

# On the declining relationship between tree growth and climate in the Midwest United States: the fading drought signal

Justin T. Maxwell<sup>1,2</sup> · Grant L. Harley<sup>3</sup> ·  
Scott M. Robeson<sup>2</sup>

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**Abstract** Tree rings are widely considered to be a reliable proxy record of variations in climate and soil moisture. Here, using data from the Midwest United States (US), we provide documentation of a deteriorating relationship between radial tree growth and drought that is consistent across multiple species and locations. We find that traditional methods for drought reconstructions produce models that have rapidly declining validation statistics in recent decades. Split-sample calibration-verification that uses the first and second halves of the record can be problematic, as those two samples may not represent a sufficiently wide range of soil moisture conditions. To investigate this problem, we develop a randomized validation procedure that generates an empirical distribution of calibration and validation statistics. We place validation statistics derived from traditional methods in the generated distribution and compare them to a stratified approach that ensures each calibration model is composed of a sample that includes both dry and wet years. We find that the deteriorating relationship between tree growth and soil moisture is an artifact of the absence of drought over an extended period of time. A model that forces each calibration period to contain extreme drought years is statistically validated. Nonetheless, if the current pluvial continues in the Midwest US, the linear relationship between tree rings and soil moisture will likely continue to deteriorate to the point where tree rings in the region will have a reduced ability to estimate past drought conditions.

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✉ Justin T. Maxwell  
maxweljt@indiana.edu

<sup>1</sup> Environmental Tree-Ring Laboratory, Department of Geography, Indiana University, Bloomington, IN 47405, USA

<sup>2</sup> Department of Geography, Indiana University, Bloomington, IN 47405, USA

<sup>3</sup> Dendron Laboratory, Department of Geography and Geology, University of Southern Mississippi, Hattiesburg, MS 39406, USA

## 1 Introduction

Drought is a common feature of the climate system across the United States (US), impacting both human societies and ecosystems (Wilhite et al. 2007; Allen et al. 2010). For example, the 2012 drought was the most recent example of severe to moderate drought occurring in the Midwest United States (US; Hoerling et al. 2014). While the 2012 drought was severe in the Great Plains (Hoerling et al. 2014) and had substantial economic and ecological implications in the Midwest (Mallya et al. 2013; Roman et al. 2015), the intensity and duration of the drought was far less than previous instrumentally recorded events in the Midwest such as the extreme droughts of the 1930s and 1950s. Currently, a broad area of the Midwest is experiencing an ongoing pluvial that is in one of the wettest periods on record (Mishra and Cherkauer 2010; Ford 2014).

Tree rings have long been considered a robust proxy record of soil moisture variations throughout the US and other regions of the world (including humid areas such as the eastern deciduous forest biome), providing historical context to instrumentally recorded droughts (e.g. Cook et al. 1999, 2010; Maxwell et al. 2011; Pederson et al. 2013, 2014). Previously, reconstructed droughts in the region have been shown to be more intense and longer lasting than the more recent instrumentally recorded droughts (Cook et al. 1999, 2010). Previous studies highlight the need to assess the temporal stability of the climate-tree growth relationship and ensure climate signal consistency through time, most notably the diverging relationship between temperature and tree growth at high latitude sites (Jacoby and D'Arrigo 1995; Barber et al. 2000; Jacoby et al. 2000; Lloyd and Fastie 2002; D'Arrigo et al. 2004; Wilmking et al. 2004; Driscoll et al. 2005; Lloyd and Bunn 2007; Pisaric et al. 2007; Esper and Frank 2009). The “divergence problem” is not widespread and is largely an artifact at regional to local scales (Büntgen et al. 2008).

Changes in the drought signal recorded by tree-rings have been documented in a few studies and examining the stability in the relationship is becoming more important with ongoing climate change. However, past studies have either documented a shift in the seasonality in climate-growth response (De Grandpré et al. 2011) or weakening climate sensitivity in response to an infestation (Saladyga and Maxwell 2015). In this study, we provide the first documentation of an apparent deteriorating relationship between radial tree growth and soil moisture across an area of the Midwest US that is not accompanied by an increase in signal during another season. The declining relationship, referred to here as the fading drought signal, appears to be consistent across multiple species and sites within the region.

## 2 Materials and methods

### 2.1 Study sites and tree-ring data

During the period 2012–2014, we collected tree-ring data from five sites across the Midwest US (Fig. S1 and see [Supplemental Material](#)), including: three old-growth sites—Pioneer Mothers (PM), Donaldson Woods (DW), and Giant City (GC); one selectively logged site—Hoot Woods (HW); and one second-generation forest—Lilly-Dickey Woods (LD). From these sites, 15 chronologies were developed from tree species commonly found in the eastern

deciduous forest (see [Supplemental Material](#)). All species (Table 1) are known to be sensitive to climate and their use in climate reconstructions is well demonstrated (Cook et al. 1999; Maxwell et al. 2015; Maxwell 2016). We used methods standard to dendrochronology for sample collection (see [Supplemental Material](#)).

## 2.2 Sample analyses

Tree cores were prepared using standard dendrochronological techniques (see [Supplemental Materials](#)). All chronologies were detrended interactively using signal-free standardization (Melvin and Briffa 2008) with a base curve being a “two-thirds” smoothing spline (i.e., it has an amplitude response of 0.5 at periods associated with 67 % of each series length; Cook and Peters 1981) to ensure that the climate variability signal was retained while the non-climatic variability was removed. Signal-free standardization was chosen after careful consideration of standardization techniques because it reduces “trend distortion” problems, where medium-frequency variance (i.e., decades to a century) can leverage the function used to remove non-climatic variance near the ends of the record (Melvin and Briffa 2008).

**Table 1** Tree ring statistics and validation statistics when using the stratified and randomized validation approaches for each species at the five sites

Species	Number of Series	Number of tress	Age of Acceptable Sample Depth <sup>a</sup>	Interseries Correlation <sup>b</sup>	Stratified CE value		95 % Confidence Interval of CE from Randomized Approach
					Group 1	Group 2	
Pioneer Mothers							
<i>J. nigra</i>	22	11	1784	0.60	0.26	0.32	0.04–0.38
<i>Q. rubra</i>	44	25	1892	0.59	0.30	0.36	0.07–0.42
<i>Q. alba</i>	30	20	1860	0.58	0.28	0.29	0.03–0.39
<i>L. tulipifera</i>	28	22	1811	0.60	0.30	0.34	0.05–0.41
Donaldson Woods							
<i>Q. rubra</i>	16	8	1828	0.61	0.20	0.36	−0.07–0.36
<i>Q. alba</i>	27	13	1736	0.62	0.25	0.54	0.16–0.51
<i>Q. velutina</i>	22	11	1731	0.64	0.36	0.41	0.13–0.48
<i>L. tulipifera</i>	20	10	1746	0.60	0.06	0.33	−0.06–0.32
Hoot Woods							
<i>Q. rubra</i>	18	11	1890	0.61	0.07	0.13	−0.17–0.16
<i>L. tulipifera</i>	17	10	1883	0.63	0.17	0.26	−0.12–0.29
Lilly-Dickey							
<i>Q. alba</i>	20	10	1878	0.72	0.31	0.36	0.06–0.41
<i>Q. velutina</i>	18	10	1878	0.64	0.26	0.34	−0.08–0.38
<i>Q. prinus</i>	20	10	1877	0.61	0.34	0.35	0.09–0.43
<i>L. tulipifera</i>	19	11	1889	0.63	0.20	0.38	0.03–0.38
Giant City							
<i>Q. alba</i>	48	26	1704	0.65	0.25	0.33	0.01–0.39

