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MODIS Derived Vegetation Index for Drought Detection on the San Carlos Apache Reservation

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Abstract A variety of vegetation indices derived from remotely sensed data have been used to assess vegetation conditions, enabling the identification of drought occurrences as well as the evaluation of drought impacts. Moderate Resolution Imaging Spectroradiometer (MODIS) Terra 8-day composite data were used to compute the Modified Soil Adjusted Vegetation Index II ($MSAVI_2$) of four dominant vegetation types over a 13-year period (2002 – 2014) on the San Carlos Apache Reservation in Arizona, US. $MSAVI_2$ anomalies were used to identify adverse impacts of drought on vegetation, characterized as mean $MSAVI_2$ below the 13-year average. In terms of interannual variability, we found similar responses between grassland and shrubland, and between woodland and forest vegetation types. We compared $MSAVI_2$ for specific vegetation types with precipitation data at the same time step, and found a lag time of roughly two months for the peak $MSAVI_2$ values following precipitation in a given year. All vegetation types responded to summer monsoon rainfall, while shrubland and annual herbaceous vegetation also displayed a brief spring growing season following winter snowmelt. $MSAVI_2$ values of shrublands corresponded well with precipitation variability both for summer rainfall and winter snowfall, and can be potentially used as a drought indicator on the San Carlos Apache Reservation given its wide geographic distribution. We demonstrated that moderate temporal frequency satellite-based $MSAVI_2$ can provide drought monitoring to inform land management decisions, especially on vegetated tribal land areas where in situ precipitation data are limited.

Keywords *Drought; Modified Soil Adjusted Vegetation Index II ($MSAVI_2$); MODIS; Precipitation; Vegetation Index Anomaly*

1. Introduction

Drought cycles are complex natural climate phenomena. The Southwestern United States has experienced persistent drought conditions since the 1990s, the severity and duration of which has not been seen in over 800 years (Cook et al., 2004; Meko et al., 2007). Climate change is projected to increase the severity and frequency of droughts in the Southwestern United States (Schwalm et al., 2012; Seager and Vecchi, 2010). Mean annual temperature is expected to increase by as much as 2 degrees Celsius by 2100 globally (IPCC, 2013). Warmer air temperatures increase atmospheric evaporative demand, further reducing available moisture for vegetation (Weiss et al., 2009). Precipitation in the Southwest US typically follows a bi-modal pattern: winter and early spring bring snow to high elevation forests and rain to lower regions, and the North American monsoon season generates rain in the summer. Climate change is expected to disrupt this existing weather patterns and hydrological cycle. Warmer temperatures will cause more winter precipitation to fall as rain instead of snow (Knowles et al., 2006), snow to melt earlier in the spring (Clow, 2010; Harpold et al., 2012) and an overall decrease in precipitation as winter storm tracks shift to the north (Christensen et al., 2004). Forest communities of the Southwest US are known to be sensitive to changes in precipitation and moisture availability (Breshears and Barnes, 1999). Trees that are stressed by drought are more prone to fire, disease outbreaks, and mortality (Williams et al., 2010). Vegetation stressed by drought can result in a decrease in net primary production (NPP) – the transfer of carbon from the atmosphere to terrestrial biomass, which reduces the overall amount of carbon stored by vegetation. A reduction in NPP over North America in the early 2000s has been attributed to large-scale droughts in the region (Zhao and Running, 2010). Thus, understanding drought impacts on vegetation can help inform natural resources management decisions, and predict carbon cycle feedback to climate change (Friedlingstein et al., 2006).

In Arizona, summer monsoon moisture is important for vegetation growth, accounting for most of the rainfall during the year (Higgins et al., 1997). Droughts appear mainly because of irregularities in the amounts of summer monsoonal rainfall and winter snowfall. Detecting the emergence of drought is difficult because of its slow onset and lagged impacts. Direct assessment of drought usually requires climate data such as the Palmer drought severity index (Palmer, 1965), but this index has been criticized for its simplicity and for the manner in which potential evapotranspiration is modeled (Sheffield et al., 2012). In situ precipitation data from sparsely distributed stations hinder the drought analysis and the ability to map spatial patterns of drought. Satellite-based information has often been used in drought studies in recent decades because of its efficiency in identifying, monitoring and assessing drought conditions on the spatiotemporal scale (Zhang and Jia, 2013; Rhee et al., 2010; Vicente-Serrano, 2007). In addition, a number of satellite-based vegetation indices have been developed for monitoring drought from space (Anderson et al., 2011; Wang and Qu, 2007; Bayarjargal et al., 2006), taking advantage of the large spatial coverage and high temporal frequency of the satellite data.

