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Detrending tree-ring widths in closed-canopy forests for climate and disturbance history reconstructions

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ABSTRACT

Canopy disturbance events in forests often increase light availability and growth rates for surviving trees. Using ring widths, release-detection methods identify the initiation of rapid growth associated with these events enabling reconstructions of forest disturbance history. Conversely, dendroclimate reconstructions minimize these rapid growth responses by detrending entire ring-width time series to resolve underlying climate signals. Incorporating advantages from both of these approaches, we present a canopy disturbance detrending method that quantifies the subsequent, additional growth from release events as a discrete time series. Our method uses radial-growth averaging to detect release events and then power transformation and age-dependent smoothing splines to detrend individual release events, separating canopy disturbance responses from climatic effects. We test our canopy disturbance detrending method on both a coniferous and a broadleaf ring-width chronology from two contrasting temperate forests in eastern North America with known disturbance histories. The resulting disturbance growth time series agrees with the documented forest histories for each forest. Removing the effects of canopy disturbance from the ring-width series in each chronology improves climate correlations with monthly values of temperature and precipitation and may recover more low-frequency variation with past climate compared to other common detrending methods. Our method provides an alternative approach for detrending disturbance events in closed-canopy forests that should be accessible and useful for both ecological and climatological reconstructions.

1. Introduction

Ring widths often record growth releases in trees receiving increased light availability after surviving forest canopy disturbance events. Ranging from asynchronous endogenous tree mortality such as gap-phase dynamics, to more synchronous exogenous stand-wide mortality (Shugart, 1984; White, 1979), canopy disturbance events are important in the long-term development of forests from tropical to boreal latitudes (McCarthy, 2001; Seidl and Turner, 2022). Growth releases can be detected in tree-ring widths and used to reconstruct canopy disturbance events and their long-term legacies in forest composition and structure (Henry and Swan, 1974; Lorimer and Frelich, 1989; Marshall, 1927; Nowacki and Abrams, 1997; Oliver and Stephens, 1977; Stephens, 1956). Because growth patterns created by these release events add non-climatic information to ring-width time series, these events also degrade reconstructions of past climate, presenting a significant challenge for paleoclimate studies in forested regions (Cook and Kairiukstis, 1990).

Climate and disturbance are recognized as two important drivers of tree growth in a conceptual model of tree growth (Cook, 1987) representing ring width (R_t) as a summation of the effects of a biological age trend (A_t), climate (C_t), endogenous and exogenous disturbance events (D_t), and other factors (E_t) on radial growth. Radial-growth averaging methods identify the frequency and relative magnitude of past canopy disturbance events, but these methods do not isolate a tree's growth response as a discrete time series such as represented by D_t. Conversely, dendroclimatic methods minimize A_t (Fritts, 1976) typically using negative exponential functions and also D_t using smoothing splines (Cook and Peters, 1981) and data-adaptive power transformations (Cook and Peters, 1997) on ring-width time series, but not in a manner

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that explicitly identifies canopy disturbance events. Warren (1980) introduced an additive detrending approach for removing canopy disturbance events using a general exponential curve; however, more recently age-dependent splines were developed to capture the rapid increase in a tree's earliest ring-widths followed by decreased growth as tree age increases as a time-varying response (Melvin et al., 2007). Melvin et al. (2007) applied age-dependent splines to reconstruct climate using regional curve standardization (Briffa et al., 1992; Helama et al., 2017); but they also suggested that time-varying splines may have other applications in dendrochronology. Here, we recognize that while canopy disturbance events may result in various ring-width patterns (*sensu* Lorimer and Frelich, 1989), these patterns also often feature a rapid increase in ring widths followed by a gradual decrease. Lastly, we also note that time-series statistical methods using autoregressive outliers and intervention detection (Druckenbrod, 2005; Druckenbrod et al., 2013) have previously been the only method capable of both identifying release events and detrending disturbance-growth time series; however, a recent experimental test suggests that these methods may not be more accurate than radial-growth averaging in detecting the timing of these events (Trotsiuk et al., 2018).

Building on these previous methods, we develop a new approach that incorporates radial-growth averaging to identify release events and age-dependent splines with data-adaptive power transformation to detrend a ring-width series into its discrete underlying components, including the responses of trees to canopy disturbance and climatic variation. Using two example chronologies from eastern North America, an coniferous species from a diverse, mesic forest (Palmaghatt Ravine, New York) and a broadleaf species from a drier forest (Democrat Ridge, Missouri), we (1) present our canopy disturbance detrending method with examples using individual tree-ring width series, (2) compare reconstructions of canopy disturbance events with documented forest histories, and (3) evaluate monthly climate correlations with tree-ring widths and how those correlations vary with increasing time period using wavelets.

