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Using NDVI to measure precipitation in semi-arid landscapes

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ABSTRACT

Measuring precipitation in semi-arid landscapes is important for understanding the processes related to rainfall and run-off; however, measuring precipitation accurately can often be challenging especially within remote regions where precipitation instruments are scarce. Typically, rain-gauges are sparsely distributed and research comparing rain-gauge and RADAR precipitation estimates reveal that RADAR data are often misleading, especially for monsoon season convective storms. This study investigates an alternative way to map the spatial and temporal variation of precipitation inputs along ephemeral stream channels using Normalized Difference Vegetation Index (NDVI) derived from Landsat Thematic Mapper imagery. NDVI values from 26 years of pre- and post-monsoon season Landsat imagery were derived across Yuma Proving Ground (YPG), a region covering 3,367 km^2 of semiarid landscapes in southwestern Arizona, USA. The change in NDVI from a pre-to post-monsoon season image along ephemeral stream channels explained 73% of the variance in annual monsoonal precipitation totals from a nearby rain-gauge. In addition, large seasonal changes in NDVI along channels were useful in determining when and where flow events have occurred.

1. Introduction

Plant growth in the semi-arid landscapes of southwestern North America is strongly dependent upon local and infrequent precipitation usually delivered from monsoon season storms (Huxman et al., 2004; Sutfin et al., 2014). Measuring the quantity and spatial and temporal distribution of precipitation is necessary for understanding the abiotic and biotic components within these landscapes. Rain gauges measure precipitation with high local precision, but gauges are sparse relative to the spatial variability of precipitation in the American southwest (Adams and Comrie, 1997; Goodrich et al., 2008; Petrie et al., 2014). The advent of weather radar approximately 25 years ago allowed for spatially continuous precipitation data, but methodological changes over time complicate observation of trends over multiple decades (Hardegree et al., 2008). In addition, accuracy is often contingent upon the storm type, the height of the radar beam, and topography, making radar data, at times, unreliable, especially in earlier versions (Kitzmiller et al., 2013; Birtwistle, 2015). In water-limited systems where the relationship between precipitation influence and vegetation response is robust, precipitation may indirectly be measured through satellite imagery to improve upon the discrepancy in spatial and temporal datasets (Wang et al., 2003; Barbosa et al., 2006; Méndez-Barroso et al., 2009; Barbosa & Lakshmi Kumar., 2016). During periods of convective monsoon season storms, high-intensity precipitation events tend to generate run-off (Snyder and Tartowski, 2006; Shaw and Cooper, 2008; Lichvar et al., 2009; Svoray and Karnieli, 2011), and strong transmission losses within the ephemeral stream channels keep these run-off events local (Goodrich et al., 2008). Riparian vegetation along these channels maintains higher densities that can register a response to precipitation and runoff visible in satellite imagery.

Not all rain events produce enough precipitation to generate a noticeable vegetation response in satellite imagery. The fraction of rain that is available to plants varies depending on the type, quantity, and timing of precipitation (Brooks et al., 2011). Small rain events (<2 mm) may only influence the microbial community which aids in the production of carbon and nitrogen that are

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necessary for other biological processes (Collins et al., 2008). Some plants such as summer annuals will only respond to substantial rain events such as pulse events that may initiate growth, while other vegetation responds primarily to cumulative rain events (Ogle and Reynolds, 2004). While upland plants are too small and sparse to register a response to precipitation visible in satellite imagery, larger plants and higher vegetation densities that exist along ephemeral stream channels where runoff is concentrated (Shaw and Copper, 2008) have the ability to see such changes. The response of vegetation cover to precipitation may not be linear over wide ranges of variation in precipitation. For example, when precipitation increases beyond a certain point, vegetation cover may no longer increase, since water is no longer the limitation to growth (Méndez-Barroso et al., 2009). The variation in precipitation quantities and frequencies can have profound effects on the vegetation composition over annual and decadal intervals (Snyder and Tartowski, 2006). In this respect, inter- and intra-annual climatic variability can support a diverse set of vegetation, i.e. herbaceous plant seeds can endure for multiple years until the right conditions exist to initiate growth (Bowers et al., 2004) or significant flood events can promote tree recruitment and seedling success (Friedman and Lee, 2002).

Remote sensing imagery is frequently used in studies that investigate and classify vegetation spatially and temporally. Landsat 5 TM has demonstrated its efficacy through its longevity, moderate spatial and temporal resolution, multispectral sensors and availability to the public. For these reasons, Landsat 5 TM has been widely and successfully used as a tool in research studies, including vegetation classification and change detection (Kerr and Ostrobsky, 2003), vegetation health (Vogelmann et al., 2009), long-term land cover analyses (Nguyen et al., 2014; Wang et al., 2003), and ecosystem responses (Pettorelli et al., 2005; Barbosa et al., 2006; Méndez-Barroso et al., 2009; Barbosa & Lakshmi Kumar., 2016). Normalized Difference Vegetation Index (NDVI), which uses the Red and Near Infrared (NIR) bands, can be explicitly related to vegetation productivity (Richard and Poccard, 1998; Ichii et al., 2002; Pettorelli et al., 2005; Brooks et al., 2011) and precipitation influences (Nicholson and Farrar, 1994; Wang et al., 2003; Barbosa et al., 2006; Barbosa & Lakshmi Kumar., 2016).