Measurements of decreased vegetation productivity through remotely sensed satellite images can serve as a proxy for monitoring drought. For example, recent insect outbreaks (Meddens and Hicke, 2014; Walter and Platt, 2013; Dennison et al., 2010) and forest die-off events (Anderegg et al., 2013; Allen et al., 2010) in western North America observed through satellite imagery have been attributed to persistent drought conditions over the region. Remote sensing data derived vegetation Indices are often used to measure vegetation response to climactic conditions over time, and therefore time-series data are crucial for monitoring vegetation response as it relates to variabilities of temperature and precipitation. Because actively photosynthesizing vegetation is highly absorptive in the red spectrum and highly reflective in the near infrared, the Normalized Difference Vegetation Index (NDVI) is one of the most widely used vegetation indices for monitoring drought and vegetation health (Tucker, 1979; Ji and Peters, 2003; Anyamba and Tucker, 2005; Yengoh et al., 2015). In dryland environments, however, background soil and exposed surface reflectance can blur the vegetation signal (Lu et al., 2015). To control for this effect, the Modified-Soil Adjusted Vegetation Index ($MSAVI_2$) was developed to account for differences in soil brightness that can be found in arid to semi-arid regions (Qi et al., 1994). Although $MSAVI_2$ has been used to monitor vegetation growth in various ecosystems (Mariotto and Gutschick, 2010; Heiskanen, 2006; Gonsamo and Chen, 2014), it has less commonly been used for drought detection and monitoring vegetation temporal responses to drought.

The impacts of drought on vegetation depend on the local climatic regimes and vegetation types in the region, so it is almost impossible to develop a universal drought monitoring approach that spans different regions. For our study area of San Carlos Apache Reservation in the semi-arid Southwest US, we developed a drought monitoring approach using high temporal frequency MODIS-derived $MSAVI_2$, which is particularly effective in arid and semi-arid regions (Qi et al., 1994). We established a 13-year mean $MSAVI_2$ as a baseline for four vegetation cover types over the entire San Carlos Apache Reservation and compared annual $MSAVI_2$ variability to the baseline (as anomalies) for drought detection. Specifically, our objectives were to: (1) assess the severity of drought in the past 13 years using $MSAVI_2$ anomalies, (2) compare drought impacts on different vegetation types, (3) identify time lags between vegetation responses and precipitation, and (4) identify indicator vegetation types for drought detection on the San Carlos Apache Reservation.

2. Methods

2.1. Study Area

The study area encompassed the entire San Carlos Apache Reservation (33.82°N, -110.75°W – 32.86°N, -109.48°W, Figure 1) in east-central Arizona. The reservation covers approximately 7,447 km^2, with elevation ranging from 600 to 2,400 meters above sea level (ASL). Its diverse habitat includes high desert grasslands and shrublands, pinon-juniper/chaparral/oak woodlands and is dominated by ponderosa pine forests. The coldest month in the town of San Carlos (33.351^{o}N, -110.452^{o}W, 819 m ASL) is January with a mean low temperature of 0^o C and high of 13^o C; July is the warmest month with mean low and high temperatures of 17^o C and 35^o C, respectively. Mean yearly rainfall ranges from 300 to 560 mm per year, with both precipitation and temperature dependent on elevation and season. From November through March, storms originating from the Pacific generally bring snowfall to the higher elevation ponderosa pine forests. The North American Monsoon brings summer rainfall from moisture originating in the Gulf of Mexico and the Gulf of California, usually lasting from late June through September (Higgins et al., 1997).

2.2. MODIS Satellite Imagery

We used 8-day composite surface reflectance data from the MODIS satellite at 250-meter spatial resolution for a 13-year study period (2002-2014). A maximum of 46 dates were available each year. Each image date was visually examined for cloud/cloud-shadow related artifacts. If these artifacts covered more than 10% of the reservation land, the image date was excluded from use in our analysis. In addition, the average of the two nearest valid dates was used to minimize effects of any missing scenes.

