



Is increased precipitation during the 20th century statistically or ecologically significant in the eastern US?

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ABSTRACT

We address the climate versus disturbance debate to understand drivers of change in human-environment systems. We examine whether recent increased precipitation episodes ('pluvials') are unique and have ecological implications for the humid climate of the eastern United States. Robust statistical analyses presented here indicate that the 20th century was wet, but not significantly different than other centuries during the last millennium. Statistical methods did not establish increased precipitation episodes as an unusual change that correlated with transition shifts in eastern forests during the early 20th century. Additionally, modest precipitation change was not ecologically significant enough to result in forests composed of drought-tolerant trees in the past or drought-intolerant trees currently. We conclude that fire is a parsimonious explanation for composition and structure of historical open fire-tolerant oak and pine forests. Fire exclusion was unprecedented during early 20th century and loss of this driver provides a mechanism for forest transitions.

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Introduction

The eastern United States experienced a mixture of increased and decreased precipitation during the past century, with above average precipitation in the Northeast (Peterson et al., 2013), which may result in change to ecosystems. McEwan, Dyer, and Pederson (2011) suggested that anomalous wet intervals ('pluvials') during the past century were unprecedented when compared to the past 500 years in the eastern US, using tree-ring reconstructions of Palmer Drought Severity Index (PDSI; Cook, Meko, Stahle, & Cleaveland, 1999; Palmer, 1965). Using similar data, Fye, Stahle, and Cook (2003) did not identify moisture anomalies during the twentieth century in the eastern US. Kangas & Brown (2007) highlighted an increase in pluvial anomalies since 1970, detected at short (24 month) but not long timescales, using nationwide weather station data. Studies also have demonstrated onset of pluvials as early as 1800 (Pederson et al., 2013). Hunt (2011) concluded that pluvial anomalies were infrequent, did not persist, and lacked spatial synchronicity.

It is uncertain whether recent pluvials fall within the historical range of variability in the eastern US (Bailey, 1983). There is not agreement in defined thresholds for identification of pluvials using PDSI values. McEwan et al. (2011) defined pluvials as PDSI values ≥ 0.25 lasting more than three years, while Fye et al. (2003) used PDSI values ≥ 1 , with onset after change of sign from negative to positive for two consecutive years. The PDSI values at least represent a comprehensive

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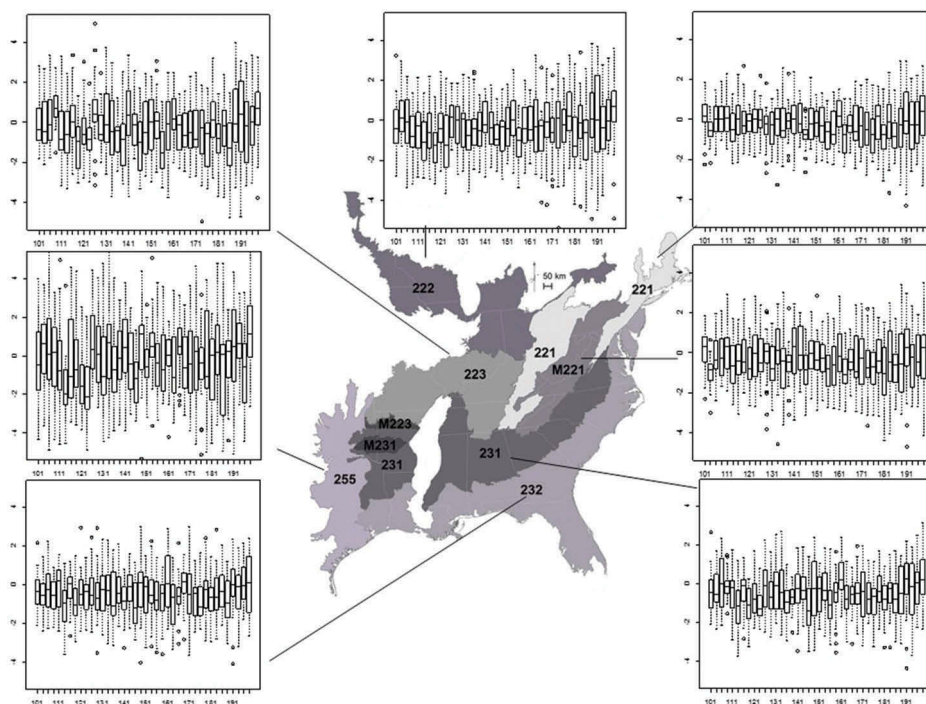


