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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 ⩽−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), intolerant ($-3, -2, -1$), balanced, or mixed. Cells were assigned 'tolerant' if the greatest absolute value among the weighted IV sums was from the tolerant class, and likewise for 'intolerant'; 'balanced' was assigned if the sum was within ±5% of half the total sum of the weighted IVs. 'Mixed' was assigned if the maximum absolute value was shared (tied) among multiple classes. Using the dominant tolerance class, we mapped the distribution of drought tolerance for the overall forest species composition of each cell for the eastern US. In this calculation, the final class is often determined by a single or relatively few common species. For a second view of overall tolerance to drought, which better considers all species, tolerance classes were normalized to account for all species having suitable habitat within a cell by adding the weighted IV sums of each tolerance class ($-3, -2, -1, 1, 2, 3$), and then dividing the total weighted IV sum by the unweighted IV sum of each species.

$$N_{class} = [(IV_{DIT1} * -1) + (IV_{DIT2} * -2) + (IV_{DIT3} * -3) + (IV_{DT1}) + (IV_{DT2} * 2) + (IV_{DT3} * 3)]/IV_{sum}$$

Defining the drought class based on the dominant potential habitat allows us to examine how the dominant tree species could be affected by drought conditions. Including all potential species' habitats provides information on how the forest might be affected as a community.

Drought tolerance classes for each 20 km grid were used to analyze trends related to drought conditions based on calculated scPDSI values. The frequency of PDSI-derived drought and near normal conditions was calculated and mapped. These data are summarized at the state level in Supplemental Table S3.

3. Results

3.1. Cumulative drought severity index for the conterminous US

CDSI values represent the overall droughtiness during a period, and based on CDSI values using the NCDC climate divisions and the WWDT gridded scPDSI values (Fig. 1), 35–36 states had greater CDSI values during the 1987–2013 period as compared to the 1960–1986 period (Table 1). Mean CDSI values from WWDT gridded scPDSI values were generally lower than those from NCDC data with the exception of 13 states during the 1960–1986 period and 12 states during the 1987–2013 period. A paired t-test of CDSI values confirmed that the mean differences between datasets and between periods were significant ($P < 0.04$). Between the two periods, based on NCDC data, 33 states experienced increases in CDSI values while 15 decreased. Based on gridded scPDSI values, 25 states had increased mean CDSI values whereas 23 decreased. The percent change among states ranged from a decrease of 83% (Massachusetts) for climate division data and 79% (Rhode Island) for gridded mean CDSI values to increases of 286% (Arizona) and 341% (South Carolina) for climate division data and gridded mean CDSI values, respectively (Table 1). Regardless of the source of data, the eastern US had lower CDSI values than the West, and between the two periods, the West has shown a much larger increase in CDSI values compared to the East (Peters et al., 2014).

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

The frequency (Figs. 2 and 3), duration of the longest consecutive period (Fig. 4) and mean interval (Supplemental Table S3 and Fig. S4) of each drought severity class calculated from scPDSI values at 20 km grids indicate that, for most of the 1961–2012 period, the eastern US experienced near normal conditions. However, the frequency of near normal conditions decreased during the 1990s and continued to decrease through the end of the period of analysis (Fig. 2), at which time increases in both wet and dry conditions have been reported. Extreme drought was very rare, never occupying more than about 5% of the region (primarily during the 1960s); however, after three decades of very low levels of extreme drought (<2% of the region), the 2000s have witnessed a rise in classes both of extreme drought and of extremely moist conditions (Fig. 2). The greatest frequency of near normal conditions during the growing season (May–September) occurred within the western Great Lake states, in Iowa, and along the New England coast (Fig. 3). Frequencies of drought conditions tended to be widely dispersed across the region and localized as severity increased from moderate to extreme (Fig. 3). The duration of the longest consecutive number of months within any particular class of drought provides a glimpse of the nature of droughts in the past decades. Most are short (<6 months), though conditions lasting longer than 24 months have been distributed across the eastern US (Fig. 4). This pattern is similar to that of the conterminous US mentioned previously, in which the West has had greater CDSI values in recent decades.

3.3. Tree species drought tolerance in the eastern US

Among the 134 tree species used to examine the relationship between potential forest composition and recent drought conditions, 5, 40, and 43 species were intolerant to drought (DIT classes 3, 2, 1, respectively), while 26, 15, and 5 were tolerant to drought (DT classes 3, 2, 1, respectively) (Supplemental Table S2). Drought tolerance calculated from the dominant composition of tree species' habitat indicates that most of the eastern US falls into drought intolerant class 2 (DIT2, 45.9%), followed by Balanced (19.5%), and drought tolerant classes comprising 6, 11.5, and 12.5% (DT1, DT2, DT3, respectively) (Fig. 5A). The remaining classes of DIT1, DIT3, and Mixed cover less than 4.6% of the region. Though the classification in this map is based on multiple species within the tolerant/intolerant class contributing to the dominance, the assignment might be driven largely by a single or few species.

Accounting for the tolerance of all species with suitable habitats (i.e., IV > 0) within a weighted averaging approach greatly generalized the results, with 48% of the eastern US as having a balanced composition (Fig. 5B). Of the remaining area, most was either somewhat tolerant (DT1; =18%) or somewhat intolerant (DIT1; =29.8%). All of the more severe classes combined occupied only 4.2% of the area.

3.4. Combining drought conditions with species tolerance

Examining the recent drought conditions against the current distributions of tree species revealed that eastern forests, whether defined by the dominant class (Fig. 5A) or including all species (Fig. 5B), have all faced mainly near normal conditions (Fig. 6). Using the dominant species classification, intolerant class 2 (DIT2) represents ~46% of the eastern US, but experienced conditions similar to the other classes. Intolerant class 3 (DIT3) experienced slightly more normal conditions than the other classes (Fig. 6A). However, using all species to define drought tolerance, the DIT3 class had the smallest area of normal conditions and the largest area of moderate and severe (Fig. 6B). The source of these differences is the number of grids assigned to each class and the underlying modeled habitat. With the dominant definition, DIT2 and Balanced account for 65% of the East, whereas Balanced and DIT1 constitute 77% based on all species.

4. Discussion

Understanding the implications of long-term persistent drought conditions is important as we witness the drastic impacts that