To understand the effects of climate on vegetation within the reservation land area, band 1 (red) and band 2 (near infrared) of the 8-day composite MODIS surface reflectance data were used to calculate $MSAVI_2$ for each date. The $MSAVI_2$ index was calculated as follows:

$$MSAVI_2 = \frac{2*NIR+1-\sqrt{(2*NIR+1)^2-8*(NIR-RED)}}{2},$$

Where NIR and RED are the surface reflectance of the near infrared and red bands, respectively. For each individual year, the mean $MSAVI_2$ value was calculated for the whole Reservation using the 8-day composite MODIS data. The resultant annual mean $MSAVI_2$ images were used to calculate a mean $MSAVI_2$ value for the 13-year study period as a baseline to generate $MSAVI_2$ anomalies. The $MSAVI_2$ anomalies were defined as the difference between the annual mean $MSAVI_2$ value of a given year and the 13-year $MSAVI_2$ average for a given pixel (Figure 1). On a pixel-by-pixel basis, each annual anomaly image was classified, highlighting areas within the reservation that had experienced drought impacts (negative $MSAVI_2$ anomalies) for the study period. A cumulative drought image was generated by quantifying the number of years out of the 13-year period that had experienced vegetation stress due to drought (negative $MSAVI_2$ anomalies). The cumulative drought image was then classified into six classes to characterize the drought impacts on various vegetation types on the San Carlos Apache Reservation (Table 1).

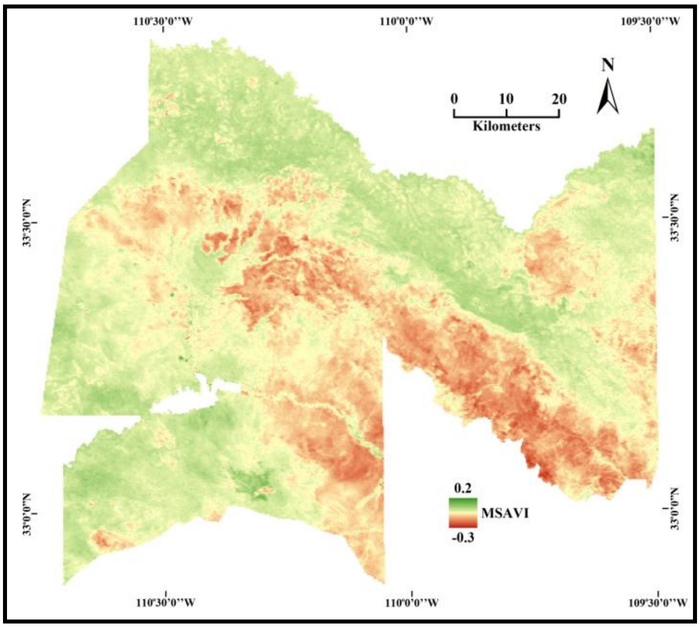

Figure 1: *Sample MODIS-Derived $MSAVI_2$ Anomaly (year 2009) of the San Carlos Apache Reservation*

2.3. LANDFIRE Vegetation Layer

We obtained the 2012 Landscape Fire and Response Management Tools (LANDFIRE) vegetation layer (http://LandFire.gov). LANDFIRE, a shared program between the wildland fire management programs of the U.S. Department of Agriculture and U.S. Department of Interior, provides several geospatial layers for natural resource management (Rollins and Frame, 2006). The 2012 LANDFIRE vegetation layer consist of several specific vegetation types. For this study, we consolidated the LANDFIRE vegetation classes into the following categories: grassland, shrubland, woodland, forest and others (e.g. developed, water) (Figure 2).

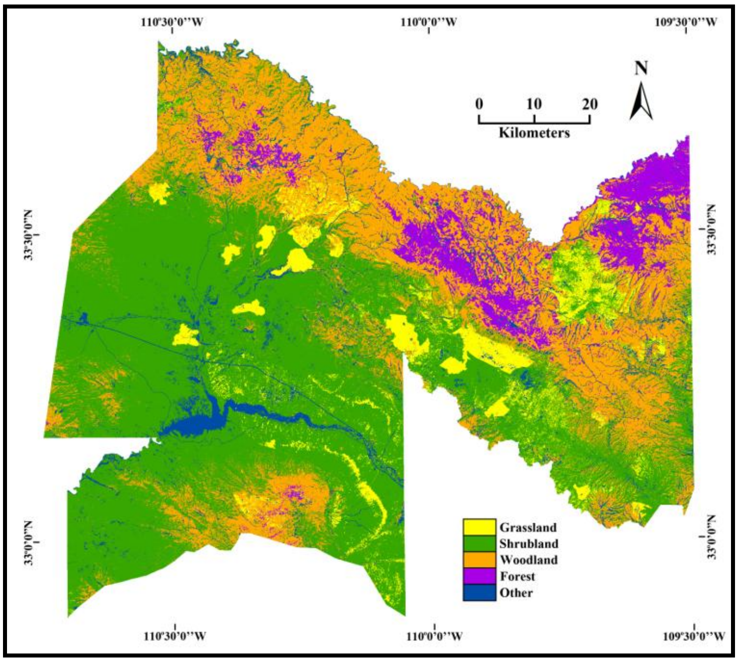

Figure 2: *LANDFIRE Derived Vegetation Types of the San Carlos Apache Reservation Consolidated into Five Simplified Land Cover Types*