<sup>a</sup> Based on express population signal (EPS) value being greater than 0.85 (Wigley et al. 1984)

<sup>b</sup> Based on all core samples from all trees

## 2.3 Climate data

We obtained climate data for the climate divisions that contained a study site (climate divisions Indiana 4, 5, and Illinois 8) from the National Climatic Data Center (NCDC) for the period 1895–2013, including monthly mean, mean minimum, and mean maximum temperature, precipitation, and the Palmer Drought Severity Index (PDSI; Palmer 1965). The PDSI is frequently used as the basis for dendroclimatic drought reconstructions (Cook et al. 1999; Cook and Krusic 2004; Pederson et al. 2012, 2013). To ensure the deteriorating signal was not an artifact of PDSI or its method of calculation, we also obtained gridded self-calibrated PDSI (scPDSI; Dai 2013) and gridded 6-month Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al. 2010) for each grid that contained a site and then averaged the selected gridded data.

## 2.4 Climate analysis

We used the program DendroCLIM2002 (Biondi and Waikul 2004) to examine the possible changes in the climate response through time for each of the species chronologies. The program calculates correlation coefficients between each species chronology and the monthly NCDC climate division variables (temperature, precipitation, and PDSI) using 1000 bootstrapped samples. First, we conducted a 42-year moving window correlation analysis of the chronologies with PDSI for each month from April of the previous growing season to December of the current year. The deteriorating relationship is present with different window lengths (e.g., 75 years). We chose 42 years as a suitably long window and also because that is double the number of monthly predictors, which is the smallest length to allow enough degrees of freedom for the moving analysis (Biondi and Waikul 2004). The correlation values are reported for the last year of the window, creating a reporting period of 1936 to the last year of growth. Based on these results, we performed the analysis on the season with the strongest correlations (JJA) with tree-growth. Lastly, to further evaluate the JJA PDSI signal strength, we also calculated correlations of the tree-ring chronologies with monthly temperature and precipitation from the previous growing season April to current year December for the same moving window interval.

## 2.5 Impacts on climate reconstructions

To examine how changes in the relationship between tree growth and soil moisture impact climate reconstructions, we developed reconstruction models for each site and for the region. Tree-ring chronologies were used as the predictors to reconstruct summer (JJA) PDSI using a principal components (PC) regression analysis (Meko 1997; Cook et al. 1999 and see [Supplemental Material](#)). PC regression was used because it allows the development of multiple-species proxies, which have been shown to improve PDSI reconstructions in this area (Maxwell et al. 2015; note that GC has only one species—*Q. alba*).

Initially, model validation was performed using a split-period calibration-verification procedure that is common in dendroclimatic reconstructions (see [Supplemental Material](#)). For both late and early calibration models, we calculated validation statistics including  $R^2$  between the predicted and observed PDSI values for the verification periods, reduction-of-error (RE; Fritts 1976), and the coefficient-of-efficiency (CE; Nash and Sutcliffe 1970).

To determine how the time-varying drought signal influenced the site and regional climate reconstruction, we examined validation statistics for a series of iterative reconstructions by removing the most recent year and re-standardizing the chronologies at each iteration (i.e., 1895–2013, 1895–2012, etc.) using split-period calibration/verification. We conducted 35 iterations for each site reconstruction (with the exception of DW where the common period was shorter, thus 31 iterations), resulting in the last iterative reconstruction spanning from 1895–1979. Examining iterative reconstructions allows us to simulate validation statistics as if the tree-ring data were collected in 1979, 1980, or any year up to 2013. The period 1979–2013 is also the period of the fading signal, allowing us to determine the timing and impact of the deteriorating signal on model validation. Using the iterative procedure also helps to evaluate whether the deteriorating signal is an artifact of a particular detrending (our use of signal-free standardization also addresses this issue). If end-of-record distortion were the cause of the deteriorating signal, all iterations would have poor validation statistics, as opposed to those that only use the most recent data.

We also evaluate a randomization procedure for validating reconstructions. This approach is comparable to but distinct from ensemble approaches (Li et al. 2007; Wahl and Smerdon 2012) that allow for the confidence of the reconstruction to be evaluated. Ensemble approaches are useful because they use the behavior of the time series to generate error distributions. A limitation, however, is that (as implemented) they do not characterize how different portions of the “calibration-validation space” influence model performance (i.e., they consistently use the same data for calibration and validation). Our primary goal is to evaluate how different calibration-validation samples influence the relative performance of the model. We use a procedure that is similar to the traditional split-period method except that the samples (halves) are selected randomly and the calibration/validation procedure is repeated a large number of times (here, using 1000 random samples). From these random samples, we develop validation statistics and confidence intervals. This approach contextualizes the split-period validation statistics in two ways: (1) it avoids the possibility of selecting halves such that one or both are unrepresentative of conditions during the entire period of record and (2) it places the validation procedure within a probabilistic framework (similar to the ensemble approach). If the data have strong serial correlation, however, there is potential bias introduced by the two samples not being independent. As a result, we recommend that this method be used with the split-period calibration and that autocorrelation functions (acfs) be inspected. Importantly, the randomization procedure usually samples blocks or runs of data. As most tree-ring and climate data (especially in the eastern US) have acfs that are near-zero at lags of 2 years or longer (Fig. S2), any data values separated by more than 1 year are effectively independent. The acfs, therefore, portray a worst-case scenario as the random sampling approach would have to use every other year of the time series to have bias as large as that suggested by the lag-1 autocorrelation coefficients.