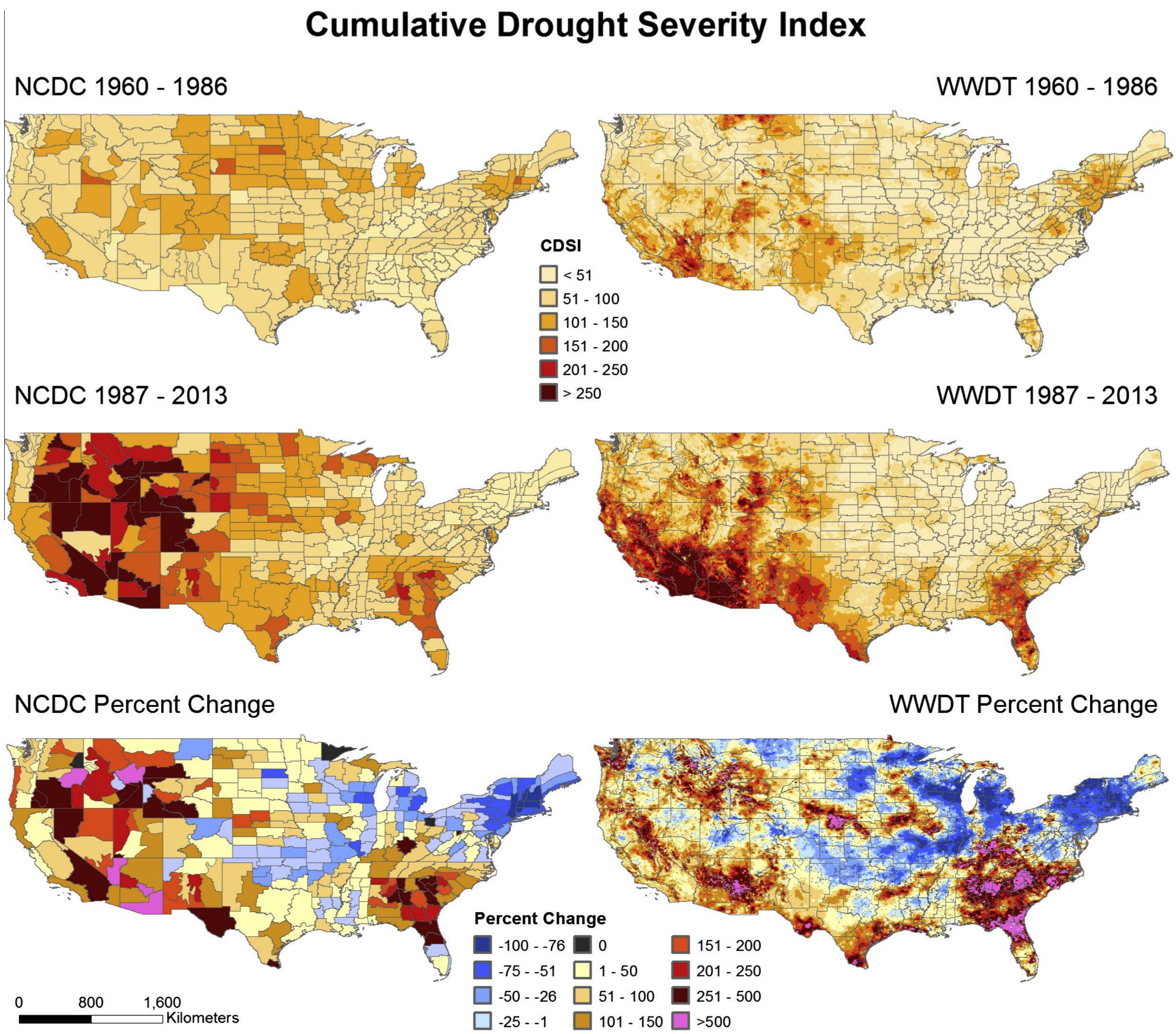

Fig. 1. A cumulative drought severity index (CDSI) for 1960–1986 and 1987–2013, calculated from Palmer Drought Severity Index (PDSI) values obtained from National Climatic Data Center (NCDC) and WestWide Drought Tracker (WWDT) self-calibrated PDSI data. The NCDC values are reported at climate divisions; WWDT values have a 2.5 arc-minutes grid with climate divisions overlaid for reference. The percentage of change from the 1960–1986 period to the 1987–2013 shows decreases (blue gradient) and increases (red gradient) as CDSI is influenced by the frequency and intensity of drought conditions. Decreases can result from more normal conditions rather than increased precipitation.

drought is having on western forest communities and strive to understand how changing drought patterns in the eastern US may emerge with projected climate change. The PDSI uses a 3-month moving window to determine the start and end of conditions, which is ideal for events occurring over multiple months. The CDSI weights the occurrence of monthly conditions for an extended period, in this case two periods of 27 years each, to assign a single value representing the overall droughtiness. Events that span many months with high intensity will have a greater impact on vegetation than might be suggested by the CDSI, but the index is useful for mapping and comparing drought conditions among multiple-year periods and among locations.

The scPDSI algorithm generates monthly values similar to the method developed by Palmer (1965). However, instead of using data from a limited region (i.e., central Iowa and western Kansas) to empirically derive values for the water balance coefficients; the algorithm uses calibration to incorporate historical patterns of climate variability within each location (in this case a 20×20 km grid cell). By accounting for local trends in the climatological record, the scPDSI values at the grid-cell level address the issue of spatial comparability (Alley, 1984; Wells et al., 2004). In this way, comparisons among fine-scale locations can be made that might not otherwise be appropriate for conditions aggregated to climate divisions, because the number and distribution of meteorological stations differ widely among divisions.

CDSI values from the two datasets (NCDC and WWDT) resulted in different spatial patterns and values when summarized at the scale of climate divisions (Fig. 1 and Supplemental Table S1). The gridded WWDT values captured more local influence within climate divisions due to calibration and the fine-scale resolution. Distinct patterns also emerged among CDSI values between the two time periods, and even more so with WWDT data: (1) the western US had higher values than the East; (2) values tended to increase from the 1960–1986 period to the 1987–2013 period; and (3) within the East, CDSI values in the more recent period were lower in the mid-Atlantic and Northeast and higher in the Southeast. Given these trends and the uncertainties of future drought predictions (Dai, 2012), it will be important for resource managers to consider how species may respond to variability in drought patterns and how forestry practices can address drought.

Table 1
Cumulative drought severity index (CDSI) calculated from climate division (NCDC) and gridded (WWDT) data for the conterminous US. Weights of 1, 2, and 3 were used for the moderate, severe, and extreme drought classes, respectively, as defined by the Palmer Drought Severity Index, and were applied to the monthly frequencies of conditions. Climate divisions were used to calculate the mean CDSI value among gridded data, and values for both datasets were averaged to the state level.

State	Cumulative drought severity index					
	1960–1986		1987–2013		Percent change	
	NCDC	WWDT	NCDC	WWDT	NCDC	WWDT
Alabama	41	28	107	81	157.7	189.4
Arizona	61	94	237	255	286.5	171.3
Arkansas	68	64	87	83	28.4	28.4
California	85	112	175	214	105.0	91.2
Colorado	133	94	183	105	37.7	12.4
Connecticut	117	121	31	42	−73.7	−65.5
Delaware	117	104	79	75	−32.9	−27.3
Florida	74	60	115	152	55.1	151.2
Georgia	46	39	161	163	247.4	313.0
Idaho	101	53	205	107	103.7	101.8
Illinois	87	46	92	34	5.7	−25.9
Indiana	64	34	77	23	20.2	−31.1
Iowa	86	38	111	55	28.4	45.9
Kansas	92	54	106	51	15.6	−4.6
Kentucky	38	17	94	45	148.3	167.8
Louisiana	84	61	90	84	7.8	37.9
Maine	71	58	36	45	−49.8	−21.7
Maryland	76	79	94	77	23.2	−2.9
Massachusetts	123	105	20	26	−83.4	−75.5
Michigan	92	53	80	29	−12.7	−46.2
Minnesota	107	49	129	48	21.1	−2.6
Mississippi	68	50	75	62	10.0	24.2
Missouri	80	55	71	42	−12.0	−23.1
Montana	86	77	210	94	142.9	21.5
Nebraska	84	33	158	64	89.4	97.4
Nevada	80	105	251	191	214.1	81.8
New Hampshire	72	75	27	24	−63.2	−67.2
New Jersey	92	113	62	76	−32.2	−33.0
New Mexico	80	92	156	168	94.7	82.7
New York	81	98	40	34	−50.6	−65.4
North Carolina	51	34	106	109	107.4	222.7
North Dakota	99	54	152	64	53.9	18.9
Ohio	65	46	67	29	4.3	−36.8
Oklahoma	104	88	86	66	−17.2	−24.6
Oregon	70	63	208	105	197.3	65.3
Pennsylvania	79	88	51	48	−35.7	−45.0
Rhode Island	81	100	20	21	−75.3	−79.4
South Carolina	44	29	138	128	213.0	341.1
South Dakota	137	65	159	63	15.9	−2.7
Tennessee	58	29	98	65	70.9	127.0
Texas	71	68	132	131	85.2	92.6
Utah	92	108	203	144	120.4	33.3
Vermont	97	81	28	21	−71.6	−73.6
Virginia	78	81	72	78	−6.7	−3.4
Washington	77	47	132	84	72.7	80.1
West Virginia	56	51	61	47	8.9	−8.0
Wisconsin	104	70	83	26	−20.5	−62.4
Wyoming	97	72	237	126	144.5	74.5

A major concern is if and when the water stress of future climates exceeds that observed over the previous 120 years, compositional shifts may occur rapidly, which is now apparent in the West (Allen and Breshears, 1998; Allen et al., 2010; Williams et al., 2013). Indeed, the North American Drought Atlas (Cook and Krusic, 2004) and further analysis (Pederson et al., 2014) indicate that 1950–2005 was one of the wettest periods since 1500 over much of the eastern US, suggesting that future drought may have relatively large impacts on eastern forests.

The scPDSI calculated for 20×20 km grid cells for the eastern US differs from that provided by the WestWide Drought Tracker in that the calibration period was 1961–2012 rather than 1895–present, and finer resolution soil available water supply was used (county soil surveys rather than state soil survey data). Because the number and quality of weather stations varied in the early part of the 20th century, we calibrated our PDSI values based on the 1961–2012 period, which has had a relatively stable number of stations (Menne et al., 2009). While self-calibration greatly improves the calculation of PDSI values, the influence from land use and management actions are not well represented moving away from meteorological stations. However, we assume that the temperature values interpolated to 4 km grids are representative of the average conditions and the influence from land cover change is reflected in climate observations. Calculating scPDSI values among the same grids used to model species' suitable habitat provides compatibility between data on historical drought conditions and current and potential tree habitat.

Though modeled IVs for species represent potential suitable habitat that would occur based on recent conditions, we acknowledge that species may or may not actually be present or as abundant as suggested by these data. However, the modeled habitat does provide information which landowners and managers can use to derive a list of possible species that could inhabit the landscape. Drought tolerance levels were assigned to species based on the literature, which reports general characteristics of a species that could differ among regions. Impacts on species related to recent drought conditions will vary at a fine scale: trends may or may not be captured from the local scale to the 20×20 km grids to the climate divisions. Site conditions (i.e., aspect, soil texture, and topography) could weaken or intensify the impacts of drought on species; thus our results should be interpreted at a macro scale.