2.4. PRISM Precipitation Data

Precipitation, from either winter snowfall or summer rainfall is the driving factor for vegetation green-up response (Davenport and Nicholson, 1993). Accurate and timely measurements of precipitation are important for the assessment of vegetation response. However, there are no currently established long-term weather stations on the San Carlos Apache Reservation and very few exist nearby. Instead, we obtained 4-km gridded precipitation data from the Parameter-elevation Relationships on Independent Slopes Model (PRISM) Climate Group at the Oregon State University (http://prism.oregonstate.edu). The PRISM datasets use a digital elevation model and point data to produce daily estimates of precipitation and temperature (Daly et al., 2002), especially the incorporation of radar data to produce the enhanced hybrid gridded precipitation data from 2002 on (http://www.prism.oregonstate.edu/documents/PRISM_datasets.pdf). The daily precipitation data were averaged into 8-day composite values to correspond with the composite MODIS data for the study period of 2002 to 2014.

2.5. Statistical Analysis

The lag between precipitation and vegetation response can vary depending on land cover type (Wang et al., 2003). For each individual date of the study period (2002-2014), mean $MSAVI_2$ values of each vegetation type were computed using MODIS-derived $MSAVI_2$ and vegetation classes from LANDFIRE. Using the same drought impacts classes identified for $MSAVI_2$ values, the mean $MSAVI_2$ value for each of the four vegetation types that fell within the medium to severe impact classes (Table 1) was calculated and compared with 8-day precipitation data from PRISM. Recognizing the inherent variability within the 8-day $MSAVI_2$ data, a running average of five image dates was calculated to best represent the vegetation response throughout the entire study period. To evaluate the most appropriate time lag between vegetation responses and precipitation events, we compared Pearson correlation coefficients between $MSAVI_2$ and precipitation for seven different time lags (32 – 80 days).

All image processing was performed using ERDAS Imagine 2014 (Hexagon Geospatial, GA, US) and statistical analyses were conducted in Microsoft Excel 2010 (Microsoft Corporation, WA, US).

Table 1: *Drought Impacts Classification and Vegetation Composition*

Drought Impacts	Drought years*	Grassland	Shrubland	Woodland	Forest	Other	Total
	# years	km^2	km^2	km^2	km^2	km^2	km^2
Low	1 -4	16	31	121	55	16	239
Low-Medium	5	82	268	401	116	63	930
Medium	6	204	972	781	168	143	2,268
Medium-High	7	179	1,500	627	118	135	2,559
High	8	55	869	191	37	57	1,209
Severe	9 -11	7	193	25	4	12	242

*Drought years are defined as years with mean $MSAVI_2$ values below the 13-year average as negative anomalies

3. Results

3.1. Drought Impacts on Vegetation

Drought impacts were evaluated using the number of years with mean annual $MSAVI_2$ values below the 13-year (2002-2014) average (negative anomalies) (Table 1). The entire San Carlos Apache Reservation experienced at least one drought year out of the 13-year study period. The most severely impacted areas experienced drought conditions 11 out of 13 years. The total area in each drought impact class followed a normal distribution, with most areas in the medium and medium-high impact classes, followed by high and low-medium classes, and severe and low classes covering the smallest area (Table 1).

Drought impacts varied across vegetation types. Woodland and forest areas showed a decreasing trend along a drought impact gradient (Figure 3), indicating they were more buffered during drought occurrences. Shrubland as the most prevalent land cover type in the study area, showed the opposite trend from woodland/forests (Figure 3). When compared to other vegetation types, shrubland was the dominant land cover type in the medium-high drought impact category, and it became more predominant as the drought impact increased to the severe level, suggesting that shrubland can be used as a drought indicator vegetation type for the San Carlos Apache Reservation. Meanwhile, grasslands and other land areas did not show a significant trend along the drought impact gradient (Figure 3).

