THE BENEFIT OF INCLUDING RARELY-USED SPECIES IN DENDROCLIMATIC RECONSTRUCTIONS: A CASE STUDY USING *JUGLANS NIGRA* IN SOUTH-CENTRAL INDIANA, USA

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ABSTRACT

The benefit of using multiple species in dendroclimatic reconstructions in the eastern U.S. has been demonstrated. However, the benefit of including rarely-used species in multispecies reconstructions has been little explored. This paper shows the utility of using a rarely-used species in dendrochronology, *Juglans nigra,* in a multispecies Palmer Drought Severity Index (PDSI) reconstruction at a site in southern Indiana. First, the crossdating *J. nigra* is established, followed by determining the climate response. The standardized *J. nigra* chronology is then compared with co-occurring standardized species chronologies (*Quercus alba*, *Quercus rubra*, and *Liriodendron tulipifera*) reported in Maxwell *et al.* (2015). Using a principal component regression model, the bi-weights of each species were calculated to determine how much *J. nigra* contributed to the explanatory power of the model. *J.nigra* had a high interseries correlation (0.604) and mean sensitivity (0.304) and a strong correlation with summer PDSI, which was comparable in strength and more consistent through time than the co-occurring species. The inclusion of *J. nigra* in the composite reconstruction provided more consistency and better captured the observed PDSI variability. This is compelling evidence for why rarely-used species should be tested for inclusion in multispecies climate reconstructions.

Keywords: co-occurring species, climate signal, eastern deciduous forest, drought, tree rings, PDSI.

INTRODUCTION

Background

In general, early research in dendroclimatology in the eastern U.S. focused on broad climate reconstructions. The best way to achieve a climate reconstruction was to understand the climate sensitivity of species with large ranges (*e.g. Quercus alba*). After decades of research, we now have a reasonable understanding of the climate response(s) of these commonly-used species. This understanding facilitates comparisons to the climate responses of less commonly used species and the use of multiple species to better reconstruct past climatic conditions. Dendroclimatic reconstruction using multiple species is common worldwide, especially in mid-latitude regions (Meko *et al.* 2001; Pederson *et al.* 2001; Frank and Esper 2005; García-Suárez *et al.* 2009). The utility of multiple species for climate reconstructions in the eastern U.S. has been demonstrated (Cook and Jacoby 1977, 1983), and the inclusion of multiple species is a large reason for the continued success of the U.S. drought atlas (Cook *et al.* 1999). However, since the early success of multi-species reconstructions in the eastern U.S., only a few studies have adopted the approach. Recent work in the northeastern U.S. indicates that using multiple species improved the climate signal for PDSI reconstructions (Pederson *et al.* 2013). Similar results were found in the mid-Atlantic region for streamflow (Maxwell *et al.* 2011), southeastern U.S. soil moisture (Pederson *et al.* 2012), and for PDSI at one site in the Midwestern U.S. (Maxwell *et al.* 2015). Although some multispecies reconstructions combine only species that are commonly used for dendroclimatic reconstructions in the eastern U.S., in some cases rarely-used species have been found to perform just as well or even better than commonly-used species (Pederson *et al.* 2013; Maxwell *et al.* 2015).

Ideally, tree-ring data from rarely-used species in multiple locations with varying environmental

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site conditions (*e.g.* slope, soil, species composition) would be compared with multiple sites of more commonly-used species to examine the potential of a new species to reconstruct climate. Such a method effectively represents the range of variability of the climate responses for both the new and the common species. For example, using multiple chronologies for each species, Pederson *et al.* (2013) found that *Liriodendron tulipifera* (a rarely used species) in the northeastern U.S. outperformed *Q. alba* and was comparable to *Tsuga canadensis* (both commonly-used species) in its growth response to soil moisture variability. However, intra-site or co-occurring comparisons of different species' responses also provide useful information on the climate sensitivity of different species (Cook and Pederson 2011; Maxwell *et al.* 2015).