Figure 1. The seven selected ecological provinces and box plots of Palmer Drought Severity Index values for 1000 to 2000, in quarter-century intervals (101 = first quarter-century of the 1000s). The box shows the upper and lower quartiles with a median line. The dotted lines shows the highest and lowest value and circles represent excluded outliers. Provinces 223, 231 and 232 have significant upward trends during the 1800s (starting at 181) and 1900s.

paleoclimatic proxy of plant water availability, whereas other climate proxies are limited in sample size and extent. However, climate proxies such as PDSI are less reliable than instrumental records and if different analyses produce non-significant results, then climate proxies cannot provide a foundation for identifying anomalous climate.

To test whether 20th century precipitation was unprecedented during the last 1000 years in the paleoclimatic record, we compared PDSI using quantitative analysis rather than qualitative thresholds across seven major ecological provinces (Figure 1; Ecomap, 2007; selected ecological provinces had historical surface fire regimes). We note that the 1800s and 1900s may provide relative moisture extremes, exaggerating differences, while other centuries and other 100 year intervals (that do not begin at the start of the century) are wetter than the 1800s (Figure 1). We then present our viewpoint of whether precipitation change within the range of historic variation was ecologically significant enough to affect eastern forests. Climate traditionally has been used to explain distribution and type of ecosystems; however, new research has demonstrated complex interactions between humans and ecosystems. Anthropogenic disturbance may be a more influential driver of ecosystem change than natural drivers.

Methods

Rather than arbitrary thresholds, we used Mann-Kendall tests (common in climate studies; Zhang & Zwiers, 2004), sequential change point detection of shifts in trend means (a developing approach; Ross, 2015), and generalized linear mixed models, along with Kolmogorov-Smirnov tests (used by Cook, Ault, & Smerdon, 2015 to detect trends in PDSI), to determine if PDSI values <https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring/drought-variability> differed from the 20th century when compared to other centuries. We first used the non-parametric Mann-Kendall method to

document an increasing trend during the 1800s and 1900s (zyp package; R Core Team, Vienna, Austria). We applied prewhitening to remove serial correlation that may lead to overestimation of the significance of a trend and rejection of the null hypothesis of no trend (Zhang & Zwiers, 2004). We then tested if the 20th century was statistically different in PDSI values during the millennium, using two methods that can account for serial correlation, sequential change detection and generalized linear mixed models, and also two-sample two-sided Kolmogorov-Smirnov tests.

Sequential change detection identifies points at which the mean changes (Ross, 2015). This method does not require separation into time intervals for comparison, particularly appropriate for detecting anomalies. We used the t – test for change points (cpm package, R Core Team, Vienna, Austria; Ross, 2015). For any province with a change point during 1880 to 1960, the approximate time of forest change, we excluded years prior to 1900 until the last change point did not occur during 1880 to 1960 to demonstrate continuity of PDSI values.

We applied generalized linear mixed models, with an autoregressive heterogeneity covariance structure to compare change over time (Proc Mixed; SAS software, version 9.4, Cary, North Carolina, USA; centuries were repeated measures; multiple comparisons by least squares means). Because generalized linear mixed models can provide multiple comparisons, limiting number of tests, we also compared half-century and quarter-century intervals. Although the 1900s may represent a pluvial, other pluvials may not have occurred at such a convenient interval. We additionally identified maximum century and half-century PDSI values (i.e. rather than structured starting dates of 1000, 1100, 1200, etc., we determined the start year that had the greatest value by province).

Results

Three of the seven ecological provinces (Figure 1; 223, 231, 232) had a significant ($p < 0.05$) Mann-Kendall trend of increasing PDSI, indicating moister conditions, during the 1800s and 1900s (Table 1). Two provinces with significant trends were located in the southeastern US. Although the 20th century was wet, it was not significantly different than other centuries during the last millennium, based on sequential change detection, generalized linear mixed models, and Kolmogorov-Smirnov tests.

