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Long-term droughtiness and drought tolerance of eastern US forests over five decades

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ABSTRACT

Droughts can influence forest composition directly by limiting water or indirectly by intensifying other stressors that affect establishment, growth, and mortality. Using community assemblages of eastern US tree species and drought tolerance characteristics assessed from literature, we examine recent drought conditions in relation to the spatial distribution of species and their tolerance to drought. First we calculate and compare a cumulative drought severity index (CDSI) for the conterminous US for the periods 1960–1986 and 1987–2013 using climate division Palmer Drought Severity Index (PDSI) values and a gridded self-calibrated PDSI dataset. This comparison indicates that drought conditions in the East tend to be less frequent and generally less severe than those in the West, and that the West has had a large increase in CDSI values in the latter period. Then we focus on the past and potential future role of droughtiness in eastern forests, which are relatively more diverse than western forests but have individual species that are uniquely affected by drought conditions. We found that eastern US forests tend to be relatively balanced in the composition of drought-tolerant and -intolerant species and that drought conditions are relatively uncommon in the East. Understanding the composition and distribution of drought tolerance levels within forests is crucial when managing for the impacts of drought (e.g., managing for survival), especially given the expected rise of drought in the future.

1. Introduction

The phenomenon of drought has been widely studied (Palmer, 1965; McKee et al., 1993; Paulo and Pereira, 2006), along with its impacts on forests (McKenzie et al., 2001; Breshears et al., 2005; Allen et al., 2010; Kardol et al., 2010; Pederson et al., 2014). Various studies have also sought to further our knowledge of drought tolerance levels (e.g., indications of stress and survival rates) among tree species (Niinemets and Valladares, 2006; McDowell et al., 2008; Williams et al., 2013). However, few studies have examined the relationship between spatial distributions of drought-tolerant trees and drought occurrences within the US (Hanson and Weltzin, 2000; Gustafson and Sturtevant, 2013; Russell et al., 2014).

Drought conditions in the US are often aggregated and reported at climate divisions; subdivisions of each state into 10 or fewer units, often defined by county lines (Guttman and Quayle, 1996). These climate divisions average observations among weather stations to account for missing and incomplete data, and are widely used in ecological and meteorological models. However, gridded datasets have an advantage over aggregated observations in that conditions are not averaged across large areas (Abatzoglou, 2013). Thus, by using gridded data from sources such as the PRISM Climate Group, which interpolates values among observations using a Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 2008), drought conditions can be defined for each grid cell.

Several studies have shown differences in drought conditions when assessed at the climate division versus the station or grid cell (Wells et al., 2004; Heim, 2006; Sullivan, 2013). These differences suggest that by aggregating climate conditions to larger areas such as climate divisions, local detail is often lost or misrepresented as a regional mean. Therefore, gridded datasets should be more representative of local conditions than regionally aggregated values.

Drought indices like Palmer's provide a representative value at a particular location (i.e., climate division or grid cell) for a referenced period (i.e., weekly or monthly). Thus, analyzing conditions among locations for extended periods can require a time series analysis approach, although, there may be instances when a single integrated metric is desired. Accumulating conditions based on the frequency of occurrences for a period can provide a simplified value in which comparisons and change detection analyses can be quickly performed.

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Droughts have occurred in nearly all US forests and tree species are adapted in diverse ways to drought conditions, which may be seasonal, annual, or multi-annual in length (Hanson and Weltzin, 2000). These periods of limited water availability can place considerable stress on individuals, which may already be under pressure from competition (native and non-native), disease, insect infestation, and pollution (Grant et al., 2013). Timber harvesting and changes in land use put additional pressure on forests. In response to these amalgamated factors, forest types of the eastern US have undergone many changes, particularly in the extent of timberland. For example, between1952 and 1997: in the North – maple-beech-birch doubled, oak-pine increased, oak-hickory and pine were stable, while aspen-birch, lowland hardwoods, and spruce-fir decreased; in the South – oak-pine and upland hardwoods increased while lowland hardwoods and pine decreased; in the eastern portion of the Great Plains – hardwoods and non-pine softwoods increased (Alig and Butler, 2004). Though the extent of forest types has changed as a result of many factors and conditions, this paper focuses on the potential influence of drought trends on forest composition over the past half century.

To examine the droughtiness and drought tolerance of eastern US forests, we first use climate divisions and a gridded PDSI dataset to calculate a cumulative drought severity index (CDSI) and identify differences among values. Second, we use gridded climate data from PRISM to parameterize a self-calibrated (sc) PDSI algorithm developed by Wells et al. (2004) to examine recent drought conditions in the eastern US. Finally, we compare the distributions of modeled suitable habitat and drought tolerance for 134 tree species to drought conditions during 1961–2012. Mapping the distribution of drought-tolerant and -intolerant species enables us to assess recent trends in drought severity and consider how the species' tolerance within the forest communities may influence impacts from drought events. This effort provides a baseline to begin to understand if the signal of drought during recent decades has influenced the composition of forests in the eastern US.