To examine the potential impact of the absence of extreme drought over an extended period of time, we also use a stratified-by-every-other-ranked-value approach to separate the PDSI and tree growth data into two representative samples. In this way, PDSI values that range from driest to wettest (and their corresponding tree ring values for each chronology) are included in each stratified sample. Data associated with the first sample of this ranked/stratified list of PDSI (i.e., the 1st, 3rd, 5th, etc. values) are selected and grouped (hereafter G1) and used to calibrate a linear regression model between PDSI and tree growth. We used the remaining half of the data (G2, which are associated with the 2nd, 4th, 6th, etc. PDSI values) to verify the model by using the G1-calibrated model to predict the values of G2. The same procedure is

repeated using G2 to calibrate and G1 to verify the model. We then use the distribution of CE values derived from the randomized approach to provide a context for the CE values from both the traditional split-period method and the stratified approach. Importantly, both the randomized and stratified procedures test the ability of proxy-based models to interpolate missing values in a climatic time-series, whereas traditional split-period methods test the ability to extrapolate from one time period to another. We therefore caution that validation statistics from the randomized and stratified procedures are primarily used to provide additional context and may not be representative of a climate reconstruction.

### 3 Results and discussion

#### 3.1 Moving correlation analysis

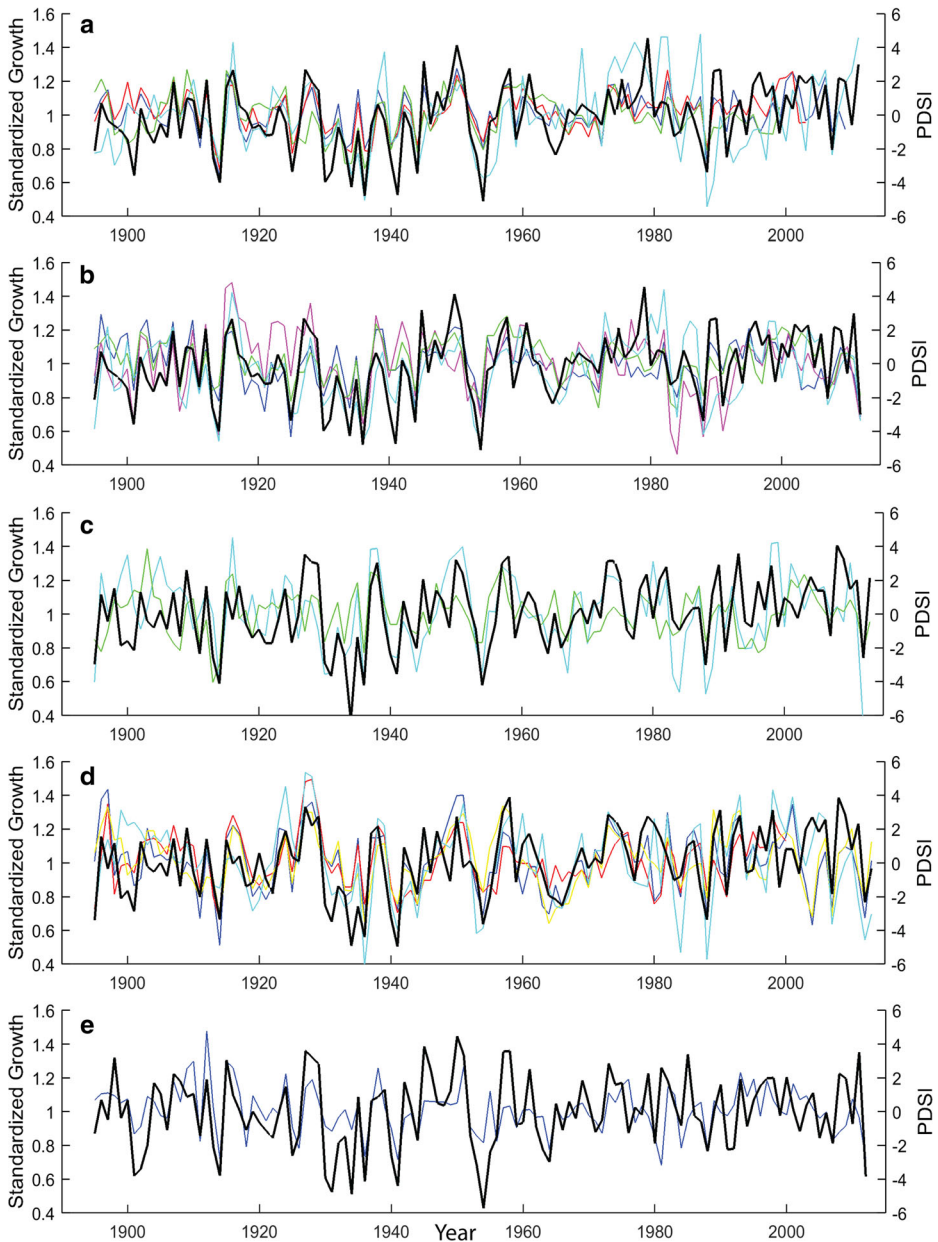
All core samples for each species had significant interseries correlation of their standardized ring widths ( $p < 0.001$ ), indicating that individual trees from the same species were growing similarly and responding to environmental factors (Table 1). Time series of PDSI with tree growth showed that tree growth from co-occurring species tracks PDSI well until  $\approx 1980$  where tree growth and PDSI become decoupled (Fig. 1). Moving-window correlations showed strong relationships between all species chronologies and PDSI for May through September, with the strongest relationship existing during JJA (Fig. S3). The strength of the relationship between JJA PDSI and tree growth, however, weakened through time in all species sampled. Of the five locations sampled, DW and GC appear to have the largest decrease in the strength of the relationship through time, while LD and PM have less severe decreases (Fig. S3). The decrease in the strength of the relationship is relatively consistent and did not appear to be associated with a single species or site. While *Q. alba* at DW, LD, and PM faded less, its signal declined dramatically at GC. Similarly, *L. tulipifera* showed a weakening but still significant relationship through time at LD and HW, but its relationship declined much more at DW and PM. The decrease in the strength of the relationship was not matched by an increase in signal strength in the other months (Fig. S3). In addition, the deteriorating signal was not related to the climate-division version of PDSI, as both scPDSI and SPEI showed similar weakening (Fig. S4).

The age of the trees also did not seem to have an impact on how much the signal deteriorates based on the expressed population signal (EPS; Wigley et al. 1984) where EPS values of greater than 0.85 indicate that there is good sample depth (Table 1). One of the two sites that had the most stable relationship through time had older trees (PM, with trees  $>250$  years) while the other was a second-generation forest with younger trees (LD with trees  $\approx 120$  years old).

The moving-window correlation analyses for precipitation and temperature also demonstrated that summer (JJA) months had the strongest relationship with tree growth (Figures S5 and S6). The relationship between precipitation and tree growth through time was inconsistent between species. While many species showed a similar declining signal of JJA precipitation as with summer PDSI, some (e.g., LD\_LITU, LD\_QUPR, HW\_LITU, and PM\_JUNI) exhibited an increase in the strength of the relationship and others (e.g., LD\_QUAL, PM\_QUAL, PM\_LITU, and PM\_QURU) demonstrated a consistent relationship through time (Figure S5).