Directional changes in PDSI occurred at least eight times per province during the 1000 years (Table 2). Two provinces (221 and M221) did not have change in PDSI values since 1834, indicating that values after this year were similar. For provinces with a change point during 1880 to 1960, we repeated the analysis after deleting years prior to 1900 until there was no change point during 1880 to 1960 to demonstrate continuity of values with the 20th century.

The PDSI values significantly differed among centuries for three of the seven ecological provinces using the structured century starting points (of 1000, 1100, ...1800; generalized linear mixed models in Table 3). Given that climate changes over time, it was not surprising that 20th century moisture availability was different than some previous centuries. The PDSI values from the 1900s were greater than the 1800s in six of seven ecological provinces (Table 3).

Table 1. Trend detection of prewhitened Palmer Drought Severity Index values during the 1800s and 1900s by ecological province using the Mann-Kendall test.

Province	Kendall's p
221	0.08
222	0.09
223	0.02
231	0.01
232	0.02
255	0.12
M221	0.11

Table 2. Comparison of Palmer Drought Severity Index values by ecological province using parametric (T-test) sequential change detection. For any province with a change point of 1880 to 1960, we excluded years prior to 1900 until the last change point did not occur during 1880 to 1960 to demonstrate continuity of PDSI values.

Province	Years	Change points															
221	All	1121	1123	1335	1337	1439	1475	1482	1562	1578	1625	1636	1698	1827	1834		
222	All	1011	1021	1044	1182	1188	1233	1245	1347	1352	1364	1395	1439	1490	1549	1581	1586 1618
			1697	1706	1735	1738	1902										
	Exclude	1011	1021	1044	1182	1188	1233	1245	1347	1352	1364	1395	1439	1490	1549	1581	1586 1618
	1735–1849		1697	1706													
223	All	1035	1041	1104	1118	1142	1154	1184	1203	1207	1249	1346	1351	1402	1409	1449	1459 1478
			1482	1564	1574	1736	1738	1882									
	Exclude	1035	1041	1104	1118	1142	1154	1184	1203	1207	1249	1346	1351	1402	1409	1449	1459 1478
	1640–1899		1482	1564	1574												
231	All	1142	1150	1179	1204	1207	1264	1269	1309	1346	1402	1453	1457	1600	1608	1643	1646 1903
	Exclude	1142	1150	1179	1204	1207	1264	1269	1309	1346	1402	1453	1457	1600	1608		
	1625–1849																
232	All	1065	1068	1123	1341	1346	1600	1608	1945								
	Exclude	1065	1068	1123	1341	1346	1600	1608									
	1660–1899																
255	All	1053	1057	1125	1166	1177	1258	1454	1474	1496	1536	1566	1694	1855	1865	1951	1957
	Exclude	1053	1057	1125	1166	1177	1258	1454	1474	1496	1536	1566	1694				
	1850–1899																
M221	All	1024	1056	1121	1123	1339	1347	1562	1570	1600	1603	1627	1636	1698	1827	1834	

Even with this recent increase in moisture, PDSI values during the 1900s were similar statistically to one or more centuries using structured starting points (of 1000, 1100, ...1800) for all ecological provinces (Table 3). The provinces had similar PDSI values during either the 1600s or 1700s and 1900s, except for 223, which only had similar PDSI values during the 1000s and 1900s. Finer time steps provided even more opportunities for overlap to occur between the 1900s and other centuries. For the half-century comparisons, for each ecological province, there were $\geq$ seven half centuries statistically similar to greatest PDSI estimates, based on mean comparisons (Supplementary Table 1). Overlap became greater using quarter century comparisons (Supplementary Table 2). There were no significant differences in comparison of PDSI values during the 1900s to maximum century values (all $p > 0.2$) or comparisons of PDSI values of maximum half-century values during the 1900s to maximum half-century values of previous centuries (all $p > 0.1$).

Kolmogorov-Smirnov tests also showed that the 1900s had a similar distribution to at least the 1000s (Table 3). For four provinces, the 1900s had a similar distribution to the 1800s and for one province (231) only the 1900s and 1000s were similar.