The objective of this study is to examine the climate response of *Juglans nigra* (black walnut) growth and to determine the utility of this species in dendroclimatic reconstructions. This objective is accomplished by (1) establishing the climate-growth relationship of *J. nigra*, specifically the soil moisture response, at one site in southern Indiana, (2) comparing the response with both commonly-used and other rarely-used co-occurring species, and (3) determining how the inclusion of *J. nigra* influences a multispecies climate reconstruction. *J. nigra* is a wide-ranging species (Little 1971; Landt and Phares 1973) with the potential to be sampled at multiple sites. However, *J. nigra* grows best in deep well-drained soils that are fertile and moist (Brinkman 1965), limiting the number of sites that contain a large number of individuals. Further, the difficulty of finding multiple old-growth (*i.e.* > 200 years) stands may be exacerbated by the high value of the wood to the furniture industry as veneer or wood paneling (Williams 1990). For this study, radial growth and climate responses between *J. nigra* and co-occurring species from a stand in Pioneer Mother Memorial Forest in southern Indiana are compared.

METHODS

Study Site

Pioneer Mothers Memorial Forest (38.54°N, 86.45°W) is a research natural area in southern Indiana located in the Hoosier National Forest. The forest encompasses 36 ha of protected old-growth mixed hardwoods with an additional 66-ha buffer where forest management is prohibited (USDA 2013). Karst landscapes dominate southern Indiana because the region remained unglaciated during the last glacial maximum. Pioneer Mothers Memorial Forest is located within the Crawford Escarpment and has loam and silt-loam soils formed from overlying sandstone in the area. The topography is typical of a karst landscape with rolling hills but with relatively abrupt changes where sinkholes are present.

The species composition is common for a central hardwood forest, with canopy dominant species including: *Quercus alba* L. (white oak), *Quercus rubra* L. (red oak), *Fraxinus americana* L. (white ash), *Liriodendron tulipifera* L. (yellow poplar), *Juglans nigra* L. (black walnut), *Fagus grandifolia* Ehrh. (American beech), and *Acer saccharum* Marshall (sugar maple). Other less common canopy dominant trees include: *Nyssa sylvatica* Marshall (black gum) and *Celtis occidentalis* L. (hackberry). Understory vegetation includes *Sassafras albidum* (Nutt.) Nees (sassafras), *Cornus florida* L. (flowering dogwood), *Cercis canadensis* L. (redbud), *Asimina triloba* (L.) Dunal (pawpaw)*,* and *Carpinus caroliniana* Walter (hornbeam).

Sample Collection and Preparation

Standard dendroclimatological methods were employed for sample collection and preparation (Stokes and Smiley 1968; Speer 2010). Eleven canopy dominant *J. nigra* trees with no visible signs of anthropogenic influence (*i.e.* axe marks or cut branches) were sampled. Two cores per tree were extracted using a 5.15-mm-diameter increment borer at approximately 1.3 meters from the ground. Tree cores were air dried, mounted for stability, and sanded with progressively finer sandpaper until rings and cell structure were clearly visible. The samples were visually cross-dated using the list method (Yamaguchi 1991). Tree-ring measurement was conducted using a Velmex measuring stage and the program MeasureJ2X (Voorhess 2000). Confirmation of visual

crossdating was made using the program COFE-CHA (Holmes 1983). The program ARSTAN (Cook 1985) was used to standardize the samples to remove both the biological growth trend and to remove variability not associated with the climate signal. A two-thirds spline, a 50% frequency response cutoff that was equal to two-thirds of the length the series (Cook and Peters 1981), was used to interactively remove from each series the noise associated with forest dynamics. Following Wigley *et al.* (1984), a cutoff of 0.85 for the expressed population signal (EPS) determined the earliest date at which the sample depth was robust enough to reconstruct climate.