The moving correlation for temperature revealed June to be the most important month for tree growth, followed by July and August (Figure S6). The strength of the relationship through time decreased consistently for all sampled sites and species, with GC\_QUAL being the only



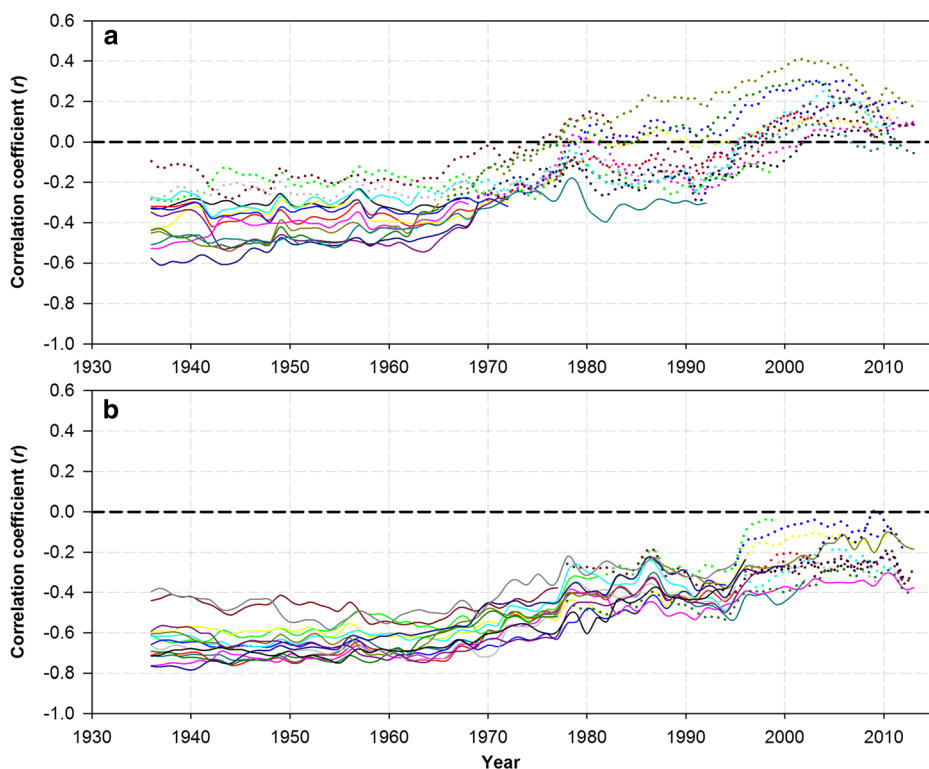


**Fig. 1** Timeseries of standardized tree-rings and PDSI (black line) for **a**) Donaldson Woods, **b**) Pioneer Mothers, **c**) Hoot Woods, **d**) Lilly-Dickey Woods, and **e**) Giant City. Each species is represented by the same line color across sites: *Q. alba* (blue), *Q. velutina* (red), *Q. rubra* (green), *L. tulipifera* (cyan), *J. nigra* (magenta), and *Q. prinus* (yellow)

chronology with a consistent relationship. In general, the summer temperature signal was not as strong as the PDSI signal and the weakening was not as temporally consistent between species in the change point; however, the temperature response seemed to be more influential than that of precipitation. To investigate the temperature relationship in more detail, we used

averages of JJA maximum and minimum temperatures separately to perform moving correlations with standardized tree-growth. For all species, maximum JJA temperatures and growth initially had strong negative correlations ranging from  $-0.4$  to  $-0.8$  in earlier iterations and declining to  $0.0$  to  $-0.4$  when more recent data are included (Fig. 2b). Minimum JJA temperatures were not as strongly correlated with growth; however, they went from generally negative to positive through time (Fig. 2a). Interestingly, temperature during JJA in this region has a slight downward trend through time, while JJA precipitation and PDSI had trended towards wetter conditions. An extended period of time where severe heat and drought conditions are not present could create conditions where tree growth is not as sensitive to soil moisture, particularly for some species in mesic deciduous forests (Brzostek et al. 2014).

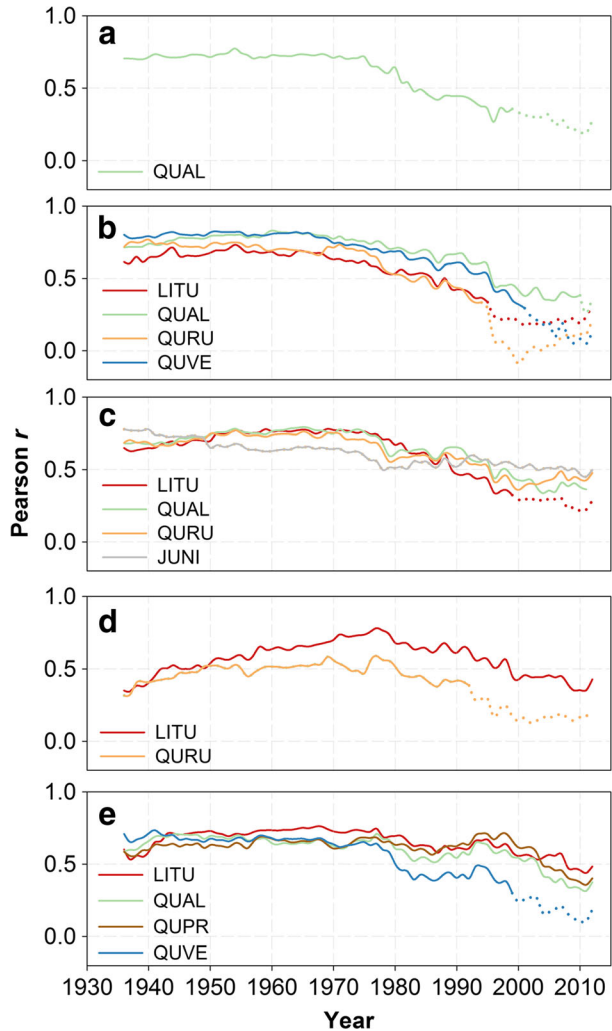
Averaging PDSI values over multiple months, particularly JJA, provided a stronger relationship (Cook et al. 1999; Maxwell et al. 2015), so we used JJA PDSI to re-estimate the moving correlation with the species chronologies. Correlations with JJA PDSI showed a similar pattern of declining signal strength through time (Fig. 3). The sites with the most stable relationship through time across species were PM and LD, but even these sites exhibited a decrease in the correlation between tree rings and JJA PDSI from  $\approx 0.65$  to  $\approx 0.4$ . Further, at least one species at PM and LD (*L. tulipifera* for PM and *Q. velutina* for LD) declined to the point of no longer being significant (Fig. 3c and e). HW did not have a monotonic decline, but nonetheless had a fading signal such that *Q. rubra* correlations decreased until the relationship