The distribution of drought-tolerant and -intolerant species, as defined by (1) the dominant composition of species potential habitats and (2) averaged over all species' habitats, provides insight into the forest communities in the eastern US. When considering only the tolerance level of dominant species, just under half of the region is moderately intolerant to drought (DIT2). This pattern can be attributed to the tolerance level of a select few species. For example, loblolly pine (*Pinus taeda*) dominates much of the southern part of the region, and it has a moderate intolerance to drought according to the Modification Factors of Matthews et al. (2011). In the North, quaking aspen (*Populus tremuloides*) and balsam fir (*Abies balsamea*) are the dominant DIT2 species, while American elm (*Ulmus americana*) is the top contributor in the central region. Each method of defining drought tolerance provides unique information: the dominant species' habitat can be used to examine trends in forest composition, and the all-species approach is useful when evaluating the overall impact of drought on a forest.

Regardless of how cells were assigned to drought tolerance classes, the western portion of the region (Fig. 5) resembles a wedge shaped pattern, which Transeau (1935) described as the "prairie peninsula"; the transition from conifers and northern hardwoods along the north and northeastern part of the region to more open and grassy landscapes. This pattern is more prominent when the dominant class is used (Fig. 5A), where the most abundant suitable habitat corresponds to green ash (*Fraxinus pennsylvanica*), American elm (*Ulmus american*), boxelder (*Acer negundo*), hackberry (*Celtis occidentalis*), bur oak (*Quercus macrocarpa*), and post oak (*Q. stellata*).

Coupling this species-based information with drought trends over five decades indicates that species-drought classes generally experienced near normal conditions. Although most of the eastern US forests are balanced to moderately tolerant to droughts (DT1 & 2), these classes experienced drought conditions only 18.8 and 19.3% (for the dominant species classes and averaged over all species, respectively) of the period. Across the eastern US, these drought tolerance classes (including Balanced) account for 37.0 and 68.9% (dominant and all species, respectively) of the area, and their prevalence might explain why droughts have not caused dramatic shifts in species compositions in recent decades.

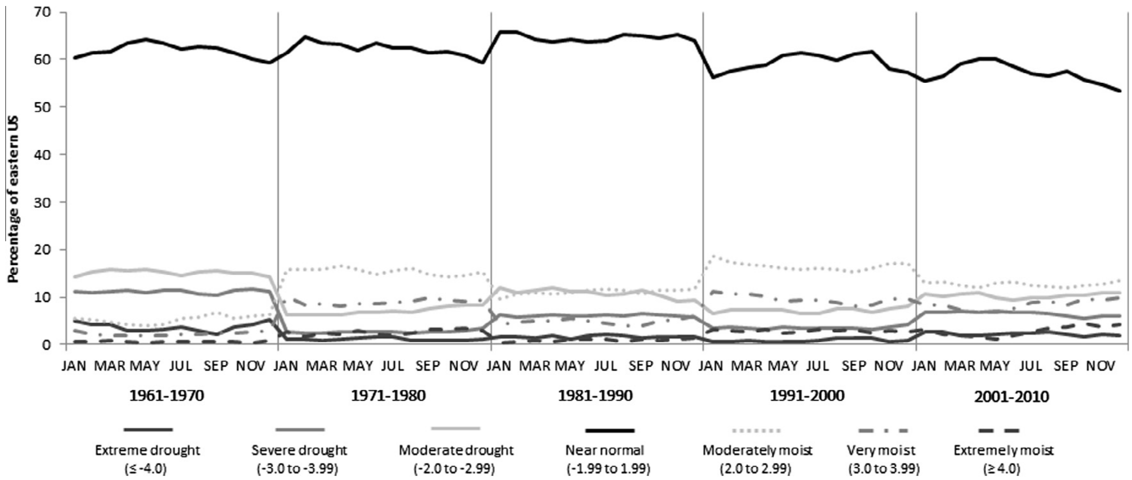

Fig. 2. Decadal frequency of self-calibrated PDSI classes presented as the percentage of 20 × 20 km grids within the eastern US.

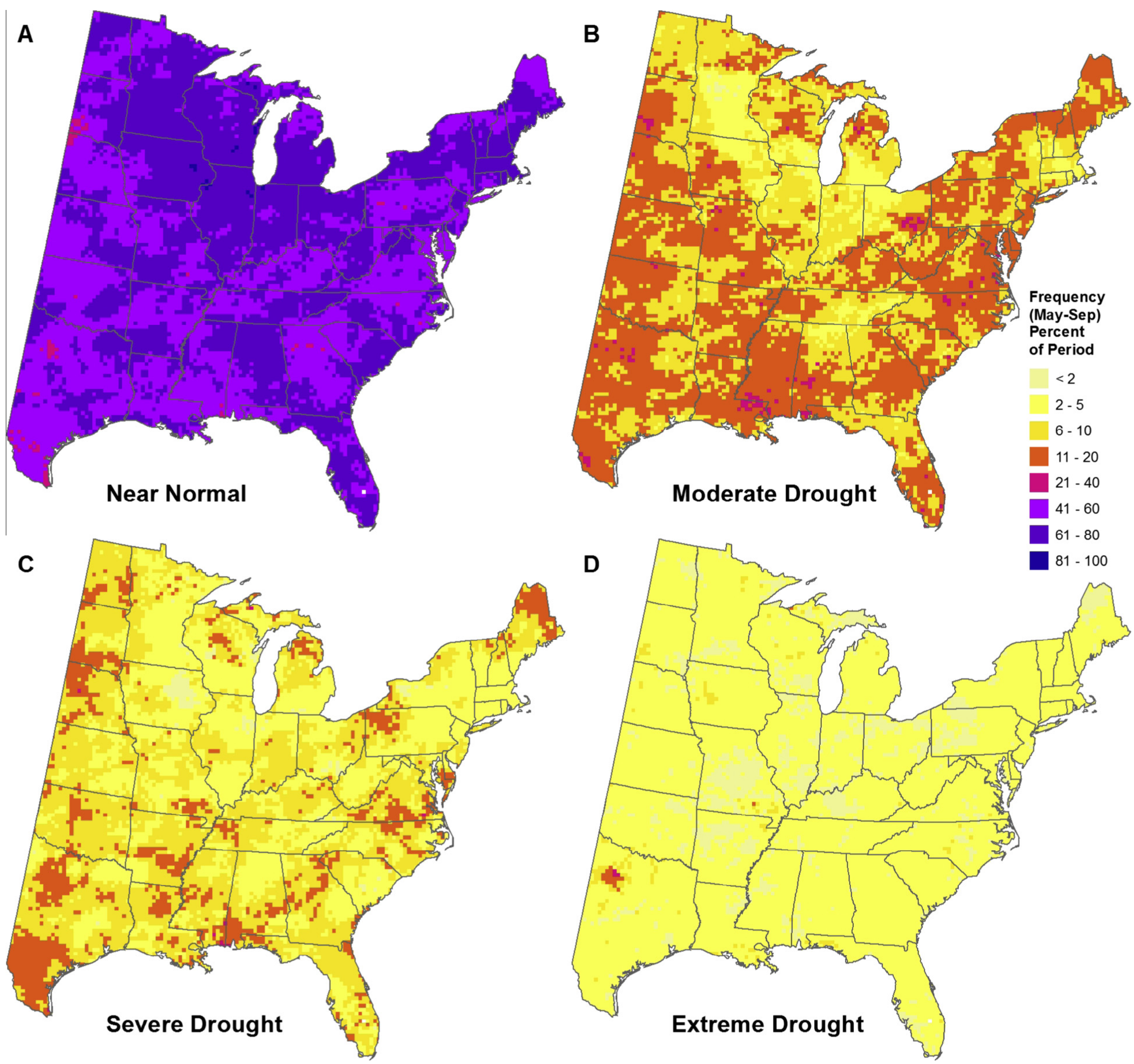

Fig. 3. Frequency of monthly drought classes (A: near normal conditions; B: moderate drought; C: severe drought; D: extreme drought) as a percentage, for the period May–September 1961–2012. The maximum potential frequency is 260 months during this period.