Climate Data and Analysis

To determine the growth response of *J. nigra* to soil moisture variability, and to compare it to other co-occurring species, monthly temperature, precipitation, and Palmer Drought Severity Index (PDSI; Palmer 1965) were gathered for the Indiana Climate Division 8 from 1895–2012 CE from the National Climatic Data Center. To calculate correlations between the climate variables and radial growth, the program Dendro-CLIM2002 (Biondi and Waikul 2004) was used. The program calculates 1000 random bootstrapped timeseries to generate correlations and reports significance at 95% confidence level. DendroCLIM2002 was also used to calculate moving correlations to examine changes in the relationship between climate and growth through time. Because of previous growing season conditions' ability to influence current-year tree growth (Fritts 1976), the previous growing season March to current growing season December was used for the analysis. To examine the stability in the relationship between the highest correlated climate variable (PDSI) and growth, a moving correlation was used with a moving window of 44 years, double the number of climate variables (Biondi and Waikul 2004). Each 44-year period was based on the last year of the window, and thus the first window correlation was based on 1895–1938 and was reported for 1938, giving a reporting period of 1938–2012.

Climate Reconstructions

The methods laid out by Maxwell *et al.* (2015) were followed insofar as to compare JJA PDSI reconstructions derived from the three species reported in that study with a newly developed *J. nigra* reconstruction. Each species-based PDSI reconstruction is derived from a regression model between PDSI (independent) and radial growth (dependent) calibrated on the common period of 1895–2012 and verified using a split-sample calibration and verification method. The instrumental PDSI record was divided in half and a regression model between PDSI and growth was calibrated on the early portion (1895–1953) and the predicted values for the later period were verified using the observed data for the same period, which were not used to calibrate the model. The same process was repeated using the later portion as calibration and verifying on the earlier portion. Verification statistics included Pearson correlation coefficients (*i.e.* r-values) between the predicted and observed series, the reduction of error statistic (RE, Fritts 1976) and the coefficient-of-efficiency statistic (CE, Nash and Sutcliffe 1971). All reconstructions were calculated using the "Arstan" standardized chronology from the program ARSTAN.

To evaluate how the inclusion of *J. nigra* influenced a composite model that was reported in Maxwell *et al.* (2015), a nested PC-regression model (Meko 1997) was used. The ring-width indices (Arstan) for all four species (*Q. alba*, *Q. rubra*, *L. tulipfera*, and *J. nigra*) for the current year (*t*) and the following year (*t+1*) were used. The current year soil moisture can influence the tree growth both during the current and the following year because of energy and resources gained in the current year (Fritts 1976). A total of eight predictors were entered into the model (the current year and *t+1* for each species). Only the predictors that had a significant ($p \leq 0.05$) correlation with PDSI were retained for the model and reduced to principal components (PCs) using a rotated (varimax) principal component analysis (Richman 1986). To determine the number of PCs to retain, the eigenvalue greater than one rule was used (Guttman 1954; Kaiser 1960). Multiple reconstruction nests were created based on the common period of the species (Meko 1997). The process involves iterative PC

Table 1. Chronology statistics of *Juglans nigra* and species used for comparison.

Species	Number of years	Missing rings	Interseries correlation	Average mean sensitivity	EPS cutoff year
J. nigra	233	0	0.604	0.304	1806
Species reported in Maxwell *et al.* (2015)					
Q. rubra	152	0	0.590	0.196	1920
Q. alba	195	1*	0.577	0.238	1870
L. tulipifera	296	7	0.595	0.324	1820

*Missing ring was associated with broken core and not climate/growth related.

regressions using the common period of the predictors. In each iteration, the youngest predictor is removed and a new nested reconstruction is calculated from the remaining predictors. The start of each nest length is determined by the earliest year at which all species have an acceptable EPS value and is reconstructed up until the previous nest. For example, the common period for all four species was 1920–2012 and the first reconstruction nest was calculated for this period. The youngest species was removed (in this case *Q. rubra*) and the next nest reconstruction was computed from the year when all remaining species had appropriate EPS values (in this case 1870) forward to the beginning of the first nest (1919). This process was repeated until only the oldest species remained, at which point the actual standardized tree-ring widths were used instead of PCs as the predictor. The standard deviation and mean of each nest was adjusted to the observed period and the nests were spliced together to create the final reconstruction. For each nest, the same split calibration and verification process as for the species-derived PDSI reconstruction were used (*i.e.* r-values, RE and CE).

