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Future changes in summer MODIS-based enhanced vegetation index for the South-Central United States

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ABSTRACT

Evaluating the response of vegetation to climate change is relevant to improving the management of both human and natural systems. Here, we quantify the response of the MODIS-based enhanced vegetation index (EVI) to temperature, precipitation, and large-scale natural variability across the South-Central U.S. for summer (JJA) from 2000 to 2013. We find statistically significant relationships between climate and EVI that vary across the region and are distinct for each land cover type: the mean coefficient of determination (R^2) between EVI and climate is greatest for pasture (0.61 ± 0.13) and lowest for forest (0.55 ± 0.14). Among the climate variables, three-month cumulative precipitation has the strongest influence on summer vegetation, particularly in semi-arid west Texas and eastern New Mexico. Summer monthly maximum temperature plays an important role in the eastern half of Texas and Oklahoma, moderated by the influence of both Atlantic and Pacific teleconnection indices over inter-annual time scales. Based on these relationships, we train, cross-validate, and, where statistically significant relationships exist, combine this multivariate predictive model with projected changes in teleconnection indices and statistically-downscaled temperature and precipitation from 16 CMIP5 global climate models to quantify future changes in EVI. As global mean temperature increases, projected EVI decreases, indicative of stressed and dry vegetation, particularly for grasslands as compared to other land types, and in Oklahoma and western, central and Gulf Coast Texas for mid- and end-of-century. These trends have potentially important implications for agriculture and the regional economy, as well as for ecosystems and endemic species that depend on vegetation.

1. Introduction

The South-Central United States is a highly agricultural region encompassing a broad range of managed land types. In 2012, income from cattle and cotton, the two major agricultural commodities, totaled $10.5 billion and $2.2 billion, respectively (TDA, 2017). Rangeland, including grass and shrub lands, provides economically important agronomic and ecological services such as forage for cattle and other livestock, and habitat for a variety of plant and animal species, many of which are endemic to the region (USFS, 2017). Species such as prairie dogs, lesser prairie chickens, bobwhite quail, and earless lizards depend on native open grasslands or rangelands for diverse use such as nesting, foraging and escape cover (Davidson et al., 2012; Grisham et al., 2014; Parent et al., 2016).

A complex network of natural and increasingly anthropogenic factor affects vegetation cover across the southern Great Plains. Sweeping changes in land use over the last century, including agriculture, energy development, water storage, and urban development, have altered the landscape and fragmented natural habitats for many native species that depend on the natural grasslands. The populations of prairie dogs, for example, have declined by 98% across their geographic ranges in the southern Great Plains (Davidson et al., 2012). Similar declines in population size have also been reported for the lesser prairie chicken and many other species (Grisham et al., 2013). Climatic influences continue to affect vegetation cover as well: through patterns of natural variability from both the Pacific and the Atlantic (e.g. Basara et al., 2013; Schubert et al., 2004; Schubert et al., 2009; Seager et al., 2005; Trenberth and Branstator, 1992; Woodhouse and Overpeck, 1998), which interact with local air temperature, land use, and soil moisture (e.g. Koster et al., 2000); and through long-term trends in temperature and precipitation occurring as a result of human-induced climate change.

Satellite-based vegetation monitoring, with its continuous spatial coverage, has proven to be an important source of information on

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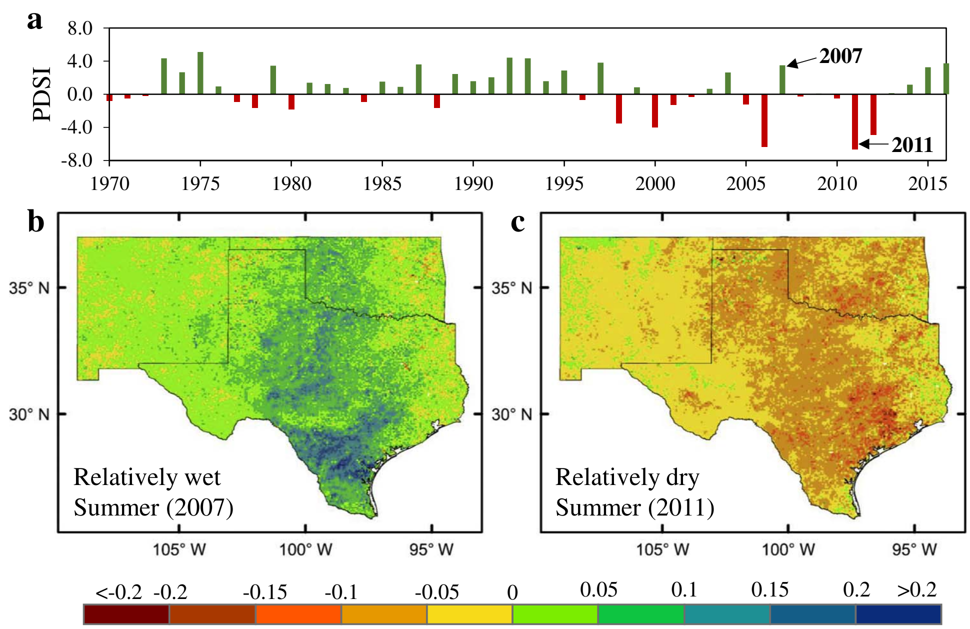