These two forest case studies exemplify many of the typical drivers of release events in closed-canopy forests and their ensuing disturbance regimes. Temperate forests in eastern North America are often dominated by gap dynamics at the scales of individual trees, but at larger spatial and temporal scales may be affected by more extensive disturbance agents including external agents such as pests and pathogens as well as physical agents including fire, windstorms, and drought (Delcourt et al., 1982, Druckenbrod et al., 2019). Natural disturbance regimes in most temperate forests typically have a return interval of 50–200 years; however, trees in these forests often require multiple release events to attain canopy status, enabling some trees to reach older ages (Runkle, 1985). Human land use and other anthropogenic activities are now also a major driver of disturbance regimes, whether directly or indirectly, in temperate forests (Gilliam, 2016, Sommerfeld et al., 2018).

2. Material and methods

2.1. Forest descriptions and documented canopy disturbance histories

Forests in the Palmaghatt Ravine (41.71 N, 74.25 W) were broadly classified as Hemlock-White Pine-Northern Hardwoods by Braun (1950) and then re-classified as Northern Hardwoods-Hemlock by Dyer (2006). Palmaghatt Ravine is located in the Shawangunk Mountains of New York State near where the first quantitative study of past hydroclimate from closed-canopy tree species in temperate mesic regions (Cook and Jacoby, 1977). Forests at Democrat Ridge (37.41 N 92.00 W), located in the Ozark Plateau, were classified as Oak-Hickory forest by both Braun (1950) and Dyer (2006).

Numerous extensive historical human impacts have been documented in the Palmaghatt Ravine forest and the larger Shawangunk Mountain region involving both harvesting and nonnative, invasive species. Selective logging of large hemlock trees (*Tsuga canadensis* (L.) Carr.) for the tanning industry began within the Shawangunk Mountains in 1849 (Thompson and Huth, 2011), leaving mostly smaller hemlocks in Palmaghatt Ravine by the end of that century (Pike, 1892). While logging was ongoing, the Palmaghatt Ravine was purchased privately for conservation in the late nineteenth century (ca. 1897 in Knickerbocker 1937) and is now part of Minnewaska State Park. Across the Shawangunk Mountains, most of the merchantable timber was logged by 1892 and the arrival of chestnut blight (*Cryphonectria parasitica* (Murrill) Barr) in 1912 led to severe mortality of American chestnut trees and salvage logging into the 1920s (Thompson and Huth, 2011; Huth and Smiley, 1985). After large-scale logging ceased in the Shawangunk Mountains in the 1930s, defoliation by another introduced organism, spongy moth (*Lymantria dispar* L.) led to widespread documented oak mortality in 1986 and 1987 (Thompson and Huth, 2011) and an earlier outbreak in 1981 that was so severe that moths in southern New York defoliated other species like hemlock in addition to hardwood species (Souto and Shields, 2000; D'Arrigo et al., 2001). Similarly, Hemlock Woolly Adelgid (*Adelges tsugae* Annand) was first documented regionally in 1991 (Morin et al., 2009) and led to widespread hemlock mortality by the end of the century (Orwig et al., 2002). Ice storms were reported to have impacted trees within Palmaghatt Ravine in 1942 and November 2002 (Yarrow, 2003).

Extensive historical logging occurred in the Ozark Plateau in the early twentieth century as European settlement reached this region more recently (Cleaveland and Stahle, 1989; Guldin, 2008); however, remnant old post oak (*Quercus stellata* Wangenh.) forests remain in the Ozarks (Stahle, 1996). The chestnut blight also spread to this region from eastern North America by 1940, decreasing the abundance of Ozark chinkapin (*Castanea ozarkensis* Ashe) (Chapman et al., 2006).