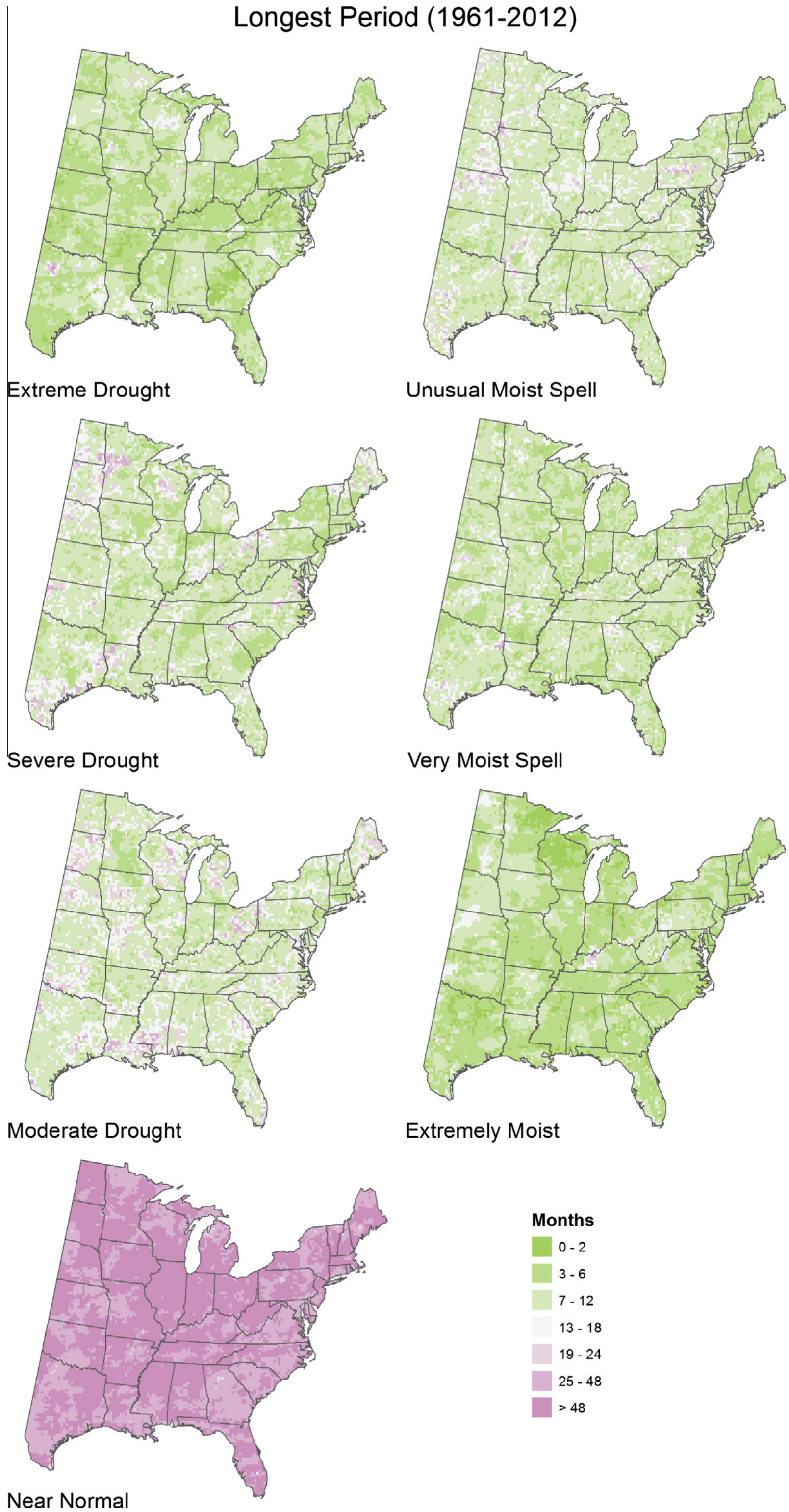

Fig. 4. Duration of longest consecutive period (monthly) for each drought class from 1961 to 2012. PDSI classes were calculated using a self-calibration algorithm, PRISM climate data, and NRCS County Soil Survey Geographic available water-holding capacity.

Additionally, the relatively short durations of droughts in the East may have allowed tree species time to recover between prolonged periods of limited water availability (Pederson et al., 2014). However, both droughts and wet conditions have increased in recent decades, and these patterns of extreme climate variability are projected to increase. Under these projected conditions, the combined stress from periods of intermingling severe droughts and very wet conditions could have the potential to initiate major changes in forest composition. Alternatively, when we define the tolerance based on habitat from all species, the different drought

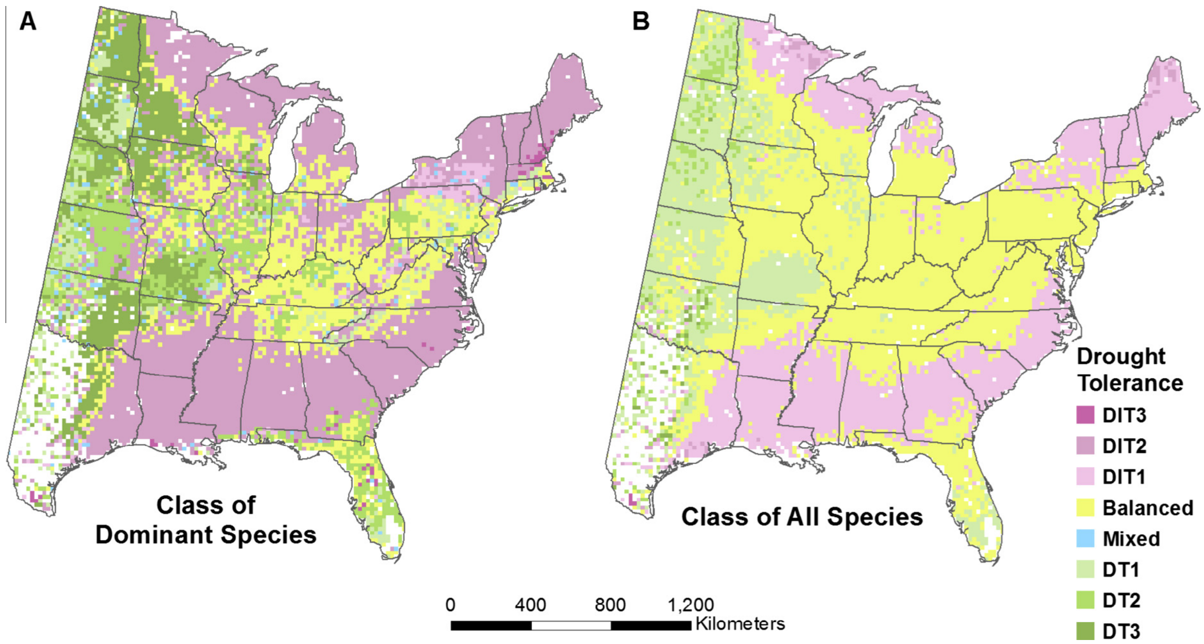

Fig. 5. Mapped distribution of drought tolerance based on (A) dominant tolerance classes among species with suitable habitat and (B) all species (mixed not used). DIT_*x* = drought intolerance class level, with 3 being the most intolerant; DT_*x* = drought tolerance level, with 3 being the most tolerant.

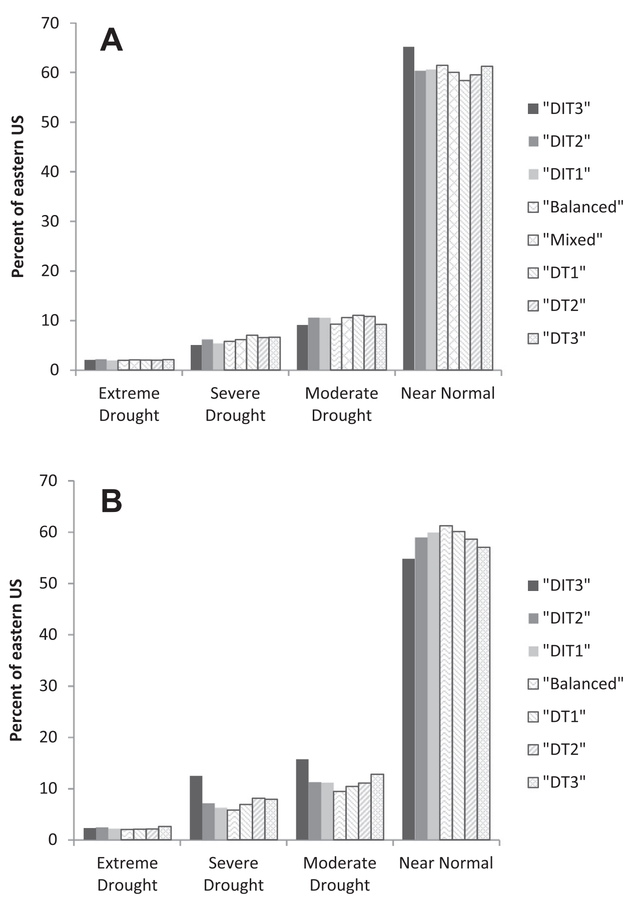

Fig. 6. Proportion of the area of drought tolerance classes of (A) the dominant species' habitat composition and (B) composition of all species' habitat experiencing drought conditions (self-calibrated) in eastern US grids, over the period 1961–2012.

tolerances contained within the community seem to suggest that eastern forests have a relatively balanced composition and as a whole, may be quite resilient to the impacts of a moderate level of drought. Should the climate models be correct, the eastern US may experience climates in the future out of the realm of that documented in this paper, with much higher temperatures and more variability in precipitation events, creating physiological drought even if overall precipitation remains the same or even increases slightly.