**Fig. 2** Moving correlations of standardized radial growth with JJA minimum temperature (a) and maximum temperature (b) for all species chronologies. Dotted lines represent a non-significant relationship. The year represents the last year of each 42-year moving window



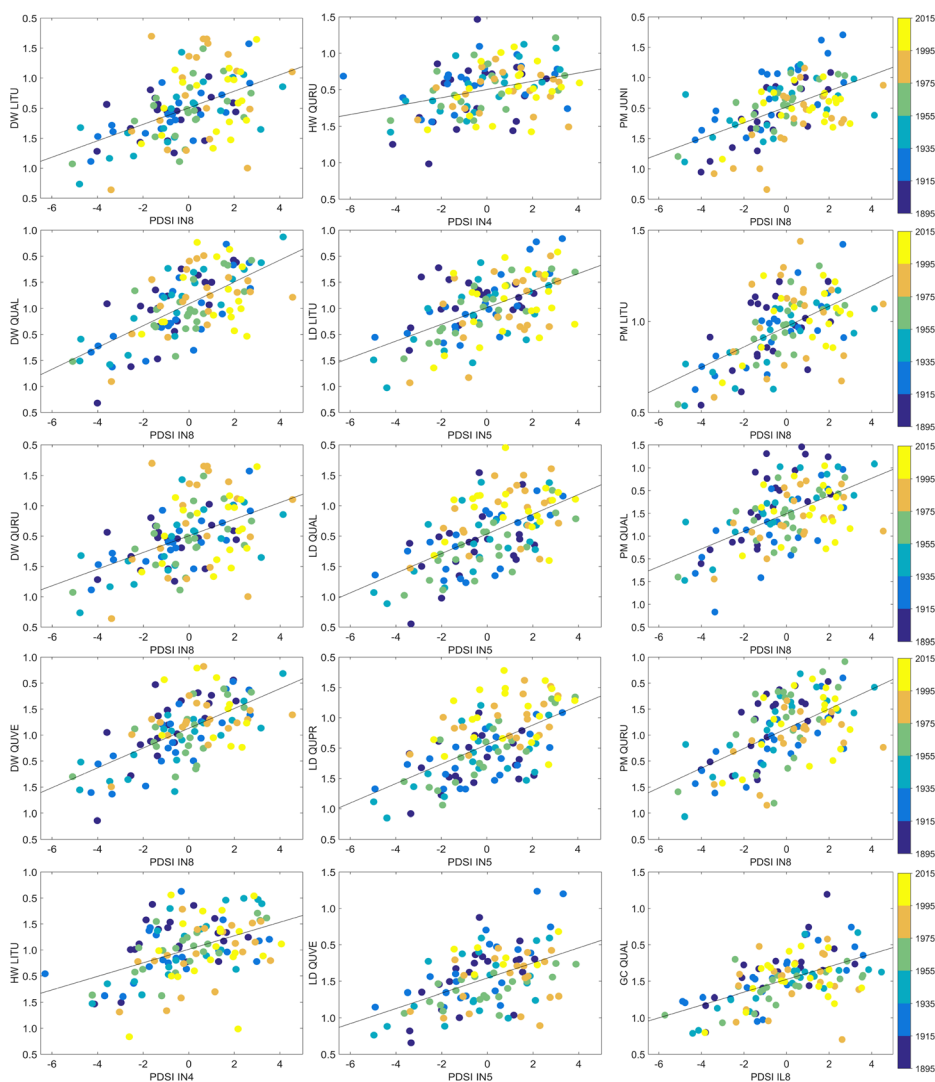
**Fig. 3** Moving correlations of standardized radial growth with JJA PDSI for **a**) Giant City *Q. alba*, **b**) Donaldson Woods *L. tulipifera*, *Q. alba*, *Q. rubra*, and *Quercus velutina*, **c**) Pioneer Mothers *L. tulipifera*, *Q. alba*, *Q. rubra*, and *J. nigra*, **d**) Hoot Woods *L. tulipifera*, *Q. rubra*, and **e**) Lilly-Dickey *L. tulipifera*, *Q. alba*, *Q. prinus*, and *Q. velutina*. Dotted lines represent a non-significant relationship. The year represents the last year of a 42-year moving window



was not significant in recent decades (Fig. 3d). DW showed the most consistent decline in correlation (from 0.7 to 0.2), with two species (*Q. rubra* and *L. tulipifera*) fading until the relationship was no longer significant (Fig. 3b). Of the species studied, *L. tulipifera*, *Q. rubra*, and *Q. velutina* exhibited the greatest declines while *Q. alba* showed more modest decreases across sites. However, *Q. alba* at GC showed a dramatic decrease in the PDSI signal – dropping from correlations of  $\approx 0.7$  in the early part of the record to less than 0.3 in the most recent windows.

### 3.2 Impact on climate reconstructions

The scatterplots showed that PDSI in the most recent 20-year period has been mostly positive (Fig. 4; inspection of instrumental precipitation and temperature data confirm that the most recent