Species Contributions to Climate Reconstruction

To compare how much *J. nigra* contributed to the final PDSI reconstruction in relation to the other species, the relative explained variance was calculated for each species following Frank and Esper (2005) and Pederson *et al.* (2013). The absolute standard regression coefficients (beta weights values), which represent the principal component regression analysis predictor loadings, were taken for each species chronology. For species chronologies with significant predictors in years *t* and *t + 1*,

the beta weights were summed. The percentage of each absolute summed beta weights was then calculated for each species chronology from the overall absolute beta weight sum.

RESULTS AND DISCUSSION

J. nigra Chronology Statistics

The eleven *J. nigra* trees and the associated 22 cores retained in the final chronology had an interseries correlation of 0.604 and a mean sensitivity of 0.304. The standardized *J. nigra* chronology had sufficient sample depth (determined by the EPS value > 0.85) back to 1806, which is older than the co-occurring species reported in Maxwell *et al.* (2015). *J. nigra* has the highest interseries correlation and the second highest mean sensitivity (Table 1) compared to co-occurring species. Additionally, no missing rings were present because of the initial flush of spring growth that results in the semi-ring porosity of the wood in *J. nigra* (Figure 1). These characteristics make *J. nigra* a strong candidate for use in dendroclimatology, suggesting that *J. nigra* individuals have a common climate response, easily distinguishable rings, and a high sensitivity to environmental changes.

Climate Signal of *J. nigra*

The climate response for *J. nigra* is dominated by summer (JJA) conditions, with current-year precipitation, temperature and PDSI being

Figure 1. Example of semi-ring porous annual growth rings for *J. nigra*. Bark end is on the left and the inner portion of tree on the right.
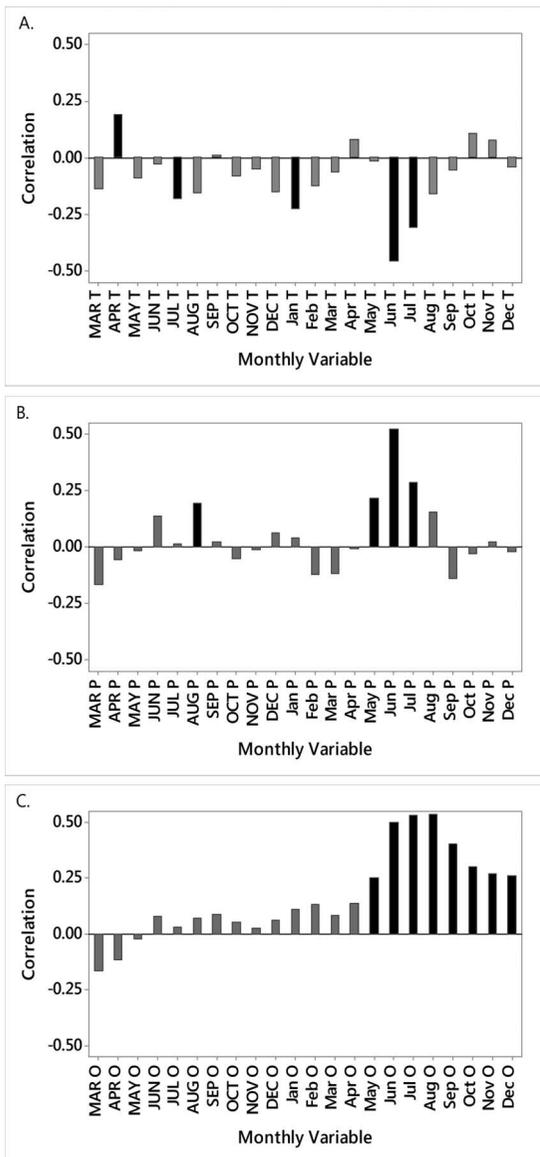
Figure 2. Climate response of *J. nigra* for monthly (A) temperature, (B) precipitation, and (C) PDSI. Black columns represent significant (*p* < 0.05) relationships.