The results presented provide an overall depiction of the spatial distribution of 134 tree species based on modeled output and species drought tolerance from the literature. This macro-level analysis, though not precise at the forest stand level, helps further our general understanding of eastern US forests and the impacts of past and pending future drought conditions.

5. Conclusion

Drought is one of the many stress factors that affect the establishment, growth, and mortality of trees. Given that the recent trend of increasing frequency of drought conditions over much of the US is projected to continue into the future, understanding the spatial and temporal distribution of these conditions and how tree species are distributed along this gradient is important to developing and implementing management practices. Unlike the western US, which has shown large increases in the CDSI since 1986, the eastern US so far has had fewer and less intense droughts. Trees living under predominately near normal conditions, as is the case in the East, likely reflect the broader tree communities and drought tolerance classes of forests where drought occurrence has been infrequent. Our analyses of overall species tolerances indicate that, in general, the level of resilience to drought (DT1-balanced-DIT1, Fig. 5) for the eastern US forests is sufficiently balanced that dramatic compositional changes from low-level droughts between 1960 and 2013 would not be expected. However, when the analysis focuses on the numerically dominant tree species across the East, a larger proportion of both drought intolerance and tolerance appears. Nonetheless, as we move into the more variable climate that many climate projections predict, forest drought impacts will likely be amplified for specific portions of the country over short durations.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2015.02.022.

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Supplemental Table S1. Cumulative drought severity index (CDSI) calculated from climate division (NCDC) and gridded (WWDT) data for the conterminous US. Weights of 1, 2, and 3 were used for the moderate, severe, and extreme drought classes, respectively, as defined by the Palmer Drought Severity Index, and were applied to the monthly frequencies of conditions. Climate divisions were used to calculate the mean CDSI value among gridded data.

		Cumulative Drought Severity Index					
		1960-1986		1987-2013		Percent Change	
STATE	**DIVISION**	**NCDC**	**WWDT**	**NCDC**	**WWDT**	**NCDC**	**WWDT**
Alabama	101	32	20	106	69	231.3	237.6
	102	37	17	104	84	181.1	401.5
	103	46	25	89	70	93.5	187.2
	104	45	15	143	89	217.8	476.4
	105	37	20	153	93	313.5	356.9
	106	36	28	92	57	155.6	106.5
	107	42	34	87	92	107.1	173.9
	108	56	64	79	90	41.1	41.2
Arizona	201	28	104	254	254	807.1	145.0
	202	80	77	190	217	137.5	182.1
	203	78	69	258	240	230.8	247.5
	204	46	47	305	249	563.0	426.4
	205	57	124	120	263	110.5	112.4
	206	92	133	220	308	139.1	132.5
	207	48	103	311	250	547.9	142.6
Arkansas	301	86	81	68	58	-20.9	-27.8
	302	68	65	49	56	-27.9	-14.1
	303	51	54	81	75	58.8	38.4
	304	83	103	41	55	-50.6	-46.1
	305	45	42	70	66	55.6	58.4
	306	53	55	100	119	88.7	118.4
	307	71	56	139	109	95.8	93.9
	308	73	53	116	90	58.9	70.5
	309	79	71	118	115	49.4	61.4
California	401	51	102	106	182	107.8	77.9
	402	73	91	104	167	42.5	83.0
	403	79	75	155	200	96.2	164.7
	404	119	103	134	200	12.6	93.8
	405	121	114	188	215	55.4	88.6
	406	102	134	243	247	138.2	83.6
	407	52	163	294	287	465.4	76.5
Colorado	501	117	114	169	110	44.4	-3.7
	502	144	86	268	109	86.1	26.1
	503	125	88	109	77	-12.8	-12.4
	504	150	94	79	95	-47.3	1.3
	505	128	86	289	136	125.8	57.8
Connecticut	601	149	125	25	31	-83.2	-75.4
	602	107	105	28	39	-73.8	-63.0
	603	94	132	39	56	-58.5	-58.0

		1960-1986		1987-2013		Percent Change	
STATE	DIVISION	NCDC	WWDT	NCDC	WWDT	NCDC	WWDT
Delaware	701	123	97	39	45	32	47
	702	111	111	118	106	106	95
Florida	801	43	30	104	120	242	403
	802	39	20	167	175	428	884
	803	42	44	174	195	414	447
	804	87	93	85	178	98	192
	805	83	76	117	150	141	198
	806	92	69	74	102	80	149
	807	135	92	87	142	64	154
Georgia	901	33	18	176	122	533	694
	902	59	28	136	140	231	496
	903	45	40	176	171	391	422
	904	41	34	209	155	510	462
	905	55	59	143	184	260	312
	906	45	52	162	181	360	351
	907	47	41	155	150	330	366
	908	41	45	138	161	337	357
	909	52	38	157	200	302	526
Idaho	1001	76	41	82	51	108	124
	1002	91	40	121	55	133	139
	1003	98	55	110	67	112	120
	1004	80	44	244	123	305	277
	1005	109	66	328	137	301	207
	1006	154	67	184	104	119	154
	1007	107	68	244	157	228	230
	1008	146	43	115	89	79	206
	1009	73	56	320	175	438	315
	1010	72	47	301	109	418	232
Illinois	1101	108	65	120	48	111	74
	1102	131	80	93	39	71	49
	1103	85	33	175	78	206	238
	1104	90	48	132	54	147	112
	1105	80	50	66	24	83	48
	1106	69	24	96	36	139	153
	1107	71	36	62	11	87	31
	1108	96	41	36	10	38	24
	1109	55	40	50	8	91	20
Indiana	1201	74	40	86	38	116	94
	1202	67	44	93	42	139	96
	1203	97	68	95	32	98	47
	1204	57	23	58	11	102	48
	1205	51	18	79	21	155	118
	1206	88	61	63	28	72	46
	1207	52	26	67	11	129	42
	1208	46	12	87	18	189	144
	1209	41	11	61	8	149	78

		1960-1986		1987-2013		Percent Change	
STATE	DIVISION	NCDC	WWDT	NCDC	WWDT	NCDC	WWDT
Iowa	1301	119	53	114	65	96	121
	1302	72	36	144	71	200	199
	1303	94	64	81	49	86	75
	1304	111	48	92	41	83	85
	1305	112	39	99	59	88	152
	1306	87	39	124	62	143	159
	1307	66	20	105	40	159	198
	1308	58	18	112	57	193	308
	1309	59	22	128	53	217	245
Kansas	1401	71	33	146	50	206	152
	1402	92	25	110	41	120	163
	1403	88	36	134	62	152	169
	1404	93	59	113	53	122	89
	1405	86	45	140	50	163	110
	1406	98	68	88	52	90	76
	1407	95	79	93	59	98	75
	1408	96	61	76	48	79	78
	1409	109	76	57	46	52	60
Kentucky	1501	41	24	98	28	239	114
	1502	29	14	71	41	245	295
	1503	32	10	116	42	363	428
	1504	49	19	90	68	184	362
Louisiana	1601	114	90	117	105	103	116
	1602	100	89	79	75	79	84
	1603	81	81	68	75	84	92
	1604	113	83	86	92	76	111
	1605	66	50	93	87	141	175
	1606	78	38	76	68	97	178
	1607	50	35	97	98	194	276
	1608	81	38	102	90	126	237
	1609	70	44	94	67	134	153
Maine	1701	54	41	45	46	83	111
	1702	73	63	38	53	52	84
	1703	86	69	24	37	28	54
Maryland	1801	86	96	147	142	171	148
	1802	65	76	110	102	169	135
	1803	73	58	88	50	121	86
	1804	79	88	78	68	99	76
	1805	106	115	76	72	72	62
	1806	86	91	63	60	73	66
	1807	84	69	69	71	82	104
	1808	28	39	117	48	418	125
Massachusetts	1901	165	125	18	33	11	26
	1902	113	94	18	18	16	20
	1903	90	95	25	25	28	27

