecosystems, primary productivity monitoring, and wildfire fuel conditions in drylands, which is valuable for wildfire monitoring. Study results may be also useful for ecological niche modeling of invasive species in the region. Knowing that vegetation dynamics had a close relationship with moisture regime, substrate characteristics, leaf water content, and moisture-sensitive vegetation indices should be integrated into future studies to further explain the spatial heterogeneity of greenness periods in the area.

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