significantly correlated with growth (Figure 2). However, summer PDSI had the strongest association with *J. nigra* growth. Previous summer conditions were also important for growth, with previous-year precipitation and temperature being significantly related to growth (Figure 2). The strongest signal (summer PDSI) is stable through time when examining the moving windows in

DendroCLIM2002 (Figure 3A). This finding was somewhat surprising because Maxwell *et al.* (2015) found that other co-occurring species had varying degrees of fading in the PDSI signal through time (Figure 3B, C, and D). The strength and the stability of the climate signal gives *J. nigra* great potential value in dendroclimatic studies. The total hours of sunshine parameter was also examined because Stahle *et al.* (1991) found that it was a strong predictor of growth in the central US. However for all species in this site, the signal was relatively weak and thus was not included in the analysis.

Comparison of Composite Chronologies

The composite chronology that included *J. nigra* explained 46 percent of the variance in summer PDSI for Indiana climate division 8 (Table 2), an increase from the 40 percent reported in Maxwell *et al.* (2015). Further, the composite chronology including *J. nigra* spans from 1806–2013, expanding the previous chronology by 14 years because of the high interseries correlation and sample depth of *J. nigra* at the turn of the 19th Century. Although this is a marginal increase in length, it is conceptual evidence of the potential value of including *J. nigra* in the composite PDSI reconstruction. The difference between the chronologies with and without *J. nigra* is larger in the earlier portion where *J. nigra* provides better sample replication and thus a more accurate reconstruction of PDSI (Figure 4). When sampling small forest stands (such as the one at Pioneer Mothers) with