2.2. Forest sampling design

These two sites also differed in sampling designs. Democrat Ridge followed a classic dendroclimatology-oriented design sampling trees that appeared old while Palmaghatt Ravine used an ecological plot design where all trees were sampled above diameter thresholds. At Democrat Ridge, post oaks were selectively sampled for an annual streamflow reconstruction (Cleaveland and Stahle, 1989). At Palmaghatt Ravine, five circular plots were surveyed along a 1-km transect extending along a moisture availability gradient (*sensu* Whittaker, 1956). Sampling at Palmaghatt Ravine surveyed a closed-canopy, temperate deciduous forest with ecological communities that have a stronger resemblance to the Mesophytic and Appalachian oak section of Dyer (2006). Tree species in the wetter end of our transect are dominated by eastern hemlock and yellow birch (*Betula alleghaniensis* Britton). The dominant species in the plot at the drier end were chestnut oak (*Quercus montana* Willd.) and northern red oak (*Q. rubra* L.). In the intermediate plots, additional species included red maple (*Acer rubrum* L.), sweet birch (*B. lenta* L.), white ash (*Fraxinus americana* L.), and tulip poplar (*Liriodendron tulipifera* L.). Here, we use *T. canadensis* samples from the two most mesic plots along this transect for analysis.

In the plots at Palmaghatt, live and dead trees were sampled based on diameter at breast height (DBH) within nested circular plots to sample trees across size classes: 8 m radius for trees $\geq$ 13.5 cm DBH, 20 m for trees $\geq$ 25.0 cm, and 30 m for trees $\geq$ 40 cm following a design similar to Martin-Benito et al. (2020). This approach samples trees proportionally across canopy strata to capture both the fading record of forest canopy disturbances present only in older canopy trees as well as the fading forward record typically present in younger, canopy subordinate trees (Druckenbrod et al., 2019). For both sites, two cores were typically collected per tree, visually crossdated, and statistically checked using Cofecha (Holmes, 1983).

2.3. Example of canopy disturbance detrending method on an eastern hemlock ring-width series

Canopy disturbance detrending involves consecutive steps applied onto each ring-width series (Table 1). Fig. 1 shows an example application of this method to a time series from a core extracted from an older eastern hemlock at Palmaghatt Ravine, which had an earliest ring of 1737 (see Appendix Fig. A1 for an example post oak series). Release events are identified following the earlier canopy accession settings of 15-year running means and a 50% percentage growth increase threshold using radial-growth averaging (Lorimer and Frelich, 1989). When more than one adjacent year was greater than this threshold, the maximum percentage growth value was used to determine the year of release in this example (Altman, 2020).

The ring-width series is then power transformed to reduce its heteroscedasticity since the variance of ring-width series generally increase with their mean (Cook and Kairiukstis, 1990). Quantifying a series' heteroscedasticity enables an adjustment of the variance of a series when its mean values are reduced through subtraction from detrending (Cook and Peters, 1997). This enables a re-scaling of the variance at a new mean level after canopy disturbance detrending.

Beginning with the most recent event, the ring-width series is detrended from the initial year of each release event to the last year of the series using an age-dependent spline with an initial stiffness set to 10 years to capture the often rapid growth response after a canopy disturbance event. The initial value of each detrended release is set to the transformed ring-width value of the first year of the release. This process iterates until all release events have been detrended (Fig. 1B-D). The core in Fig. 1 detected release events in 1786, 1893, and 1937. This series also shows how an age-dependent spline is capable of detrending both transient (e.g., 1786) and sustained (e.g., 1893 and 1937) canopy release events. For this method, sustained release events occur when disturbance detrended ring-width values remain less than initial ring-width values for the remainder of the series after the release event. Conversely, transient events occur when detrended values only decrease initial ring-width values for a certain sequence of years after the release event instead of the entire remaining series. Transient release events terminate when the detrended value would be greater than the initial ring-width value, indicating that a tree likely returned to suppressed growth conditions.

After removing endogenous and exogenous disturbance events (D_t) using radial-growth averaging and an age-dependent spline, one can employ common dendroclimatic methods to detrend an age trend across the entire series. Here we use an age-dependent spline across the entire power-transformed series to remove A_t. The transformed, D_t detrended series along with D_t and A_t detrended series may also be re-expressed back in the original units of tree-ring width (Fig. 1E), producing a disturbance and age standardized series resembling the underlying age trend common in many trees. The gray-shaded difference between the initial and disturbance-detrended series can be viewed as a disturbance-growth time series measured in units of ring-widths per year that may have ecological applications (*sensu* Druckenbrod et al., 2013). Dividing the disturbance-standardized series by A_t creates a climate index (Fig. 1F), C_t, as traditionally used in dendroclimatology.

Table 1
Description of general steps in canopy disturbance detrending method.