		1960-1986		1987-2013		Percent Change	
STATE	DIVISION	NCDC	WWDT	NCDC	WWDT	NCDC	WWDT
Michigan	2001	71	52	173	56	244	108
	2002	69	48	138	82	200	172
	2003	61	38	64	22	105	58
	2004	78	36	73	23	94	62
	2005	93	47	76	11	82	23
	2006	110	63	44	11	40	18
	2007	106	51	59	19	56	37
	2008	74	51	63	26	85	50
	2009	117	68	60	11	51	17
	2010	140	80	52	26	37	33
Minnesota	2101	124	58	176	63	142	109
	2102	119	43	122	36	103	85
	2103	88	56	88	26	100	46
	2104	105	40	126	38	120	94
	2105	106	37	143	55	135	146
	2106	129	54	124	42	96	78
	2107	109	59	149	72	137	121
	2108	72	35	146	67	203	192
	2109	110	61	91	33	83	54
Mississippi	2201	69	59	82	92	119	156
	2202	62	44	66	47	106	105
	2203	58	35	62	43	107	125
	2204	95	73	102	73	107	99
	2205	61	46	59	46	97	99
	2206	58	34	85	47	147	141
	2207	58	43	71	59	122	139
	2208	71	47	54	64	76	136
	2209	65	54	68	78	105	144
	2210	84	65	100	72	119	111
Missouri	2301	89	43	102	55	115	129
	2302	117	59	81	49	69	83
	2303	84	61	72	34	86	56
	2304	62	65	52	37	84	57
	2305	78	58	46	25	59	43
	2306	52	43	71	52	137	122
Montana	2401	83	46	240	77	289	167
	2402	61	37	410	77	672	211
	2403	100	130	119	118	119	90
	2404	74	68	222	99	300	146
	2405	74	51	280	107	378	210
	2406	107	123	62	84	58	68
	2407	105	84	134	92	128	110
Nebraska	2501	99	57	201	136	203	240
	2502	124	56	175	82	141	146
	2503	103	45	146	71	142	159
	2505	59	12	168	34	285	289
	2506	78	24	132	33	169	140
	2507	49	34	146	87	298	256
	2508	59	9	123	26	208	290
	2509	98	25	176	46	180	183

STATE	DIVISION	1960-1986 NCDC	1960-1986 WWDT	1987-2013 NCDC	1987-2013 WWDT	Percent Change NCDC	Percent Change WWDT
Nevada	2601	79	81	410	158	519	196
	2602	104	86	271	108	261	125
	2603	59	90	100	186	169	206
	2604	77	162	221	311	287	191
New Hampshire	2701	49	62	32	22	65	36
	2702	95	87	21	26	22	30
New Jersey	2801	111	116	48	61	43	53
	2802	94	115	55	73	59	64
	2803	71	109	84	93	118	86
New Mexico	2901	97	84	95	134	98	160
	2902	132	88	183	138	139	156
	2903	91	120	148	159	163	133
	2904	58	60	155	160	267	265
	2905	64	92	114	199	178	216
	2906	68	84	220	162	324	194
	2907	69	123	162	210	235	170
	2908	61	82	169	179	277	218
New York	3001	54	102	43	30	80	30
	3002	116	124	36	40	31	32
	3003	71	86	20	23	28	27
	3004	84	153	54	102	64	66
	3005	143	128	31	39	22	30
	3006	53	102	49	30	92	29
	3007	62	78	35	19	56	24
	3008	69	66	34	8	49	12
	3009	62	58	52	28	84	48
	3010	91	82	44	21	48	25
North Carolina	3101	63	41	141	113	224	273
	3102	59	50	103	134	175	265
	3103	55	44	88	103	160	236
	3104	57	40	123	141	216	351
	3105	50	27	139	145	278	528
	3106	40	16	97	88	243	535
	3107	38	21	64	69	168	328
	3108	46	31	91	83	198	270
North Dakota	3201	97	53	131	56	135	106
	3202	105	54	137	65	130	119
	3203	107	50	128	60	120	118
	3204	71	47	167	71	235	152
	3205	91	53	148	57	163	109
	3206	103	57	116	48	113	84
	3207	88	57	209	89	238	158
	3208	106	55	199	85	188	154
	3209	121	57	133	44	110	77

STATE	DIVISION	1960-1986 NCDC	1960-1986 WWDT	1987-2013 NCDC	1987-2013 WWDT	Percent Change NCDC	Percent Change WWDT
Ohio	3301	111	80	70	26	63	33
	3302	93	59	66	22	71	37
	3303	70	49	53	33	76	68
	3304	64	71	74	32	116	46
	3305	40	22	70	33	175	148
	3306	52	36	52	21	100	59
	3307	93	80	78	29	84	37
	3308	46	27	63	25	137	93
	3309	46	19	97	40	211	212
	3310	30	18	50	29	167	162
Oklahoma	3401	101	111	80	80	79	72
	3402	94	95	88	63	94	66
	3403	79	71	72	59	91	83
	3404	115	110	77	69	67	62
	3405	126	82	102	63	81	76
	3406	106	78	74	54	70	69
	3407	140	105	77	71	55	67
	3408	103	61	109	62	106	100
	3409	70	78	94	78	134	100
Oregon	3501	37	59	107	121	289	205
	3502	51	57	92	102	180	181
	3503	63	77	71	156	113	201
	3504	47	81	58	110	123	137
	3505	60	55	259	96	432	173
	3506	114	67	185	74	162	110
	3507	99	62	372	95	376	154
	3508	64	46	428	71	669	155
	3509	96	66	304	117	317	177
Pennsylvania	3601	122	129	32	49	26	38
	3602	118	116	39	34	33	29
	3603	83	117	35	42	42	36
	3604	63	78	57	53	90	68
	3605	57	86	46	37	81	44
	3606	105	105	46	35	44	33
	3607	55	61	83	66	151	107
	3608	65	75	77	79	118	106
	3609	72	61	43	45	60	74
	3610	53	51	52	42	98	84
Rhode Island	3701	81	100	20	21	25	21
South Carolina	3801	44	36	102	136	232	377
	3802	44	23	208	175	473	747
	3803	49	20	154	143	314	702
	3804	43	32	91	92	212	283
	3805	36	25	177	156	492	629
	3806	44	24	116	86	264	359
	3807	48	42	116	109	242	259

		1960-1986		1987-2013		Percent Change	
STATE	DIVISION	NCDC	WWDT	NCDC	WWDT	NCDC	WWDT
South Dakota	3901	149	70	200	99	134	143
	3902	129	46	194	59	150	128
	3903	182	67	79	26	43	39
	3904	97	53	222	78	229	146
	3905	153	88	199	106	130	120
	3906	128	55	132	56	103	102
	3907	129	63	121	28	94	44
	3908	134	71	135	53	101	76
	3909	132	74	147	66	111	89
Tennessee	4001	62	31	111	89	179	285
	4002	66	35	113	71	171	201
	4003	51	21	107	54	210	263
	4004	51	27	62	46	122	167
Texas	4101	63	118	106	140	168	119
	4102	58	83	122	111	210	135
	4103	94	56	103	66	110	118
	4104	103	64	132	100	128	157
	4105	30	77	150	185	500	239
	4106	79	83	105	122	133	146
	4107	90	47	190	116	211	248
	4108	76	30	95	85	125	282
	4109	67	67	123	177	184	262
	4110	50	53	189	203	378	386
Utah	4201	75	103	235	147	313	143
	4202	49	95	205	207	418	217
	4203	96	86	268	111	279	129
	4204	123	103	124	109	101	106
	4205	115	79	257	93	223	118
	4206	113	154	172	164	152	107
	4207	75	138	163	179	217	129
Vermont	4301	118	111	14	20	12	18
	4302	84	73	40	21	48	28
	4303	90	59	29	24	32	40
Virginia	4401	89	57	78	70	88	123
	4402	90	98	95	88	106	90
	4403	81	102	67	82	83	81
	4404	66	72	68	52	103	72
	4405	87	110	44	80	51	73
	4406	52	45	82	94	158	206
Washington	4501	49	42	71	114	145	275
	4502	76	26	92	66	121	257
	4503	46	25	85	87	185	343
	4504	40	35	62	99	155	279
	4505	54	41	67	98	124	238
	4506	78	61	141	68	181	111
	4507	90	58	270	97	300	168
	4508	109	79	230	88	211	111
	4509	90	37	170	53	189	145
	4510	133	65	133	73	100	113

		1960-1986		1987-2013		Percent Change	
STATE	DIVISION	NCDC	WWDT	NCDC	WWDT	NCDC	WWDT
West Virginia	4601	47	56	76	31	162	56
	4602	47	47	44	33	94	71
	4603	75	36	64	37	85	102
	4604	54	41	55	46	102	112
	4605	57	55	61	67	107	122
	4606	57	74	67	70	118	94
Wisconsin	4701	104	54	159	39	153	73
	4702	88	60	138	53	157	87
	4703	77	54	102	42	132	77
	4704	97	58	91	15	94	25
	4705	85	63	51	18	60	28
	4706	80	62	50	15	63	25
	4707	127	90	64	30	50	33
	4708	148	107	47	16	32	15
	4709	129	83	41	9	32	11
Wyoming	4801	73	35	405	68	555	194
	4802	124	33	115	63	93	192
	4803	77	83	359	156	466	187
	4804	66	62	117	156	177	250
	4805	103	77	157	132	152	172
	4806	112	72	329	104	294	144
	4807	131	98	167	138	127	141
	4808	118	102	157	128	133	126
	4809	73	89	212	186	290	208
	4810	91	71	349	130	384	183

Supplemental Table S2. Tree species modeled for habitat suitability and drought tolerance class. Negative drought classes correspond to drought-intolerant classes (DIT -1,-2,-3), while positive values represent drought-tolerant classes (DT 1,2,3). Importance Value (IV) sum for all 20 × 20 km cells in the eastern US indicate the species' relative abundance based on modeled inventory data.