limited older trees (<40 individuals for each species), which are common in the Midwestern US, it is important to be able to increase sample depth back in time. In this paper, the more traditionally used species (both *Qurecus* species) lacked sample depth back through time. Although the oldest trees at the site were *L. tulipifera*, the number of available trees to sample was limited with a sample depth of less than 15 samples pre-1860 (Maxwell *et al.* 2015). Thus, the addition of *J. nigra*, which has an additional 16 samples that go beyond 1860, is providing much needed sample depth and more accurately representing soil moisture during this period.
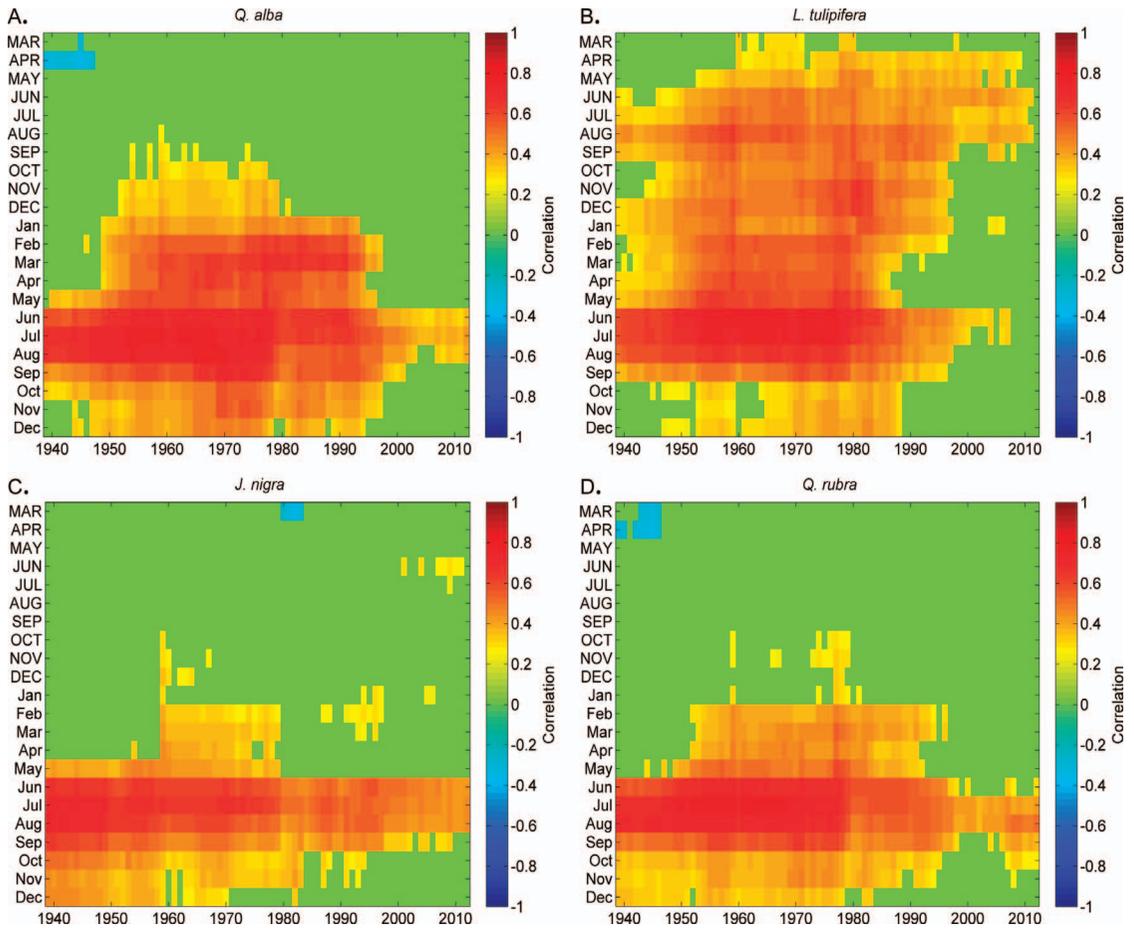
Figure 3. Moving interval correlation analysis between monthly PDSI and radial growth for (A) *J. nigra,* and the species reported in Maxwell *et al.* (2015), (B) *L. tulipifera,* (C) *Q. alba*, and (D) *Q. rubra* from March of the previous (in all upper-case letters) growing season to December of the current year during the period 1895–2010. The x-axis represents the final years of each lagged 44-year interval. All colored values except green represent correlation coefficients that are statistically significant (*p* < 0.05, see legend). Insignificant values are shaded green.

The moving correlation of the composite chronology with *J. nigra* shows a significant and stable relationship between PDSI and tree growth through time (Figure 5A). Although there is a weakening of the signal in the more recent windows, the relationship remains significant. Compared to the composite chronology without *J. nigra*, the chronology with *J. nigra* is generally more correlated with PDSI through most of the current-year growing season (Figure 5B). It should be noted that because of the fading strength of the correlation, the last two nests (nests beginning in 1820 and 1806) had CE values that were barely