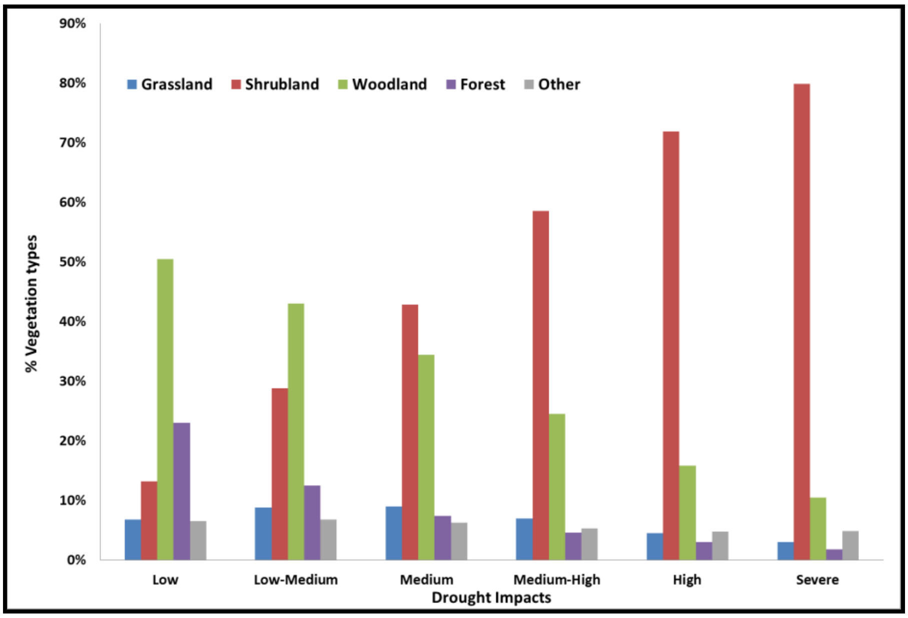

Figure 3: *Vegetation Type Distribution within Each Drought Impact Category*

3.2. Interannual Variability of Vegetation Response

All four vegetation types showed fluctuating interannual variability (Figure 4). However, grasslands and shrublands displayed a larger range of variability on an annual basis compared to woodlands and forests on the San Carlos Apache Reservation. The relatively "muted" response of woodlands and forests corresponded to the lower percentage of these two vegetation types in the higher drought impact classes (Figure 3). The differences between the two vegetation groups – grassland/shrubland and woodland/forest, were more obvious when we compared the mean $MSAVI_2$ values of the two vegetation groups (Figure 4, insert). Therefore, from here on, we used the two broader vegetation groups – grassland/shrubland and woodland/forest to further probe the mechanisms of the vegetation response to drought.

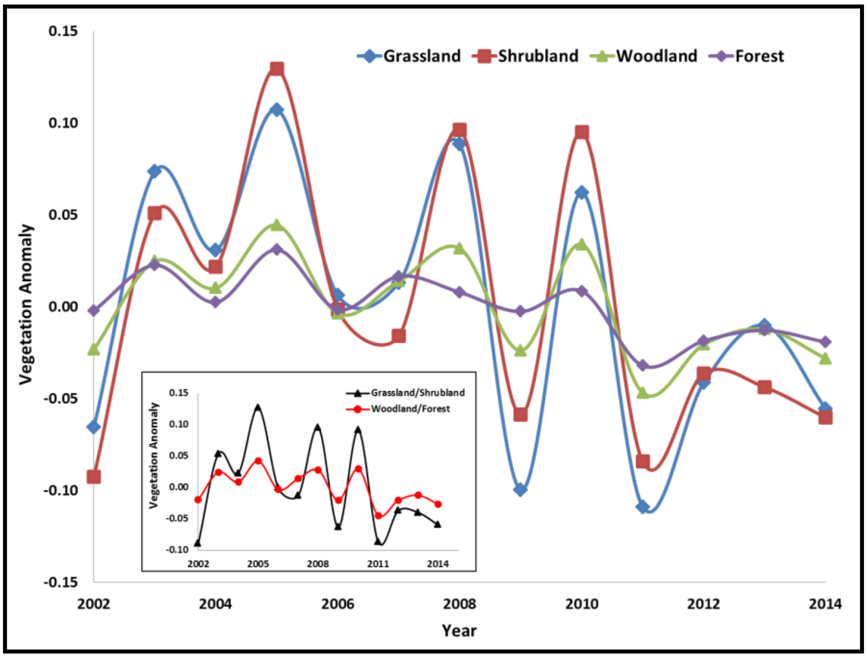

Figure 4: *Mean Annual Vegetation Anomalies for 2002-2014. The Vegetation Anomalies were averaged across Medium to Severe Drought Impacts Classes Identified in Table 1. The Insert Graph Shows the Grouped Vegetation Anomalies of Grassland/Shrubland and Woodland/Forest, Respectively*