The objective of this research was to determine if changes in vegetation measured via satellite imagery can be used to quantify the highly variable and localized precipitation inputs along ephemeral stream channels in the Sonoran desert. If proven acceptable, NDVI from Landsat TM imagery could be used where radar or rain-gauge data are unavailable or unreliable and could be extended to other arid landscapes globally. For large-scale rain events, this analysis will also indicate not only where rain fell, but where the precipitation was transported, something that rain gauge and radar data are unable to directly measure. Specifically, this study took 26 years of Landsat TM scenes bracketing each monsoon season in a semi-arid ecosystem in southwestern Arizona. The change in NDVI values were measured along ephemeral stream channels, between pre- and post-monsoon season Landsat 5 & 7 TM imagery from 1986 to 2011. These data recorded the intensity and spatial distribution of plant growth (an increase in chlorophyllic content; Pettorelli et al., 2005) from monsoon season rain events. Using this methodology outside the ephemeral stream network would not be as useful because the vegetation in semi-arid uplands is too sparse for Landsat imagery to measure such subtle changes. Implicit in the use of NDVI change to estimate precipitation are assumptions that growth is limited by water availability and that plants are using water from local precipitation. Where growth is strongly influenced by temperature, groundwater inputs, or river flow derived from distant precipitation, the signal of local precipitation can be obscured, especially if these complicating factors vary spatially within the region of interest.

2. Study site

This research took place at the Department of Defense (DoD) installation, Yuma Proving Ground (YPG; Fig. 1), located within the Sonoran Desert in southwestern Arizona, USA. YPG encompasses 3,367 km^2 of semi-arid landscape with elevations ranging from 54 to 870 m. During two separate rainy seasons - monsoon and winter, YPG receives an average total of 95 mm/yr of precipitation (Western Regional Climate Center, 2012). This bimodal pattern leads to scattered rain events throughout the year, supporting a unique and diverse plant community that can include larger woody species, such as ironwood (*Olneya tesota*), paloverde (*Parkinsonia* spp.), acacia (*Acacia greggi)*, and mesquite (*Prosopis* spp.), as well as columnar cacti (Sutfin et al., 2014). Sutfin et al. (2014) describe five general channel types that occur within this area: piedmont headwaters, bedrock, bedrock with alluvium, incised alluvium, and braided channel types. These stream types can be differentiated by the channel geometry, width-to-depth ratio, slope, stream power, and shear stress and have a fundamental influence on the vegetation (Sutfin et al., 2014).

Summer precipitation is driven by monsoon rains producing localized, high intensity storms that are influenced by topography. The American monsoon season develops from warm air that forms over the Mexican Plateau, then travels westward causing evaporation rates to increase over the eastern tropical Pacific Ocean and Gulf of California (Adams and Comrie, 1997). The moist air mass typically moves north into northwestern Mexico and Arizona then disperses outward, although variations in weather and the position of the midtropospheric subtropical ridge lead to high variability in monsoon season precipitation (Adams and Comrie, 1997). Large swaths of desert pavement coupled with low vegetation densities within the uplands allow rain water to move easily into stream channels, producing short-lived flow events. In contrast, winter precipitation typically originates from frontal storms that develop over the Pacific Ocean and tend to deliver more widespread, less intense, and longer-lasting rain events, leading to higher infiltration rates with less run-off (Snyder and Tartowski, 2006; Stromberg et al., 2007). Many plant and animal species rely on the combination of these two rainy seasons that result in varying degrees of dependence. In this paper, we focus on using vegetation to quantify monsoon season precipitation because its high spatial variability is especially problematic for quantification by the limited rain-gauge network (Birtwistle, 2015).

3. Materials and methods

The methods applied in this research are summarized in Fig. 2. Riparian areas influenced by precipitation and flow were delineated across YPG and were used to isolate NDVI values. NDVI values were processed from each Landsat image over a period of 26 monsoon seasons. For each monsoon season, the pre- and post-monsoonal NDVI scenes were overlaid to create the change in NDVI scene (ΔNDVI-S). The mean NDVI value of the top ten percent of pixel values (MTT) within each Riparian Area Polygon (RAP) unit was extracted from each ΔNDVI-S and was used to analyze the relationship between precipitation and the production of plant biomass. The change in MTT values was related to annual monsoon precipitation using rain-gauge data to assess the effectiveness of this dataset. In addition, we examined temporal variation in the vegetation response to two large precipitation events by examining NDVI of multiple images before and after each event. These methods are detailed below.