Common Name	Scientific Name	Model Reliability	Drought Class	IVsum
balsam fir	*Abies balsamea*	High	-2	9519
Florida maple	*Acer barbatum*	Medium	1	187
boxelder	*Acer negundo*	Medium	3	14132
black maple	*Acer nigrum*	Low	-1	181
striped maple	*Acer pensylvanicum*	High	-2	2081
red maple	*Acer rubrum*	High	1	47858
silver maple	*Acer saccharinum*	Medium	-2	7835
sugar maple	*Acer saccharum*	High	-1	27948
mountain maple	*Acer spicatum*	High	-2	515
Ohio buckeye	*Aesculus glabra*	Low	-1	549
yellow buckeye	*Aesculus octandra*	Medium	-2	397
serviceberry	*Amelanchier sp.*	Medium	-2	1526
pawpaw	*Asimina triloba*	Low	-2	552
yellow birch	*Betula alleghaniensis*	High	-1	4067
sweet birch	*Betula lenta*	High	-1	3632
river birch	*Betula nigra*	Low	-2	788
paper birch	*Betula papyrifera*	High	-2	6703
gray birch	*Betula populifolia*	Medium	-1	751
cittamwood/gum bumelia	*Bumelia lanuginosa*	Low	2	50
American hornbeam, musclewood	*Carpinus caroliniana*	Medium	-2	6507
water hickory	*Carya aquatica*	Medium	1	1238
bitternut hickory	*Carya cordiformis*	Low	2	4195
pignut hickory	*Carya glabra*	High	-2	9615
pecan	*Carya illinoensis*	Low	-1	825
shellbark hickory	*Carya laciniosa*	Low	-2	202
shagbark hickory	*Carya ovata*	Medium	-1	8241
black hickory	*Carya texana*	High	1	2930
mockernut hickory	*Carya tomentosa*	High	1	9770
American chestnut	*Castanea dentata*	Medium	1	169
northern catalpa	*Catalpa speciosa*	Low	1	430
sugarberry	*Celtis laevigata*	Medium	-2	3851
hackberry	*Celtis occidentalis*	Medium	2	13010
eastern redbud	*Cercis canadensis*	Medium	-1	3037
Atlantic white-cedar	*Chamaecyparis thyoides*	Low	-2	167
flowering dogwood	*Cornus florida*	High	-2	14892
common persimmon	*Diospyros virginiana*	Medium	-1	4194
American beech	*Fagus grandifolia*	High	-1	12659
white ash	*Fraxinus americana*	High	-1	18408
black ash	*Fraxinus nigra*	High	-2	4605
green ash	*Fraxinus pennsylvanica*	Medium	1	20012
blue ash	*Fraxinus quadrangulata*	Low	1	63
waterlocust	*Gleditsia aquatica*	Low	-2	94

Common Name	Scientific Name	Model Reliability	Drought Class	IVsum
honeylocust	*Gleditsia triacanthos*	Low	2	5804
loblolly-bay	*Gordonia lasianthus*	Medium	-1	724
Kentucky coffeetree	*Gymnocladus dioicus*	Low	-1	336
silverbell	*Halesia sp.*	Medium	-1	60
American holly	*Ilex opaca*	High	-1	2390
butternut	*Juglans cinerea*	Low	-2	318
black walnut	*Juglans nigra*	Medium	-2	8664
eastern redcedar	*Juniperus virginiana*	Medium	2	13509
tamarack (native)	*Larix laricina*	High	1	2233
sweetgum	*Liquidambar styraciflua*	High	-2	28185
yellow-poplar	*Liriodendron tulipifera*	High	-1	12919
Osage-orange	*Maclura pomifera*	Medium	1	5626
cucumbertree	*Magnolia acuminata*	High	-2	480
southern magnolia	*Magnolia grandiflora*	Medium	-2	492
bigleaf magnolia	*Magnolia macrophylla*	Low	-1	26
sweetbay	*Magnolia virginiana*	High	-1	3318
red mulberry	*Morus rubra*	Low	-1	4689
water tupelo	*Nyssa aquatica*	Medium	-3	1811
swamp tupelo	*Nyssa biflora*	High	-3	5305
ogeechee tupelo	*Nyssa ogeche*	Medium	-2	79
blackgum	*Nyssa sylvatica*	High	-1	10796
eastern hophornbeam, ironwood	*Ostrya virginiana*	Medium	1	9598
sourwood	*Oxydendrum arboreum*	High	1	4278
redbay	*Persea borbonia*	High	-1	1177
white spruce	*Picea glauca*	Medium	-1	1520
black spruce	*Picea mariana*	High	-2	3176
red spruce	*Picea rubens*	High	-2	2875
jack pine	*Pinus banksiana*	High	2	3192
sand pine	*Pinus clausa*	Medium	-3	875
shortleaf pine	*Pinus echinata*	High	-2	10087
slash pine	*Pinus elliottii*	High	2	14744
spruce pine	*Pinus glabra*	Medium	-2	238
longleaf pine	*Pinus palustris*	High	-1	4849
Table Mountain pine	*Pinus pungens*	Medium	2	100
red pine	*Pinus resinosa*	Medium	-2	3421
pitch pine	*Pinus rigida*	High	-1	1203
pond pine	*Pinus serotina*	High	-3	1158
eastern white pine	*Pinus strobus*	High	-3	8628
loblolly pine	*Pinus taeda*	High	-2	46705
Virginia pine	*Pinus virginiana*	High	1	5817
water elm	*Planera aquatica*	Low	-1	411
sycamore	*Platanus occidentalis*	Medium	1	4035
balsam poplar	*Populus balsamifera*	High	-2	2273
eastern cottonwood	*Populus deltoides*	Low	1	9346
bigtooth aspen	*Populus grandidentata*	High	-2	3959
quaking aspen	*Populus tremuloides*	High	-2	18067
wild plum	*Prunus americana*	Low	-1	310
pin cherry	*Prunus pensylvanica*	Medium	-2	792
black cherry	*Prunus serotina*	High	2	21157
chokecherry	*Prunus virginiana*	Low	-1	1267
white oak	*Quercus alba*	High	1	28284
swamp white oak	*Quercus bicolor*	Low	-1	1000

Common Name	Scientific Name	Model Reliability	Drought Class	IVsum
scarlet oak	*Quercus coccinea*	High	1	4565
durand oak	*Quercus durandii*	Low	-1	6
northern pin oak	*Quercus ellipsoidalis*	Medium	3	1178
southern red oak	*Quercus falcata var. falcata*	High	1	7348
cherrybark oak, swamp red oak	*Quercus falcata var. pagodaefolia*	Medium	-1	2021
bear oak, scrub oak	*Quercus ilicifolia*	Low	2	155
shingle oak	*Quercus imbricaria*	Medium	2	1779
bluejack oak	*Quercus incana*	Medium	-1	501
turkey oak	*Quercus laevis*	High	2	1398
laurel oak	*Quercus laurifolia*	High	-1	5168
overcup oak	*Quercus lyrata*	Medium	-2	1694
bur oak	*Quercus macrocarpa*	Medium	3	12197
blackjack oak	*Quercus marilandica*	Medium	3	3453
swamp chestnut oak	*Quercus michauxii*	Medium	-1	713
chinkapin oak	*Quercus muehlenbergii*	Medium	1	2313
water oak	*Quercus nigra*	High	-1	11570
nuttall oak	*Quercus nuttallii*	Low	1	633
pin oak	*Quercus palustris*	Medium	-1	1927
willow oak	*Quercus phellos*	Medium	-1	3591
chestnut oak	*Quercus prinus*	High	1	7933
northern red oak	*Quercus rubra*	High	1	18801
Shumard oak	*Quercus shumardii*	Low	2	233
post oak	*Quercus stellata*	High	3	14630
black oak	*Quercus velutina*	High	2	16081
live oak	*Quercus virginiana*	Medium	1	2790
black locust	*Robinia psuedoacacia*	Low	-2	4685
peachleaf willow	*Salix amygdaloides*	Low	-1	255
black willow	*Salix nigra*	Low	-2	4866
sassafras	*Sassafras albidum*	High	2	7563
American mountain-ash	*Sorbus americana*	Medium	-1	35
bald cypress	*Taxodium distichum*	Medium	-2	3014
pond cypress	*Taxodium distichum(var.nutans)*	High	1	3335
northern white-cedar	*Thuja occidentalis*	High	-2	4672
American basswood	*Tilia americana*	Medium	-1	8479
eastern hemlock	*Tsuga canadensis*	High	-2	5951
winged elm	*Ulmus alata*	High	-1	7378
American elm	*Ulmus americana*	Medium	-2	28934
cedar elm	*Ulmus crassifolia*	Low	-1	544
slippery elm	*Ulmus rubra*	Medium	1	8758
rock elm	*Ulmus thomasii*	Low	-1	326

Supplemental Table S3. Duration of the longest consecutive period and mean interval of monthly drought and near normal conditions for the period 1961–2012. Values of self-calibrated PDSI among 20×20 km grids are summarized for 37 states.