3.3. Precipitation Variability and Vegetation Response

Correlation coefficients between vegetation responses and precipitation increased as lag time increased and tended to level off after the 64-day lag time (Figure 5). Although the correlation coefficients increased slightly beyond lag time of 64 days, the explanatory power of the relationship between precipitation and $MSAVI_2$ did not substantially increase, especially for the woodland/forest areas (Figure 5). The lag time referred here is defined as the onset of the precipitation event to the initiation of $MSAVI_2$ peak, which may occur after the initial vegetation growth. The peak $MSAVI_2$ date corresponded well with the peak precipitation date during the summer monsoon using a lag time of 64 days (Figure 6, shaded monsoon periods). With the 64-day lag time, both grassland/shrubland and woodland/forest vegetation groups showed a strong growth response to the summer monsoon rainfall, with woodland/forest having a higher mean $MSAVI_2$ value and a longer growing season following the onset of the monsoon (Figure 6). Overall, grassland/shrubland showed a higher correlation coefficient with precipitation than that from the woodland/forest vegetation group (Figure 5), mostly due to the C_3 shrubland green-up in response to the winter snowmelt (Figure 6, between shades). Grass species on the San Carlos Apache Reservation are dominated by C_4 grasses that are dormant during the cold winter season and respond rapidly to summer monsoon; whereas C_3 shrub and forb species green-up after winter snow melt, followed by a longer and more dominant growing season during summer monsoon. Thus, shrubland and annual herbaceous vegetation can be used as a proxy for precipitation variability for both summer rainfall and winter snowfall.

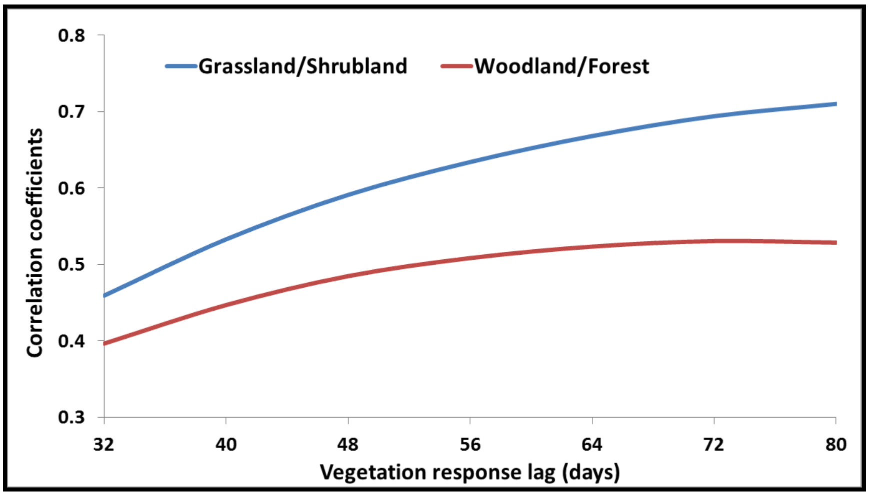

Figure 5: *Correlation Coefficients between $MSAVI_2$ and Precipitation along a Gradient of Lag Time. All Correlation Coefficients Have P-Values <0.001*