2. Methods

2.1. Palmer Drought Severity Index

The Palmer Drought Severity Index (PDSI, Palmer, 1965) describes the relative moisture supply of a location derived from precipitation and temperature data. It was originally developed using data from central Iowa and western Kansas to empirically derive values for the water balance coefficients. A recent improvement to the original PDSI equation calibrates climate variables to long-term conditions for a location of interest, or for individual grid cells across a region. This self-calibration process (scPDSI) accounts for local climate trends and generates values that can be compared among regions.

PDSI values were obtained from two sources: the National Climatic Data Center (NCDC), which reports values at climate divisions (NCDC, 2014), and the Western Regional Climate Center's WestWide Drought Tracker (WWDT), which provides a gridded dataset derived from a self-calibration process (Abatzoglou, 2013). WWDT scPDSI data are calculated using the Wells et al. (2004) algorithm and parameterized with PRISM climate data and soil available water-holding capacity from state soil survey geographic data. The gridded data have a resolution of 2.5″ (~4 km), and a calibration period as the full length of record (i.e., 1895–present).

2.2. Cumulative drought severity index for the conterminous US

We used data from both PDSI sources to calculate a cumulative drought severity index (CDSI). The frequency of monthly PDSI conditions, defined using NCDC (2014) classes for drought, where values of −2.0 to −2.99 indicate moderate, −3.0 to −3.99 are severe, and $\leqslant -4.0$ are extreme, received a weight of 1, 2, or 3, respectively. These weighted occurrences were summed over the periods of 1960–1986 and 1987–2013 and mapped by climate divisions and ~4 km grid cells. Additionally, a mean CDSI was calculated for each climate division from the gridded data (Supplemental Table S1), and then divisional values from both datasets were aggregated to a single mean value for each state. The change in value from the 1960–1986 to the 1987–2013 periods was calculated as a percentage to examine the trend among periods and datasets.

2.3. Drought characteristics in the eastern US, 1961–2012

We calculated scPDSI values for 20 × 20 km grid cells that spatially corresponded to modeled tree species' habitat, as derived from USDA Forest Service Forest Inventory and Analysis (FIA) data (Iverson et al., 2008). The scPDSI algorithm (Wells et al., 2004) was parameterized with (1) soil available water supply to a depth of 150 cm, derived from Natural Resources Conservation Service (NRCS) county soil geographic survey data (NRCS, 2009) prepared using methods described in Peters et al. (2013); (2) latitude from the grid's centroid; (3) monthly precipitation; and (4) temperature values obtained from PRISM climate data (PRISM Climate Group, 2012) at a 4 km resolution for the period 1961–2012 (rather than the full length of record as with the WWDT data). Climate values were aggregated from the 4 km resolution by taking the mean values of precipitation and temperature that intersected the 20 km grids. Additionally, monthly mean temperatures were averaged for the 52 year period and used as a climate normal for the calibration process.

The scPDSI algorithm was designed to process data for a specific location; thus to generate gridded output, the parameters had to be updated at each location. Python code was used to extract values from raster data, update the parameter files, run the scPDSI algorithm, and copy output files. Individual output files for each grid were compiled into an eastern US dataset and the frequency, duration of longest consecutive period, and mean interval of each PDSI class were calculated from monthly values. The frequency of each PDSI class was graphed by decade and mapped for the period May–September along with duration.

2.4. Tree species drought tolerance in the eastern US

Using FIA data for the period 1980–1993, Iverson et al. (2008) modeled the distributions of potential suitable habitat in the eastern US based on importance values (IVs) derived from the relative number of stems and basal area of species reported at survey plots for 134 tree species. IVs represent a species' relative abundance and were averaged among plots contained within each 20 × 20 km cell (Iverson et al., 2008), therefore combining IVs from individual species provides a way to examine the probable composition of species within a grid cell. Potential habitat suitability (IV > 0) modeled under the 1961–1990 climate normals define the current habitat distributions of eastern tree species in this analysis.

Species' characteristics related to drought tolerance were used to develop two maps of species drought tolerance across the eastern US. Each species was scored from −3 (very drought intolerant, DIT3) to +3 (very drought tolerant, DT3) based on a literature review of its overall habitat range (Matthews et al., 2011) (Supplemental Table S2), and this score was multiplied by the IV of each species within each grid cell to derive a weighted IV. These weighted IVs were summed among species for each of the three drought tolerance and three intolerance classes within a cell to classify the underlying forest as dominantly tolerant (1,2,3),