		Longest Period												Mean Interval											
		Extreme Drought			Severe Drought			Moderate Drought			Near Normal			Extreme Drought			Severe Drought			Moderate Drought			Near Normal		
STATE	GRIDS	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX
AL	383	2	7.3	22	2	10.3	27	5	10.2	22	19	63.2	190	1.3	3.8	10	1.1	3.9	7.8	1.7	3.4	7.3	5.5	13.6	38.9
AR	390	2	7.5	22	2	10.3	27	5	10.3	22	19	62.8	190	1.3	3.9	10	1.1	3.9	7.8	1.7	3.4	7.3	5.5	13.6	38.9
CT	51	4	6.7	8	5	11.0	18	6	10.3	19	19	78.3	188	2.0	4.1	7	2.6	4.3	7.5	2.3	3.4	7.3	7.8	15.3	28.6
DE	24	5	6.9	8	6	11.5	18	6	10.8	19	19	83.8	181	2.2	4.3	7	2.8	4.3	7.5	2.3	3.3	4.6	7.8	15.4	28.6
FL	455	2	7.7	22	2	10.7	36	5	10.7	27	19	62.2	190	1.3	4.0	10	1.1	3.9	12.6	1.7	3.5	7.4	5.5	13.5	38.9
GA	429	2	7.6	22	2	10.7	36	5	10.5	25	19	62.4	190	1.3	4.0	10	1.1	3.9	12.6	1.7	3.5	7.3	5.5	13.5	38.9
IL	420	2	7.5	22	2	10.5	31	5	10.5	22	19	62.5	190	1.3	3.9	10	1.1	3.9	7.8	1.7	3.4	7.3	5.5	13.5	38.9
IN	272	2	7.1	22	2	10.0	20	5	10.0	22	19	64.5	190	1.3	3.8	9	1.5	3.8	7.5	1.7	3.4	7.3	5.5	13.9	38.9
IA	411	2	7.5	22	2	10.4	27	5	10.4	22	19	62.5	190	1.3	4.0	10	1.1	3.9	7.8	1.7	3.4	7.3	5.5	13.5	38.9
KS	430	2	7.6	22	2	10.7	36	5	10.5	25	19	62.0	190	1.3	4.0	10	1.1	3.9	12.6	1.7	3.5	7.3	5.5	13.5	38.9
KY	317	2	7.2	22	2	9.9	20	5	10.0	22	19	63.3	190	1.3	3.8	9	1.4	3.8	7.5	1.7	3.4	7.3	5.5	13.7	38.9
LA	374	2	7.3	22	2	10.2	22	5	10.2	22	19	63.0	190	1.3	3.9	9	1.1	3.9	7.8	1.7	3.4	7.3	5.5	13.6	38.9
ME	252	2	6.9	13	4	10.2	20	6	9.9	20	19	66.1	190	1.3	3.7	7.5	2.0	3.9	7.5	1.7	3.4	7.3	5.5	14.2	38.9
MD	108	4	6.7	10	5	10.2	18	6	9.6	19	19	74.5	190	2.0	3.9	7	2.0	3.9	7.5	2.1	3.3	7.3	7.0	14.9	29.3
MA	89	4	6.6	8	5	10.4	18	6	9.7	19	19	74.5	190	2.0	4.0	7	2.0	3.9	7.5	2.1	3.3	7.3	7.4	15.0	28.6
MI	483	2	7.8	22	2	11.2	36	5	10.8	27	25	61.8	190	1.3	4.1	10.5	1.1	4.0	12.6	1.7	3.5	7.4	5.5	13.5	38.9
MN	621	1	7.6	22	2	12.2	36	5	11.2	27	19	62.8	190	1.0	4.0	10.5	1.1	4.3	12.6	1.7	3.7	8.0	5.5	13.4	38.9
MS	361	2	7.4	22	2	10.1	27	5	10.2	22	19	63.1	190	1.3	3.9	9	1.1	3.8	7.8	1.7	3.4	7.3	5.5	13.6	38.9
MO	522	2	7.7	22	2	11.5	36	5	10.9	27	19	62.3	190	1.3	4.0	10.5	1.1	4.1	12.6	1.7	3.5	7.5	5.5	13.6	38.9
NE	310	2	7.2	22	2	9.9	20	5	10.0	22	19	63.7	190	1.3	3.8	9	1.4	3.8	7.5	1.7	3.4	7.3	5.5	13.8	38.9

		Longest Period												Mean Interval											
		Extreme Drought			Severe Drought			Moderate Drought			Near Normal			Extreme Drought			Severe Drought			Moderate Drought			Near Normal		
STATE	GRIDS	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX	MIN	MEAN	MAX
NH	85	4	6.5	8	5	10.4	18	6	9.7	19	19	74.8	190	2.0	3.9	7	2.0	3.9	7.5	2.1	3.3	7.3	7.4	15.0	29.3
NJ	72	4	6.6	8	5	10.6	18	6	9.7	19	19	78.0	190	2.0	4.0	7	2.5	4.1	7.5	2.1	3.3	7.3	7.8	15.7	28.6
NY	388	2	7.4	22	2	10.3	27	5	10.3	22	19	62.8	190	1.3	3.9	10	1.1	3.9	7.8	1.7	3.4	7.3	5.5	13.6	38.9
NC	398	2	7.6	22	2	10.2	27	5	10.3	22	19	62.7	190	1.3	4.0	10	1.1	3.8	7.8	1.7	3.4	7.3	5.5	13.6	38.9
ND	236	2	7.0	13	4	10.2	20	6	9.8	20	19	65.9	190	1.3	3.8	7.5	2.0	3.8	7.5	1.7	3.4	7.3	5.5	14.1	38.9
OH	311	2	7.2	22	2	9.9	20	5	10.0	22	19	63.5	190	1.3	3.8	9	1.4	3.8	7.5	1.7	3.4	7.3	5.5	13.7	38.9
OK	466	2	7.7	22	2	10.9	36	5	10.8	27	19	62.2	190	1.3	4.0	10	1.1	4.0	12.6	1.7	3.5	7.4	5.5	13.5	38.9
PA	337	2	7.2	22	2	10.1	27	5	10.0	22	19	63.5	190	1.3	3.8	9	1.4	3.8	7.8	1.7	3.4	7.3	5.5	13.7	38.9
RI	17	5	6.9	8	6	10.8	16	6	10.7	19	19	83.5	181	2.2	4.3	6.5	2.8	4.1	7.5	2.3	3.2	4.0	7.8	15.6	28.6
SC	241	2	7.0	13	4	10.2	20	6	9.8	20	19	66.6	190	1.3	3.8	7.5	2.0	3.9	7.5	1.7	3.4	7.3	5.5	14.2	38.9
SD	277	2	7.1	22	2	10.0	20	5	10.0	22	25	64.6	190	1.3	3.8	9	1.5	3.8	7.5	1.7	3.4	7.3	5.5	13.9	38.9
TN	327	2	7.2	22	2	10.1	27	5	10.0	22	19	63.3	190	1.3	3.8	9	1.4	3.8	7.5	1.7	3.4	7.3	5.5	13.7	38.9
TX	1104	1	7.4	24	2	11.9	36	2	11.5	32	19	60.9	190	1.0	3.9	14	1.1	4.3	12.6	1.1	3.8	11.7	5.5	13.4	38.9
VT	88	4	6.5	8	5	10.4	18	6	9.7	19	31	77.8	190	2.0	3.9	7	2.0	4.0	7.5	2.1	3.3	7.3	7.4	15.3	29.3
VA	331	2	7.2	22	2	10.1	27	5	10.0	22	19	63.2	190	1.3	3.8	9	1.4	3.8	7.5	1.7	3.4	7.3	5.5	13.7	38.9
WV	207	2	6.9	11	4	10.4	20	6	9.8	20	19	68.3	190	1.3	3.8	7	2.0	3.9	7.5	1.7	3.4	7.3	6.1	14.4	38.9
WI	417	2	7.5	22	2	10.5	31	5	10.4	22	19	62.4	190	1.3	3.9	10	1.1	3.9	7.8	1.7	3.4	7.3	5.5	13.5	38.9

Supplemental Figure S4. Mean duration of the longest consecutive period (monthly) for each drought class from 1961-2012. PDSI classes were calculated using a self-calibrating algorithm, PRISM climate data, and NRCS County Soil Survey Geographic available water holding capacity.