Discussion

Relatively wet conditions during the 20th century were not statistically different during the last millennium, based on a variety of statistical methods. Using thresholds, Fye et al. (2003) similarly did not identify moisture anomalies in the eastern US. The change point detection test uses continuous time intervals to detect anomalies. For the generalized linear mixed models, reducing the time intervals from 100 years to 25 years indicated that many 25 year intervals had similar PDSI values (i.e. no increase in pluvials). Although we were not able to examine extreme precipitation events, research has shown that heavy precipitation frequencies at the beginning of the 20th century were nearly as great as during the late 20th century (Kunkel, Easterling, Redmond, & Hubbard, 2003).

A pluvial within the statistical range of moisture variability over the last millennium is likely variation, rather than an ecologically significant driver of structural and compositional forest change that generally began during the early 20th century. Since Euro-American settlement, open *Quercus*- or *Pinus*-dominated savannas and woodlands have transitioned to dense, closed forests comprised of diverse species (Hanberry, Kabrick, & He, 2014; Hanberry & Nowacki, 2016;

Table 3. Comparison of Palmer drought severity index values by ecological province and century (19 = 1900) by ANOVA and Kolmogorov-Smirnov tests. For the ANOVA test, centuries with the same letters are not different within a given province. For the Kolmogorov-Smirnov tests, comparison between the 1900s and most recent centuries were discontinued after non-significant results.

Province	Century	Estimate	ANOVA <i>p</i>	Kolmogorov-Smirnov <i>p</i>			
221	19	−0.04	0.0754	A			
	10	−0.07		A			
	11	−0.10		A			
	12	−0.16		A	B		
	13	−0.23		A	B		
	14	−0.19		A	B		
	15	−0.40			B		
	16	−0.29		A	B		
	17	−0.38		A	B		
	18	−0.46			B		
222	19	0.16	0.0038	A			
	10	−0.20		A	B		
	11	−0.79				C	
	12	−0.33			B		
	13	−0.44			B	C	
	14	−0.48			B	C	
	15	−0.42			B	C	
	16	−0.36			B		
	17	−0.21		A	B		
	18	−0.40			B	C	
223	19	0.09	0.0005	A	B		
	10	0.25		A			
	11	−0.54				C	
	12	−0.25			B	C	
	13	−0.44				C	
	14	−0.37			B	C	
	15	−0.45				C	
	16	−0.22			B	C	
	17	−0.38				C	
	18	−0.53				C	
231	19	−0.05	0.0062	A			
	10	−0.23		A	B		
	11	−0.71				D	
	12	−0.57				C	
	13	−0.50			B	C	
	14	−0.54			B	C	
	15	−0.61				C	
	16	−0.38		A	B	C	
	17	−0.58				C	D
	18	−0.62				C	D
232	19	−0.07	0.1501	A			
	10	−0.39		A	B		
	11	−0.60			B		
	12	−0.49			B		
	13	−0.38		A	B		
	14	−0.49			B		
	15	−0.56			B		
	16	−0.33		A	B		
	17	−0.54			B		
	18	−0.54			B		
255	19	0.23	0.1446	A			
	10	0.13		A			
	11	−0.65				C	
	12	−0.52			B	C	
	13	−0.18		A	B	C	
	14	−0.20		A	B	C	
	15	−0.11		A	B		
	16	−0.08		A	B		
	17	−0.30		A	B	C	
	18	−0.23		A	B	C	

(Continued)

Table 3. (Continued).

Province	Century	Estimate	ANOVA <i>p</i>		Kolmogorov-Smirnov <i>p</i>	
M221	19	−0.13	0.4085	A		
	10	−0.30		A	B	
	11	−0.26		A	B	
	12	−0.33		A	B	
	13	−0.41		A	B	
	14	−0.24		A	B	
	15	−0.51		A	B	
	16	−0.44		A	B	
	17	−0.50		A	B	
	18	−0.60			B	
						0.1545

Nowacki & Abrams, 2008). Historical tree surveys and pollen records show that tree composition has remained relatively stable at landscape scales for at least a few thousand years after deglaciation throughout a range of moisture variability (Grimm & Jacobson, 1992; Overpeck, Webb, & Webb, 1992; Prentice, Bartlein, & Webb, 1991; Williams, Shuman, Webb, Bartlein, & Leduc, 2004). Many tree species grow successfully under the precipitation range in temperate deciduous forests (moderate annual precipitation of about 70 to 180 cm; PRISM Climate Group, Oregon State University, www.prism.oregonstate.edu/normals), despite variation such as the Medieval Warm Period and Little Ice Age. Rainfall would have to greatly increase in the humid eastern US to create a different biome.