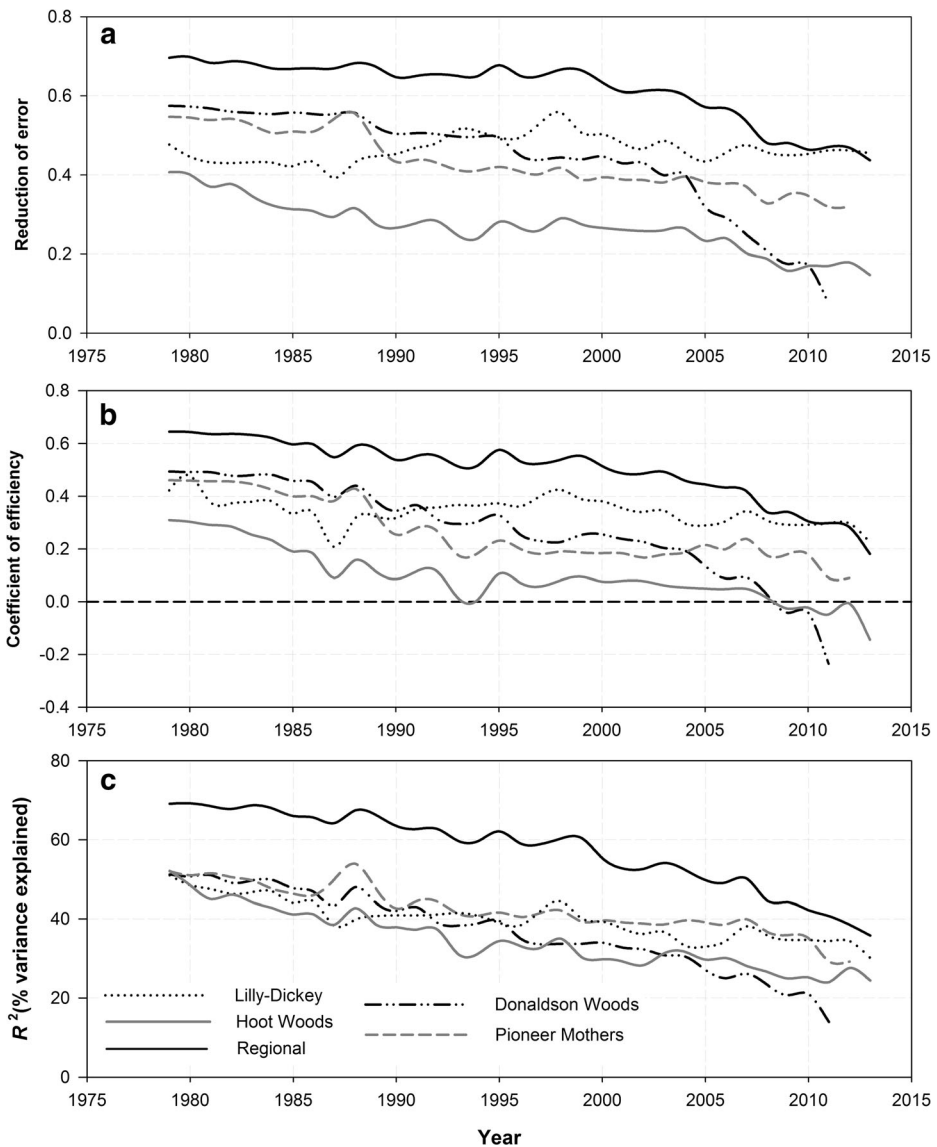


**Fig. 4** Color-coded scatter plots showing the relationship between standardized species radial growth and PDSI for 20-year increments. The most recent 20-year segment is represented in *yellow* while the earliest is *blue*. All data are used to generate the linear regression line

20 years were relatively cool and wet). These results suggest that the more recent period is not only cooler and wetter than average but also has a nearly complete lack of extremely dry years (i.e.,  $\text{PDSI} < -3$ ), which may produce the fading signal for most species. In recent decades, just two droughts affected the region, both of which were modest in magnitude (i.e.  $\text{PDSI} < -2$  during JJA of 1988 and 2012) and not comparable to the much more severe drought years of the 1930s and 1950s in terms of intensity or duration. The periods that contain the 1930s and 1950s drought events contain a much stronger relationship with soil moisture (Fig. 3).

Our site and regional JJA PDSI chronologies consisting of multiple co-occurring species show that the fading drought signal has a deleterious impact on climate reconstructions

(Fig. 5). Calibrating the iterative site and regional JJA PDSI reconstructions on the early half of the record shows that RE values are the lowest (but still positive; Fig. 5a) and CE values are lowest (Fig. 5b) when verification uses data from the period 1955–2013, with both increasing as more recent years are removed. HW CE values are the least robust through time, while DW and PM have acceptable CE values until they are barely positive starting in ca 2003 and 2010 respectively. However, CE values continue to decline to the point of being negative for HW and DW after 2008. LD has the strongest temporal stability in CE values, however they too trend weaker in the iterations (Fig. 5b). Similarly, the explained variance declines through time



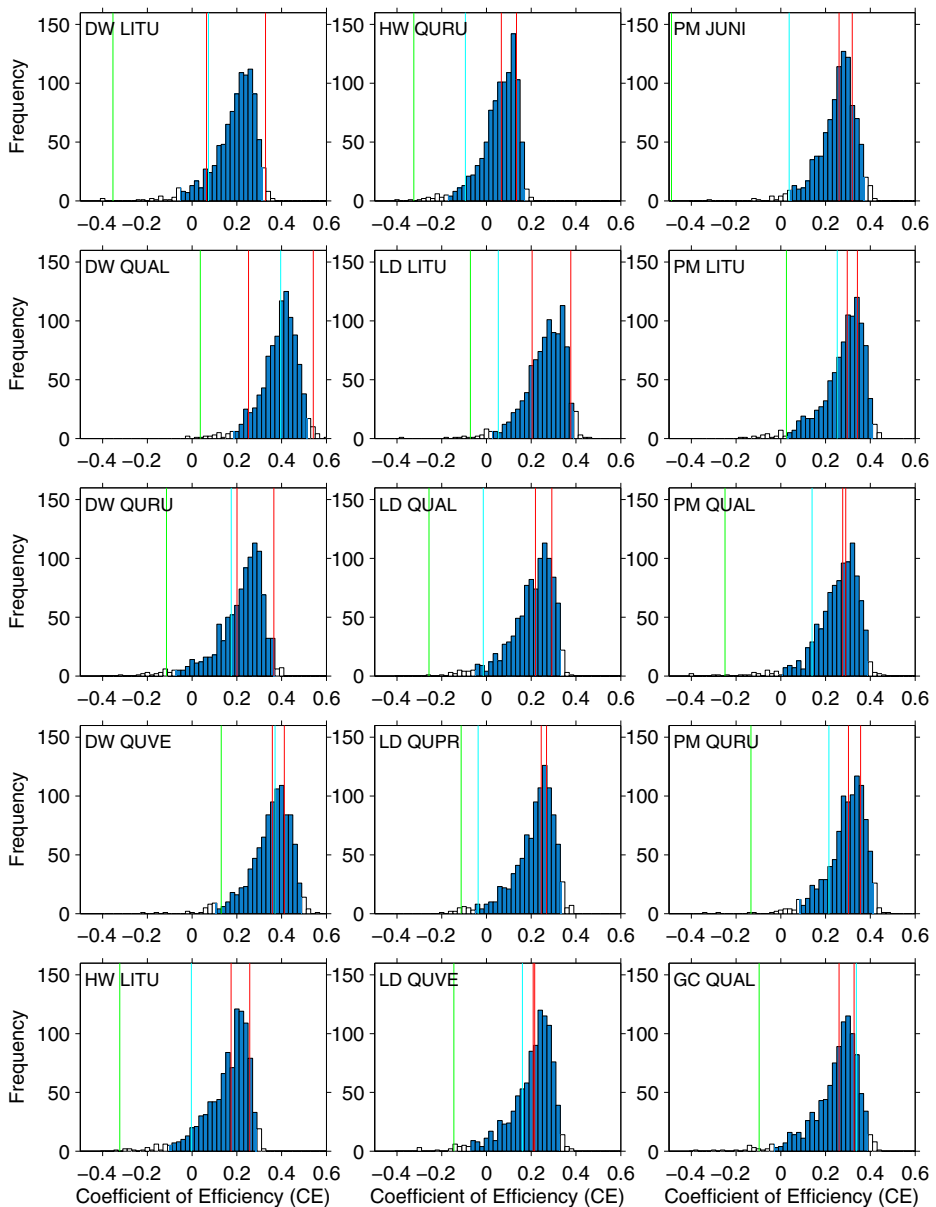
**Fig. 5** Validation statistics from the iterative climate reconstructions using the early calibration period for RE (a), CE (b), and  $R^2$  (c) for the multiple co-occurring PDSI reconstructions for each site and regionally (“Regional”)