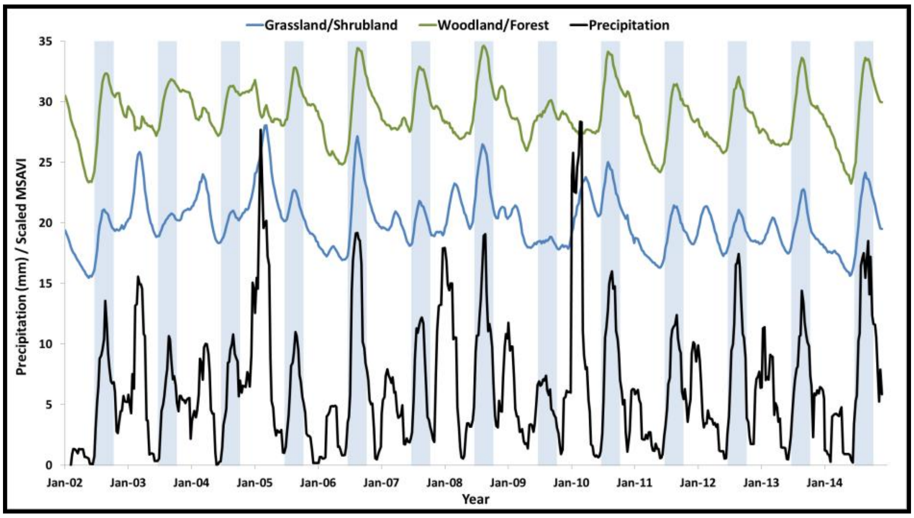

Figure 6: *Vegetation Responses and Precipitation Variability from 2002 to 2014. Scaled $MSAVI_2$ Values are Mean $MSAVI_2$ Values for Grassland/Shrubland and Woodland/Forest Multiplied by 50 for Visual Display with the Precipitation in Millimeters. The Shaded Areas Highlight the Summer Monsoon in Arizona, Which Runs Roughly from June 26th to September 30th Each Year*

4. Discussion

4.1. Effectiveness of MODIS-derived $MSAVI_2$ for Drought Monitoring

The MODIS-derived $MSAVI_2$ was effective in our study area for detecting different responses of vegetation types to changes in precipitation and drought. This index can serve as a useful drought monitoring tool, especially on tribal lands like the San Carlos Apache Reservation where ground-based weather data are sparse. Like the majority of the Southwestern US, dryland ecosystems deserve special attention because they are sensitive to changes in temperature and precipitation, and $MSAVI_2$ is particularly effective in monitoring vegetation responses to climate change in such environments.

For example, $MSAVI_2$ has been used to effectively monitor desertification in China at a large scale (Aixia et al., 2007). The related Soil Adjusted Vegetation Index (SAVI) has also been used to monitor changes in vegetation cover and processes contributing to desertification (Badreldin et al., 2014). Although NDVI has been used to monitor a host of vegetation responses to drought (Karnieli et al., 2010; Zhang et al., 2010; Yuhas and Scuderi, 2009; Yengoh et al., 2015), $MSAVI_2$ has great potential to be widely used for drought monitoring in the semi-arid Southwest US.

4.2. Grassland and Shrubland Response

Grassland and shrubland areas were more sensitive to changes in precipitation. In particular, grassland/shrubland vegetation group experienced a short green-up following winter snowmelt and an additional green-up following summer monsoon precipitation. A similar spring and summer peak in grassland greenness values as well as the general sensitivity of grasses to changes in annual precipitation has been observed in the Southwestern US (Pennington and Collins, 2007). In addition, sporadic and extreme rainfall events, brought on by climate change, can negatively impact grasslands by reducing net carbon cycling (Fay et al., 2008; Wu et al., 2011). Another consequence of decreased or sporadic rainfall will be the proliferation of invasive grass species in the southwest such as *Eragrostis lehmanniana,* already present in Arizona, which are more drought resistant than native grasses (Scott et al., 2010). Grasslands are increasingly susceptible to shrub encroachment in the semi-arid ecosystems in the Southwest US, due to the ability of shrubs to take advantage of the wide range of soil moisture conditions (Throop et al., 2012), especially in the face of increasing drought frequency and intensity in the Southwest US (Cayan et al., 2010).

Grassland above-ground productivity has long been strongly tied to precipitation, especially in regions where annual precipitation is low (Gilgen and Buchmann, 2009). This is because semi-arid grass rooting depth is typically limited to the top half meter of the soil depth, and roots are generally fine and spread widely below the surface to extract most of their moisture from the upper half meter of the soil profile (Eggemeyer et al., 2009). The shallow nature and wide distribution of roots allows C_3 grasses and annual forbs to quickly take up water and photosynthesize when moisture is available following snowmelt and summer rainfall. When immediate moisture is limited, semi-arid C_3 grasses lack the necessary root depth to draw moisture and subsequently enter into senescence. This bi-modal seasonal cycle of vegetation greenness has been observed throughout the Southwest US (Notaro et al., 2010). However, C_4 grasses dominated grassland on the San Carlos Apache Reservation usually displays a unimodal growing season during the summer monsoon, and therefore the early season green-up response displayed by the grassland/shrubland vegetation group was mostly dominated by C_3 shrub. In addition, shrubland in the Southwestern US have also been used as a proxy to indicate historic moisture availability (Mensing et al., 2004). Thus, shrubland dominated vegetation communities can serve as an effective indicator cover type or group for the onset of drought conditions for both winter and summer precipitation.