positive (0.02 and 0.01; Table 2) and indicate that the model is close to failing validation tests even when just examining *J. nigra,* which is the 1806 nest. It is not currently known if this fading signal is only present at Pioneer Mothers or if it is a coherent regional phenomenon. Updates to existing tree-ring chronologies and creation of new chronologies in the Midwest are needed to examine if the fading signal is site-specific or occurring more broadly. Although these validation statistics are concerning, it appears that *J. nigra* has a fairly consistent relationship with PDSI through time (Figure 3) with some weakening in the relationship in the more
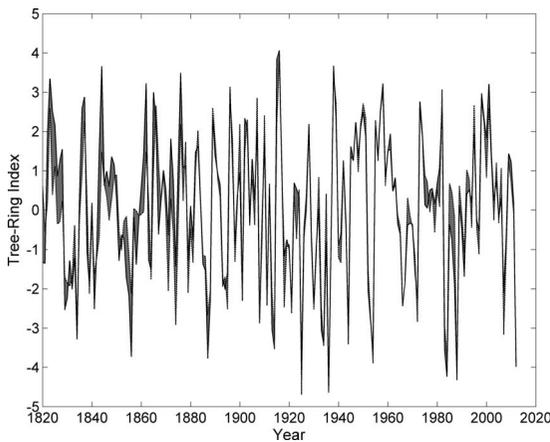
Figure 4. Timeseries of the composite chronology with *J. nigra* (solid line) and without *J. nigra* (dotted) as reported in Maxwell *et al.* (2015) and the difference (shaded area) between the standardized growth of the two composites.

recent period. Regardless, the inclusion of *J. nigra* in the composite chronology substantially increases the accuracy of the composite chronology PDSI reconstruction by providing a consistently significant relationship through time and greater sample depth at the turn of the 19th Century.

J. nigra Contribution to the Composite Chronology

J. nigra made a substantial contribution (20% of the relative explained variance; Table 3) to the composite chronology reconstruction of PDSI according to beta weight values of the principal component regression model. Although the other species reported in Maxwell *et al.* (2015) were ranked higher, the relative explained variance (*Q. alba*, 23%; *Q. rubra*, 24%; *and L. tulipifera*, 33%) of *J. nigra* is comparable to both *Quercus* species. These results support the findings of Pederson *et al.* (2013) who employed rarely-used species (*e.g. L. tulipifera, C. glabra*, and *C. ovate*) to reconstruct PDSI in New York, USA, and found that these rarely used species performed just as well as more traditionally used species (*e.g. Q. alba, J. virginiana,* and *T. canadensis*). In this study, two rarely used species, *L. tulipifera* and *J. nigra*, respectively explained more than or nearly the same amount of variance as the traditional
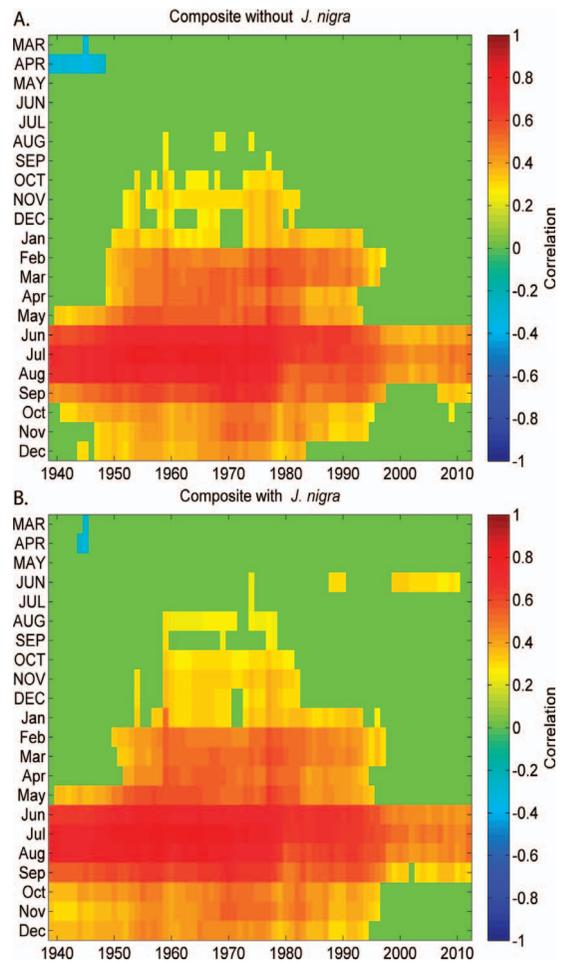

Figure 5. Moving interval correlation analysis between monthly PDSI and radial growth of (A) the composite chronology reported in Maxwell *et al.* (2015) without *J. nigra* and (B) the composite chronology with *J. nigra* added from March of the previous (in all upper-case letters) growing year to December of the current growing season during the period 1895–2010. The x-axis represents the final years of each lagged 44-year interval. All colored values except green represent correlation coefficients that are statistically significant ($p = 0.05$, see legend). Insignificant values are shaded green.