with the lowest  $R^2$  values coming from the models with the most recent data (Fig. 5c). The site reconstruction models that only include data from before 1980 explain a similar and stable amount of the variance in JJA PDSI ( $\approx 55\%$ ), similar to validation statistics found in previous drought reconstructions from this region in the early 1980s (e.g., Cook et al. 1999). However, when the iterative process includes the more recent data, all of the site reconstructions decline with the best site models (PM and LD) explaining approximately 30 % and the poorest sites declining to  $\approx 26\%$  (HW) and  $\approx 15\%$  (DW). When combining all the chronologies into a regional PDSI chronology, the iterative models show declining RE and CE values and a decrease in explained variance from  $\approx 70\%$  to 38 %, indicating that increases in the number of chronologies improved the model but the decrease in the strength of the relationship is still present (Fig. 5c). Calibrating the iterative JJA PDSI reconstructions on the late period showed stable positive values of RE and CE through time (Figure S7A and S7B), with HW being consistently marginally positive due to the weak climate signal at that site. Further, the  $R^2$  values from the late calibration model did not decline (Figure S7C) with the sites consistently explaining approximately 58 % (DW), 56 % (PM), 45 % (LD), and 28 % (HW) of the variance in JJA PDSI. The regional JJA PDSI reconstruction showed similar stability in RE, CE and  $R^2$  values explaining  $\approx 60\%$  of the variance in PDSI. The models give better validation statistics when validated on the data that have extreme drought conditions.

Using the randomized validation approach rather than the split-period method produces a distribution of CE values allowing for comparisons of the stratified and traditional validation methods (Table 1; Fig. 6). When ensuring that severe drought is present in both periods of the calibration-verification models (i.e., the stratified approach), all the resulting CE values are positive and are located in the peak of the randomized CE distribution. The traditional method of validation results in CE values distributed sporadically—and, in some cases, unrepresentatively—along the distribution of randomized CE values (Fig. 6). While, part of the difference in values can be explained from the interpolation versus extrapolation methods of the two validation statistics, split-period (i.e., extrapolation) methods have given excellent validation statistics for PDSI reconstruction from this region in the past (Cook et al. 1999).

The lack of extreme drought conditions in the more recent period produces lower/negative RE and CE values when using the early period to calibrate the model for the split-period method. Extreme drought years have the most leverage in a regression model, thus when a long period is absent of extreme values the strength of the linear relationship declines as shown in the scatter plots (Fig. 4). An extended period of time absent of extreme droughts has created an environment where trees appear to be less sensitive to the relatively low variability in soil moisture.

Interestingly, Fig. 1 indicates that growth trends between species are fairly consistent until the period of recent weakening when tree growth varies dramatically between species. Thus, one possible explanation of the deteriorating relationship is the differing methods by which trees use water. Recent work has shown a difference in water-use strategies ranging from isohydric to anisohydric (Choat et al. 2012; Manzoni et al. 2013; Klein et al. 2014; Martínez-Vilalta et al. 2014). Brzostek et al. (2014) found that chronic mild water stress influenced growth declines in mesophytic species (e.g., *L. tulipifera*) more than in xerophytic species (*Quercus* spp). When conditions are extremely dry, growth from all species is negatively impacted. However, other anthropogenic factors also could be influencing this relationship, such as increases in carbon dioxide concentrations, land-use change, and nitrogen availability. More work is needed to investigate how these variables interact and to determine if the deteriorating signal is a temporary phenomenon.



**Fig. 6** Histograms of randomly generated CE values for each species with 95 % confidence intervals marked in blue bars. Traditional split-period validation results are shown in cyan (early half calibration) and green (late half calibration). Validation results from the stratified approach are shown with red lines

## 4 Conclusions

We find that multiple species in the eastern deciduous forest from the Midwest US appear to have become less sensitive to soil moisture in recent decades. We attribute the apparent fading signal to a sustained period without extreme drought. Thus, trees in this region have not lost

the ability to give historical context to modern drought in the Midwest. Yet, if the recent pluvial continues, the linear relationship between soil moisture and tree growth will likely continue to deteriorate, which would have serious implications for future dendroclimatological studies in this region. However, when extreme drought returns in this region we expect the growth sensitivity to increase as larger water stress more effectively and consistently restrains tree growth across species.

We highlight the need for more research to understand the spatial dynamics of the fading drought signal. Future research will concentrate on (1) determining whether this phenomenon is local to the Midwest region or occurs across a more geographically extensive area (i.e., eastern US); (2) examining other mid-latitude mesic forest regions that have a range of recent drought conditions; and (3) providing a better understanding of species-specific responses to drought in order to disentangle the causes behind the inconsistent radial growth response between species during the pluvial. With a better understanding of the fading drought issue in the Midwest, and potentially across the eastern US, the annually-resolved, precisely-dated, and well-replicated proxy of tree rings should continue to provide historical context to current and future hydroclimate conditions.

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## References

- Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg ET, Gonzalez P (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For Ecol Manag* 259:660–684
- Barber VA, Juday GP, Finney BP (2000) Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* 405:668–673
- Biondi F, Waikul K (2004) DENDROCLIM2002: a C++ program for statistical calibration of climate signals in tree-ring chronologies. *Comput Geosci* 30:303–311
- Brzostek ER, Dragoni D, Schmid HP, Rahman AF, Sims D, Wayson CA, Johnson DJ, Phillips RP (2014) Chronic water stress reduces tree growth and the carbon sink of deciduous hardwood forests. *Glob Chang Biol* 20:2531–2539
- Büntgen U, Frank D, Wilson R, Carrer M, Urbinati C, Esper J (2008) Testing for tree-ring divergence in the European Alps. *Glob Chang Biol* 14:2443–2453
- Choat B, Jansen S, Brodribb TJ, Cochard H, et al. (2012) Global convergence in the vulnerability of forests to drought. *Nature* 491:752–755
- Cook ER, Krusic PJ (2004) North American summer PDSI reconstructions. *IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series*, 45
- Cook ER, Peters K (1981) The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bull* 41:45–53
- Cook ER, Meko DM, Stahle DW, Cleaveland MK (1999) Drought reconstructions for the continental United States. *J Clim* 12:1145–1162
- Cook ER, Anchukaitis KJ, Buckley BM, D'Arrigo RD, Jacoby GC, Wright WE (2010) Asian monsoon failure and megadrought during the last millennium. *Science* 328:486–489
- D'Arrigo RD, Kaufmann RK, Davi N, Jacoby GC, Laskowski C, Myneni RB, Cherubini P (2004) Thresholds for warming-induced growth decline at elevational tree line in the Yukon territory, Canada. *Glob Biogeochem Cycles* 18:GB3021
- Dai A (2013) Increasing drought under global warming in observations and models. *Nat Clim Chang* 3:52–58