Recent past and present forest composition do not signal the influence of precipitation. If relatively wet conditions were a primary driver of eastern forest composition then current forests should be composed of less drought-tolerant species. Instead, fire-tolerant oak and pine species have declined during the past century while tree species with a variety of drought tolerances have increased (e.g. Hanberry, Coursey, & Kush, 2018; Hanberry, Dey, & He, 2012). Notably, drought-tolerant *Juniperus virginiana* has expanded from fire-protected rock outcrops during the past century, while ‘swamp’ red maple (*Acer rubrum*) and planted *Pinus taeda* expanded from wetlands (e.g. Abrams, 1998; Hanberry et al., 2018, 2012). Likewise, prior to 1900, the eastern US supported greater abundance of several tree species that are relatively intolerant of drought, such as American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*) and eastern hemlock (*Tsuga canadensis*). Beech and hemlock have declined during the last century mainly due to forest use and insect and disease problems, rather than increase due to pluvials (Nowacki & Abrams, 2015). Moreover, the Coastal Plain is the wettest region in the eastern US, containing areas that receive 150 to 180 cm of precipitation annually. If precipitation was a direct driver of eastern forest composition, these areas should be dominated by species with less drought tolerance. Historically, relatively drought-tolerant longleaf pine (*Pinus palustris*) dominated the region, comprising about 75% of all trees (Hanberry & Nowacki, 2016). Longleaf pine is well-known for a ‘grass stage’, when seedlings are very resistant to fire.

If increased moisture does not provide sufficient statistical detection of trends, correlating tree composition that shifted from greater to lesser drought tolerance, or necessary mechanism for forest change in this region, then it may be unnecessary to attribute forest transition to increased moisture along with multiple, interacting factors (McEwan et al., 2011). An alternative, parsimonious hypothesis is that departures in fire regimes, which are bounded by climate conditions (Abrams, 1992; Bond & Keeley, 2005), are driving eastern forest transitions from open oak and pine forests to closed forests composed of many species. Compared to previous centuries, fires during the 20th century were much less frequent due to fire exclusion and fragmented land cover; surfaces fires are disrupted by land use that reduces or replaces herbaceous vegetation (Hanberry & Abrams, 2018; Stambaugh et al., 2015; Varner et al., 2016). Historical composition by open forests of fire-tolerant oak and pine tree species, including in relatively mesic regions, signals

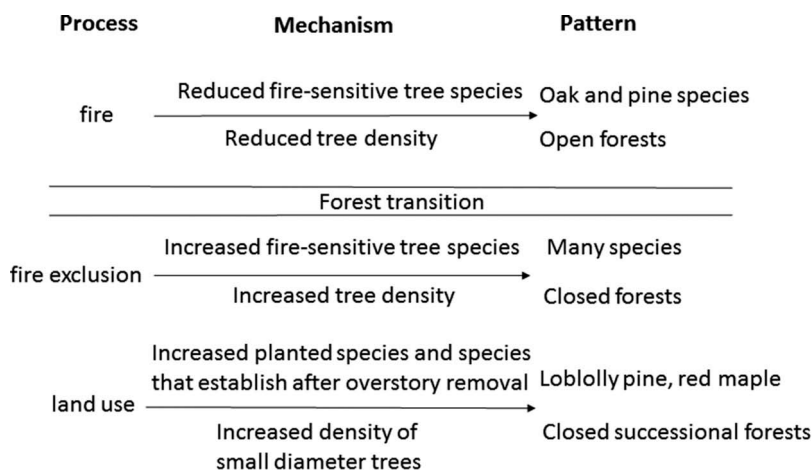


Figure 2. Flow chart displaying mechanisms and patterns for three processes: surface fire regime, fire exclusion, and land use.

fire as a mechanism and loss of that composition and structure resulted after fire exclusion (see Figure 2).