Step	Description
1	Sequentially select each ring-width series for processing (similar to other dendrochronology programs such as Cofecha, ARSTAN, etc.).
2	Detect initiation of release events using radial growth averaging
3	Power transform ring-width series to reduce heteroscedasticity.
4	Using age-dependent splines, iteratively detrend any canopy release events beginning with the most recent event, which quantifies the duration and magnitude of transient and sustained release events.
5	Re-express disturbance growth increment and D_t standardized series in original growth units
6	Detrend across the entire D_t standardized series to minimize A_t using an age-dependent spline, producing a tree-ring index that is age and disturbance standardized (A_t and D_t).

2.4. Climate data, comparison detrending methods, and tree-ring indices

We compared correlations of both the detrended Palmaghatt eastern hemlock and Democrat Ridge post oak tree-ring width chronologies with monthly climate variables between our canopy disturbance detrending method and two detrending methods commonly used in dendroclimatology (negative exponential curve and a two-thirds spline). At Palmaghatt Ravine, we used monthly climate data from (Cook et al., 2010), a homogenous record collected approximately 10 km NE within adjacent preserved forest land (Mohonk Lake USHCN substation 305426) while we used monthly climate data from PRISM (PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, data accessed 21 Dec 2022) for Democrat Ridge. R package dplR (Bunn, 2008; Bunn et al., 2022) was used to generate three standard, ring-width index chronologies for climate comparisons for both sites: a negative exponential curve, a two-thirds spline, and the canopy disturbance detrending method presented in this paper. All sampled cores, including replicates from individual trees, were included in each chronology at both sites. The seascorr function (Meko et al., 2011) in R package treeclim (Zang and Biondi, 2022) was used to investigate possible correlations with monthly precipitation and temperature as either primary or secondary climate variables. Partial correlations between secondary climate variables and tree ring chronologies suggest additional association between a chronology that is not explained by correlation between the two climate variables (Meko et al., 2011).

Bradshaw and Spies (1992) used wavelets to investigate spatial patterns of canopy gap structure, recognizing that these patterns are aperiodic. Similarly, we recognize that canopy disturbance events are also often aperiodic through time and use wavelets to express patterns over increasing time periods. Indeed, it is this lack of regularity that prevents the use of traditional spectral processing to isolate disturbance signals in tree-ring time series and provides the genesis for the climate reconstruction methods compared in this paper. We use wavelet coherence in R package biwavelet (Gouhier et al., 2021) between each chronology and significant climate variables correlated with these chronologies to investigate how these correlations vary by frequency (see Allen et al., 2017 for an example with tree-ring chronologies) and whether this method retains more decadal-scale agreement with climate.

3. Results

3.1. Canopy disturbance detrending examples with an eastern hemlock chronology and a post oak ring-width chronology

In the eastern hemlock ring-width chronology, 137 disturbance events were detected in 59 series out of 67 total series. Release events clustered in the following decades 1870s, 1920s and 1930s, and 1980s (Fig. 2A). In the post oak chronology, 94 disturbance events were detected across 52 series out of 61 total series in the chronology with the largest peaks in the decades of 1800 and 1900 (Fig. 3A). Detrending those series created a mean disturbance-growth increment time series for both chronologies (Figs. 2B and 3B gray shaded areas). The mean of the disturbance-standardized series decreases during these decades with the detrending of release events using an age-dependent spline; however, a smaller growth increase still remains from the recruitment of young, rapidly-growing trees during these disturbance events (blue line). These trees are evident by the histogram of tree ages using earliest rings per tree for the plot-based hemlock chronology (Fig. 2C). Subsequently dividing each series by its age-trend produces tree-ring width indices that may be averaged across series to isolate climate signals in both chronologies (Figs. 2D and 3C).

Re-expressing the transformed, disturbance-detrended series back to ring widths led to a negative value in year 2003 for 21 of 67 eastern hemlock series during an episode of severe suppressed growth. Ring-width values for this year were unusually small initially (with seven