(*Q. alba* and *Q. rubra*) species (Table 3). Although it is difficult to find a sufficient number of sites containing *J. nigra* to reconstruct regional climate and to find enough older (>100 years) samples within a given site (*e.g. n =* 11 at Pioneer Mothers), the strength and the stability of the climate signal gives *J. nigra* great value in dendroclimatic studies.

Table 2. Calibration and verification statistics for the nested PDSI reconstruction. RE and CE values are derived using a split-sample approach.

Calibration	R^2 (*p*-value)[a]	R^2adj[b]	Verification	*r* (*p*-value)[c]	RE	CE
Nest 1 (1920–2012) J. nigra, L. tulipifera, Q. alba, and Q. rubra						
1895–2012	0.46 (<0.001)	0.45	–	–	–	–
1895–1952	0.59 (<0.001)	0.58	1953–2012	0.57 (<0.001)	0.31	0.12
1953–2012	0.34 (<0.001)	0.33	1895–1952	0.77 (<0.001)	0.45	0.40
Nest 2 (1870–2012) J. nigra, L. tulipifera, and Q. alba						
1895–2012	0.44 (<0.001)	0.43	–	–	–	–
1895–1952	0.56 (<0.001)	0.55	1953–2012	0.56 (<0.001)	0.31	0.11
1953–2012	0.34 (0.001)	0.33	1895–1952	0.75 (<0.001)	0.48	0.37
Nest 3 (1820–2012) J. nigra and L. tulipifera						
1895–2012	0.37 (<0.001)	0.36	–	–	–	–
1895–1952	0.50 (<0.001)	0.49	1953–2012	0.47 (<0.001)	0.23	0.02
1953–2012	0.25 (<0.001)	0.24	1895–1952	0.70 (<0.001)	0.41	0.28
Nest 4 (1806–2012) J. nigra						
1895–2012	0.31 (<0.001)	0.30	–	–	–	–
1895–1952	0.42 (<0.001)	0.41	1953–2012	0.53 (<0.001)	0.10	0.01
1953–2012	0.29 (<0.001)	0.27	1895–1952	0.65 (<0.001)	0.26	0.10

[a]The R^2 and *p*-value of tree-rings regressed on PDSI for calibration period.
[b]Adjusted R^2 accounts for degrees of freedom.
[c]Pearson correlation between actual and predicted PDSI.

CONCLUSIONS

The utility of including *J. nigra* in a multispecies dendroclimatic reconstructions was examined. *J. nigra* tree rings were compared to other co-occurring species at Pioneer Mothers Research Natural Area in southern Indiana. This paper found that *J. nigra* not only performed well in terms of dendrochronology statics (*i.e.* interseries correlation and mean sensitivity) but also enhanced the quality of the PDSI reconstruction when combined with other co-occurring species. *J. nigra* radial growth had a strong correlation with summer PDSI, which rivaled the co-occurring species and was more consistent through time than any of the other species. Further, the inclusion of *J. nigra* in the composite chronology increased the overall explained variance by six percent and increased the length of the reconstruction by 14 years. *J. nigra* had a relative explained variance comparable to both *Quercus* species. The eastern deciduous forest in the U.S. has great species diversity, which should be utilized to maximize the accuracy – and possibly the length – of climate reconstructions. Species that are rarely used in dendroclimatic reconstructions may not only increase the overall explained variance of the model but also provide a more consistent model that better captures the climate variability in the region. *J. nigra* is an example of why rarely-used species have merit in dendroclimatic reconstructions and suggests that other rarely-used species also could contribute to improve climate reconstructions.

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