- De Grandpré L, Tardif JC, Hessel A, Pederson N, Conciatori F, Green TR, Oyunsanaa B, Baatarbileg N (2011) Seasonal shift in the climate responses of *Pinus sibirica*, *Pinus sylvestris*, and *Larix sibirica* trees from semi-arid, north-central Mongolia. *Can J For Res* 41:1242–1255
- Driscoll WW, Wiles GC, D'Arrigo RD, Wilmking M (2005) Divergent tree growth response to recent climatic warming, Lake Clark National Park and preserve, Alaska. *Geophys Res Lett* 32:L20703
- Esper J, Frank D (2009) Divergence pitfalls in tree-ring research. *Clim Chang* 94:261–266
- Ford TW (2014) Precipitation anomalies in eastern-Central Iowa from 1640–present. *J Hydrol* 519:918–924
- Fritts HC (1976) *Tree rings and climate*. Academic Press, New York
- Hoerling M, Eischeid J, Kumar A, Leung R, Mariotti A, Mo K, Schubert S, Seager R (2014) Causes and predictability of the 2012 Great Plains drought. *Bull Am Meteorol Soc* 95:269–282
- Jacoby GC, D'Arrigo RD (1995) Tree ring width and density evidence of climatic and potential forest change in Alaska. *Glob Biogeochem Cycles* 9:227–234
- Jacoby GC, Lovelius NV, Shumilov OI, Raspopov OM, Karbainov JM, Frank DC (2000) Long-term temperature trends and tree growth in the Taymir region of northern Siberia. *Quat Res* 53:312–318
- Klein T, Yakir D, Buchmann N, Grünzweig JM (2014) Towards an advanced assessment of the hydrological vulnerability of forests to climate change-induced drought. *New Phytol* 201:712–716
- Li B, Nychka DW, Ammann CM (2007) The “Hockey Stick” and the 1990s: a statistical perspective on reconstructing hemispheric temperatures. *Tellus Ser A* 59:591–598. doi:10.1111/j.1600-0870.2007.00270.x
- Lloyd AH, Bunn AG (2007) Responses of the circumpolar boreal forest to 20th century climate variability. *Environ Res Lett* 2:045013
- Lloyd AH, Fastie CL (2002) Spatial and temporal variability in the growth and climate response of treeline trees in Alaska. *Clim Chang* 52:481–509
- Mallya G, Zhao L, XC S, Niyogi D, Govindaraju RS (2013) 2012 Midwest drought in the United States. *J Hydrol Eng* 18:737–745
- Manzoni S, Vico G, Katul G, Palmroth S, Jackson RB, Porporato A (2013) Hydraulic limits on maximum plant transpiration and the emergence of the safety–efficiency trade-off. *New Phytol* 198:169–178
- Martínez-Vilalta J, Poyatos R, Aguadé D, Retana J, Mencuccini M (2014) A new look at water transport regulation in plants. *New Phytol* 204:105–115
- Maxwell JT (2016) The benefit of including rarely used species in dendroclimatic reconstructions: a case study using *Juglans nigra* in south-central Indiana. *Tree-Ring Res, USA*
- Maxwell RS, Hessel AE, Cook ER, Pederson N (2011) A multispecies tree ring reconstruction of Potomac River streamflow (950–2001). *Water Resour Res* 47:W05512
- Maxwell JT, Harley GL, Matheus TJ (2015) Dendroclimatic reconstructions from multiple co-occurring species: a case study from an old-growth deciduous forest in Indiana, USA. *Int J Climatol* 35:860–870
- Meko D (1997) Dendroclimatic reconstruction with time varying predictor subsets of tree indices. *J Clim* 10: 687–696
- Melvin TM, Briffa KR (2008) A “signal-free” approach to dendroclimatic standardisation. *Dendrochronologia* 26:71–86
- Mishra V, Cherkauer KA (2010) Retrospective droughts in the crop growing season: implications to corn and soybean yield in the Midwestern United States. *Agric For Meteorol* 150:1030–1045
- Nash J, Sutcliffe JV (1970) River flow forecasting through conceptual models part I—A discussion of principles. *J Hydrol* 10:282–290
- Palmer WC (1965) *Meteorological Drought*, Weather Bureau Research Paper No. 45. Washington, DC: US Department of Commerce
- Pederson N, Bell AR, Knight TA, et al. (2012) A long-term perspective on a modern drought in the American southeast. *Environ Res Lett* 7:014034
- Pederson N, Bell AR, Cook ER, et al. (2013) Is an epic pluvial masking the water insecurity of the greater New York City region? *J Clim* 26:1339–1354
- Pederson N, Hessel AE, Baatarbileg N, Anchukaitis KJ, Di Cosmo N (2014) Pluvials, droughts, the Mongol empire, and modern Mongolia. *Proc Natl Acad Sci U S A* 111:4375–4379
- Pisarcic MF, Carey SK, Kokelj SV, Youngblut D (2007) Anomalous 20th century tree growth, Mackenzie Delta, northwest territories, Canada. *Geophys Res Lett* 34:L05714
- Roman DT, Novick KA, Brzostek ER, Dragoni D, Rahman F, Phillips RP (2015) The role of isohydric and anisohydric species in determining ecosystem-scale response to severe drought. *Oecologia* 179:641–654
- Saladyga T, Maxwell RS (2015) Temporal variability in climate response of eastern hemlock in the Central Appalachian Region. *Southeast Geogr* 55:143–163.
- Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J Clim* 23:1696–1718
- Wahl ER, Smerdon JE (2012) Comparative performance of paleoclimate field and index reconstructions derived from climate proxies and noise-only predictors. *Geophys Res Lett* 39:L06703

- Wigley TL, Briffa KR, Jones PD (1984) On the average value of correlated time series, with application in dendroclimatology and hydrometeorology. *J Clim Appl Meteorol* 23:201–213
- Wilhite DA, Svoboda MD, Hayes MJ (2007) Understanding the complex impacts of drought: a key to enhancing drought mitigation and preparedness. *Water Resour Manag* 21:763–774
- Wilmking M, Juday GP, Barber VA, Zald HS (2004) Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds. *Glob Chang Biol* 10: 1724–1736