4.3. Woodland and Forest Response

Historically, increases in temperature, not precipitation, have been a leading cause of forest stress and mortality (Williams et al., 2013). In our study area, woodland and forested areas were less sensitive in their response to changes in precipitation. This could be due to deeper roots, which allow access to soil moisture that grasses and shrubs cannot access. A slower growth rate of established woodlands and forests may serve to buffer the effects of shortfalls in precipitation, especially during short-term droughts. However, for prolonged drought condition, forests can respond to severe water shortage and drought via a host of ecophysiological adaptations (Bréda et al., 2006).

Droughts in the Southwestern US are accompanied by increased temperature (IPCC, 2013), which may raise the risk of hydraulic failure and reduced carbon uptake, leading to stress or death even in drought tolerant species (McDowell et al., 2008). In ponderosa pine forests, root growth often occurs in the spring before the production of new needles (Misson et al., 2006). Although the forested areas did not show an increase in $MSAVI_2$ in the spring following snowmelt, growth likely occurred in the roots underground. Increased greenness indicated by increasing $MSAVI_2$ occurred during the summer monsoon season when both woodland and forests reached their peak $MSAVI_2$. Similarly, in the Sierra Nevada Mountains, the highest observed rates of photosynthesis in individual ponderosa pine trees occurred following summer rains when soil temperatures were warm and soil moisture levels were ideal for growth (Misson et al., 2006).

4.4. Climate Change Implications for Tribal and the Southwest Land Management

Climate change is expected to increase the frequency, severity, and duration of droughts in the Southwest US (Seager and Vecchi, 2010). Along with a general increase in temperature, precipitation is expected to become more sporadic, possibly bringing less frequent, but more intense precipitation events (IPCC, 2007). Proper management of vegetation on tribal lands will be important in order to best mitigate the impacts of climate change and existing anthropogenic activities. Predicted future droughts in this century coupled with elevated temperature can reduce the spring snowpack and summer soil moisture (Cayan et al., 2010), which will negatively impact vegetation growth. Yet, forest resources management practices such as reducing forest canopy cover and tree density, more snow is allowed to accumulate and persist into the spring (Sankey et al., 2015). Thus, forest restoration efforts can help to mitigate some of the adverse impacts of drought and climate change by maximizing the existing winter snow accumulation.

Vegetation Indices have the potential to inform broad landscape natural resources management. In the Southwestern US, water management strategies must incorporate the maintenance of natural ecosystem functions in addition to agriculture and human demand in the face of climate change (Gleick, 2010). Drought will limit existing native vegetation's ability to serve as a net carbon sink (Zhao and Running, 2010), and persisting drought conditions and warmer temperature are also expected to contribute to larger and more catastrophic forest fires (Westerling et al., 2006). Effective management of ponderosa pine ecosystems should seek to reduce stand density and reduce the buildup of understory vegetation. Such treatments have already proven to be effective. For example, forested areas that were thinned prior to the 2002 Rodeo and Chedeski fires in Arizona burned less severely and exhibited altered fire behaviors (Finney et al., 2005).

5. Conclusion

Climate change is expected to bring on more frequent and severe droughts to the Southwestern US. Drought monitoring will be essential for proper and efficient management of vegetation and water resources in this region. MODIS-derived $MSAVI_2$ can serve as an effective drought monitoring tool in regions where in situ precipitation data are sparse or not available. We created time series of MODIS-derived $MSAVI_2$ spanning 2002–2014, and paired them with PRISM precipitation data to detect drought and to measure vegetation response to bi-modal precipitation patterns that are common to the San Carlos Apache Reservation and much of the Southwestern US in general. Drought conditions, defined as negative annual $MSAVI_2$ anomalies, occurred 1-11 years out of the 13-year study period on the Reservation land, and such persistent drought condition is likely to continue throughout this century (Cayan et al., 2010). We found that C_3 shrubland dominated vegetation types experienced a brief green-up following winter snowmelt, and a second, more pronounced green-up following rainfall from the North American monsoon in late summer/early fall. Forest and woodland ecosystems were less sensitive to short term drought conditions, possibly because of deeper root networks that allow them to access deep soil moisture that grassland and shrubland vegetation cannot access. Thus, grassland/shrubland, with their higher sensitivity to changes in precipitation, can serve as indicator vegetation types for drought in this region when monitored through MODIS-derived $MSAVI_2$. Tribal forest management efforts should aim to reduce the risk of catastrophic wildfire and to mitigate the negative effects of climate change by increasing the adaptation of land management practices that prolong winter snowmelt and increase soil moisture across the landscape.

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