Fig. 1. (a) Palmer Drought Severity Index (PDSI) time series showing observed variability in dry (red) and wet (green) conditions in the South-Central U.S. (based on NOAA, 2017). Anomaly in summer (JJA) MODIS-EVI relative to a base period of 2000–2013 during (b) a wet summer (2007) and (c) a dry summer (2011). The EVI gradient from green to blue indicates more abundant and greener vegetation while the gradient from yellow to red indicates less abundant and drier than average vegetation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vegetation growth and vigor from regional to global scales. The impact of climate on vegetation indices derived from remote sensing is evident by comparing average values in a wet versus a dry summer (Fig. 1) and has been widely studied in scientific literature (e.g., Asner et al., 2004; Peters et al., 2003; Zhang et al., 2010). Across the U.S. Great Plains, a large body of research has established the importance of climate and accumulated root-zone soil moisture to vegetation health (Ji and Peters, 2003; Swain et al., 2011; Swain et al., 2013; Wang et al., 2001; Wang et al., 2007; Weiss et al., 2004).

Drought risk and more frequent high temperature days have been highlighted as major factors affecting the long-term viability of southern Great Plains ecosystems (Melillo et al., 2014). Other analyses of Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations consistently show additional warming, variable precipitation, and increased drought risk in the southern U.S. over the coming century (Cook et al., 2015; Dai, 2013). For example, Swain and Hayhoe (2015) found that both spring and summer precipitation deficits in the Southern Plains are expected to increase under climate change, with greater changes under higher amounts of global warming. Ryu and Hayhoe (2017) further demonstrated how projected trends toward drier summers are consistent across CMIP5 global climate models (GCMs), and reflect shifts in large-scale circulation patterns that already occur during dry summers in the historical period, according to both reanalysis and historical CMIP5 simulations. Spring and summer precipitation is critical for soil moisture recharge, sustaining crop and rangeland productivity as well as maintaining water levels in streams and lakes. Projected precipitation deficits could have far-reaching economic and ecological consequences.

How projected climate conditions will affect vegetation, however, remains largely uncertain. The response of vegetation to climate is determined by the water balance, which is the combined effects of precipitation and the evaporative demand of the atmosphere driven primarily by air temperature, humidity, and energy availability (Cook et al., 2014). As climate warms, evaporative demand of the atmosphere is projected to increase, and may offset any projected gain in precipitation in terms of water balance for vegetation. Climatic influences on vegetation can in turn influence terrestrial water, energy and carbon cycling (Ciais et al., 2005; Scott et al., 2009; van der Molen et al., 2011).

This study, while building on existing research documenting strong observed vegetation-climate linkages, goes one step further to calculate quantitative projections of vegetation response to future climatic variations and long-term trends in the twenty-first century. Specifically, we model the interaction of observed regional climate variables and large-scale teleconnection indices with summer vegetation as depicted by the enhanced vegetation index (EVI) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Earth Observing System-Terra platform. We then test the robustness of the model and use it to quantify the response of vegetation under future climate change scenarios.

2. Data and methods

2.1. Study area and land cover data

Our study area covers the South-Central U.S., including Texas, Oklahoma, and New Mexico. The region is characterized by a steep precipitation gradient, ranging from > 55 in. per year in the humid eastern part to about 6 in. per year in the semi-arid western part of the region. In terms of temperature, the semi-arid regions of west Texas and New Mexico are characterized by mild winters and hot and dry summers, while eastern Texas and Oklahoma experience a humid subtropical climate, with hot humid summers and mild to cool winters. Many of the major land cover types follow these temperature and precipitation gradients: the eastern half of the region is predominantly covered by forest and pasture, while the drier western half is primarily shrub, grassland and cropland (Fig. 2a; Fry et al., 2011).

Here, we use the National Land Cover Database (NLCD), 2006 (Fry et al., 2011) to identify the major land cover types in the study area. The original 30 m grids are resampled to ~6 km to match the spatial resolution of the climate data described below (Fig. 2a). The resampling uses the ArcGIS majority algorithm, an algorithm that is primarily applied to discrete rather than continuous data, as it calculates a new value for the larger cell based on the most frequently occurring values within the subset of smaller cells. Although land cover is clearly dynamic, particularly along the ecotones (boundaries between ecosystems) and over the multi-decadal time scales considered in this study, we use NLCD land cover type as a static variable to maintain consistency in the land cover-specific EVI comparison between the historical and future periods.