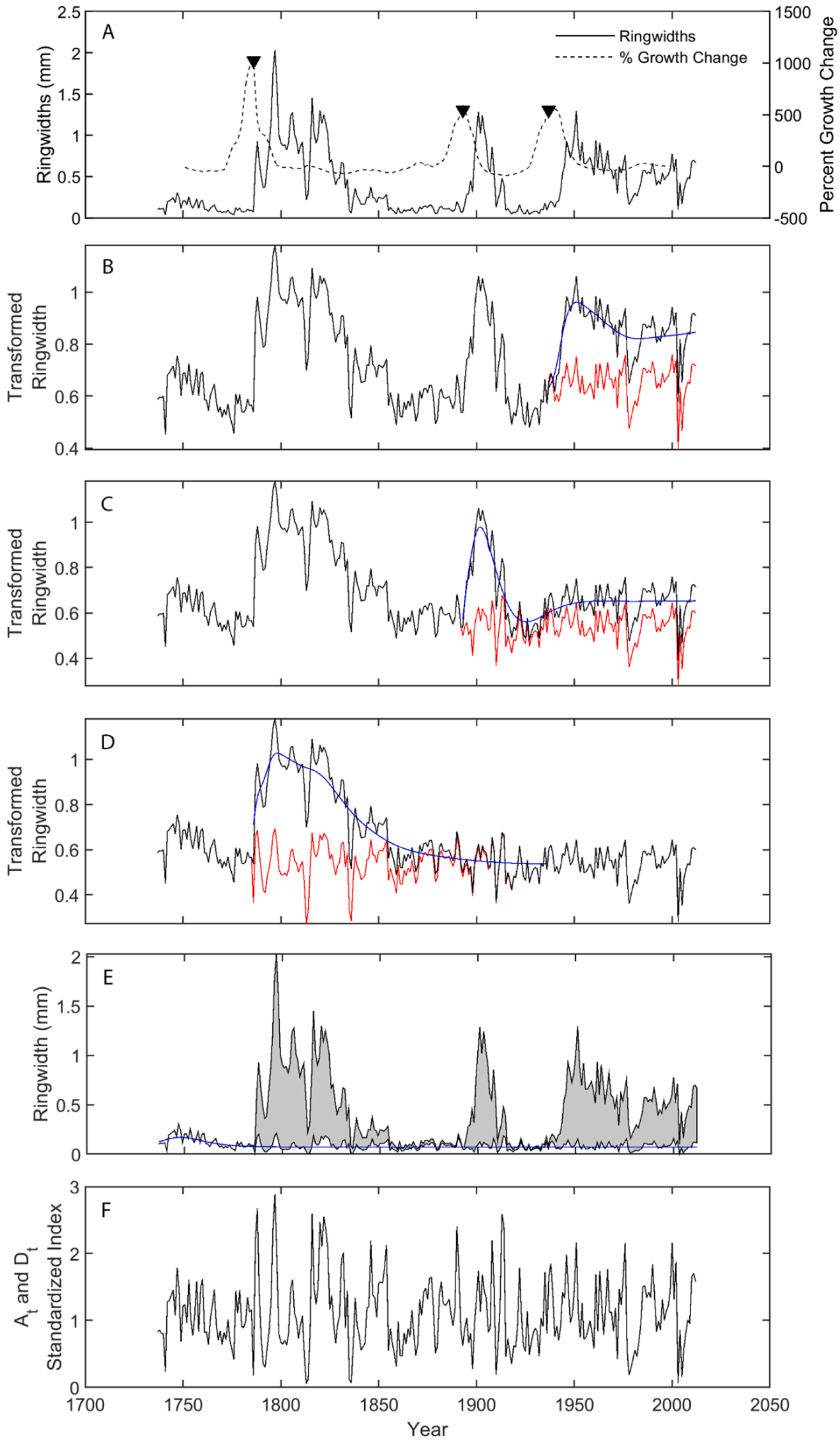

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Fig. 1. Example of the canopy disturbance detrending method on ring widths from an eastern hemlock tree in Palmaghatt Ravine, NY, USA. Three canopy disturbance events (triangles) detected from radial-growth averaging (A) that are then sequentially detrended using an age-dependent spline (B through D) on power-transformed ring widths. Ring widths re-expressed in original units with initial ring widths shown by the upper line and the disturbance-detrended series represented by the lower line. Gray shading depicts the disturbance growth increment beginning after the earliest release in 1786 and fitting an age-dependent spline to the entire series (blue line) represents the age-trend (A_t) for this tree (E). Dividing the disturbance-detrended series by the age trend produces a series that is both age and disturbance standardized index values (F).