Fire regime changes provide a mechanism for forest transition with little or no change in precipitation. Low to moderate severity fire removes small diameter woody vegetation, reducing tree density, particularly of fire-sensitive tree species, and allowing herbaceous vegetation. Herbaceous vegetation provides fine fuels that ignite more readily than coarse woody fuels, increasing fire frequency. Conversely, fire exclusion enables fire-sensitive tree species to survive and recruit to sizes less susceptible to fire injury (Abrams, 1992). As fire exclusion is prolonged, flammability markedly decreases in the forest stand, further reducing the probability of fire occurrence (Alexander & Arthur, 2010; Nowacki & Abrams, 2008).

Without fire, current forests are affected by many drivers, primarily land use; land use favors planted species and species that respond to overstory removal and openings (e.g. both plantations and old fields favor loblolly pine) and land use creates small diameter successional structure (Hanberry & Abrams, 2018; Hanberry et al., 2018). Other drivers may be indirect or act locally; for example, loss of *Castanea dentata*, which comprised 2% of all trees in the central eastern US (Hanberry & Nowacki, 2016). Without fire and without frequent overstory removal due to land use, forests become archetypical old growth forests, comprised of shade-tolerant species (Hanberry & Nowacki, 2016). The eastern US is unique because warming during the 20th century largely was confined to the northern region, with in absence of warming ('warming hole') over the rest of the eastern US (Nowacki & Abrams, 2015; Peterson et al., 2013). This may be another reason that climate does not appear to be an important driver of vegetation change (Abrams & Nowacki, 2015; Hanberry & Hansen, 2015).

In general, consideration of climate alone poorly predicts the global distribution of temperate ecosystems (Bond, Woodward, & Midgley, 2005) because alternative potential ecosystem states and species can occur within the same climate range, or even outside of climate boundaries (Svenning & Skov, 2004). Savannas and closed forests may exist within the same climate space, instead of biomes separated by climate. Alternative ecosystem states of open forests of savannas and closed forests both may occur in regions with moderate precipitation (65 cm to 125 cm) of the Afrotropics, Neotropics, and Australia (Dantas, Hirota, Oliveira, & Pausas, 2016; Dwomoh & Wimberly, 2017; Hoffmann et al., 2012; Pausas & Keeley, 2014; Staver & Levin, 2012; Warman & Moles, 2009). These studies conclude, under a range of conditions, fire regimes maintain savannas as alternative states to closed forests.

Historical open forests composed of fire-tolerant oak and pine species and current closed forests are alternate states that also occur in the temperate United States, where there is moderate precipitation and a history of fire (Hanberry et al., 2014). Moderate precipitation supplies both wet periods that produce abundant herbaceous fuels and dry periods that dry herbaceous fuels, which are necessary conditions for fire; changes that increase or decrease moisture and continuity of herbaceous fuels may affect fire frequency. Along with contemporaneous observers of historical ecosystems (e.g. accounts in Rostlund, 2018), many researchers likewise have concluded that historical fire regimes were sufficient to maintain ecosystems and fire exclusion was the primary cause of transitions. For example, Peterson and Reich (2001 and citations therein) wrote 'In many areas historically occupied by savannas and woodlands, precipitation and soil moisture are sufficient to support forests. High-frequency fire regimes have been credited with creating and maintaining savannas and woodlands in these areas prior to and during Euro-American settlement. However, reductions in fire frequency... have led to significant structural changes, including increased tree density, basal area, and canopy cover, and succession toward more fire-sensitive and shade-tolerant overstory species'.

Researchers from distinct bodies of research all have theoretical claims on causal relationships. For example, biogeographers and climatologists apply a climate lens to ecological patterns. However, the influence of human management and land use on natural systems has become increasingly apparent. The analyses presented here identified precipitation during the 20th century as within the range of variability of the past 1000 years. Instead of climate fluctuations, we propose that land use changes, primarily stemming from fire exclusion, provide a more robust explanation of recent forest dynamics. We conclude that in complex, dynamically coupled human-environment systems, research design should test statistical associations using new developments in change point and anomaly detection for time series, while considering the potential influence of human land use change over time.

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