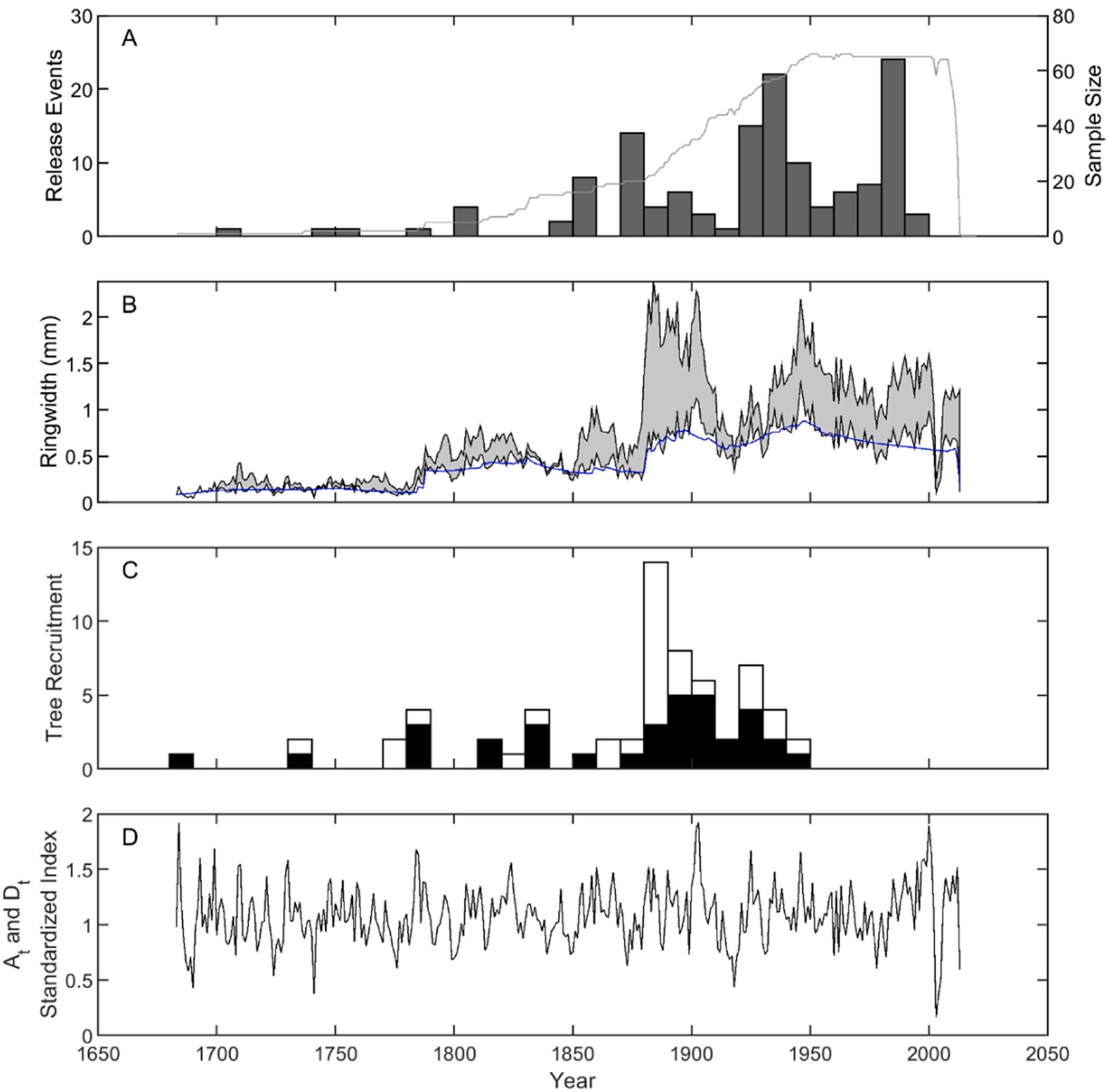

Fig. 2. Example *Tsuga canadensis* chronology at Palmaghatt Ravine, New York, USA using the canopy disturbance detrending method. Decadal histograms of canopy release events and gray line showing series sample size (A). Disturbance history chronology showing the difference of the initial average series values and the average disturbance-detrended ring widths with the gray shading representing the average disturbance growth increment across all series and an average age trend (blue line) fit to the disturbance growth series (B). Histogram of tree recruitment with hemlock trees shown in black and other species in white (C) and resulting climate index after removing age trends from the disturbance-detrended series for all eastern hemlock series (D).

series recording a missing ring at that year prior to analysis) and reduction of growth from detrending with an age-dependent spline decreased these to negative values. For this example, values for this year were set to 0.001 mm to allow for the smallest possible measured growth rate. With the modified negative exponential detrending method and two-thirds spline methods, one hemlock series each also produced negative values and were detrended instead by their mean within dplR. In contrast, none of the canopy disturbance detrended series in the post oak ring-width chronology had negative values when re-expressed from transformed units to ring widths nor did the modified negative exponential, or two-thirds spline detrending produce negative values.

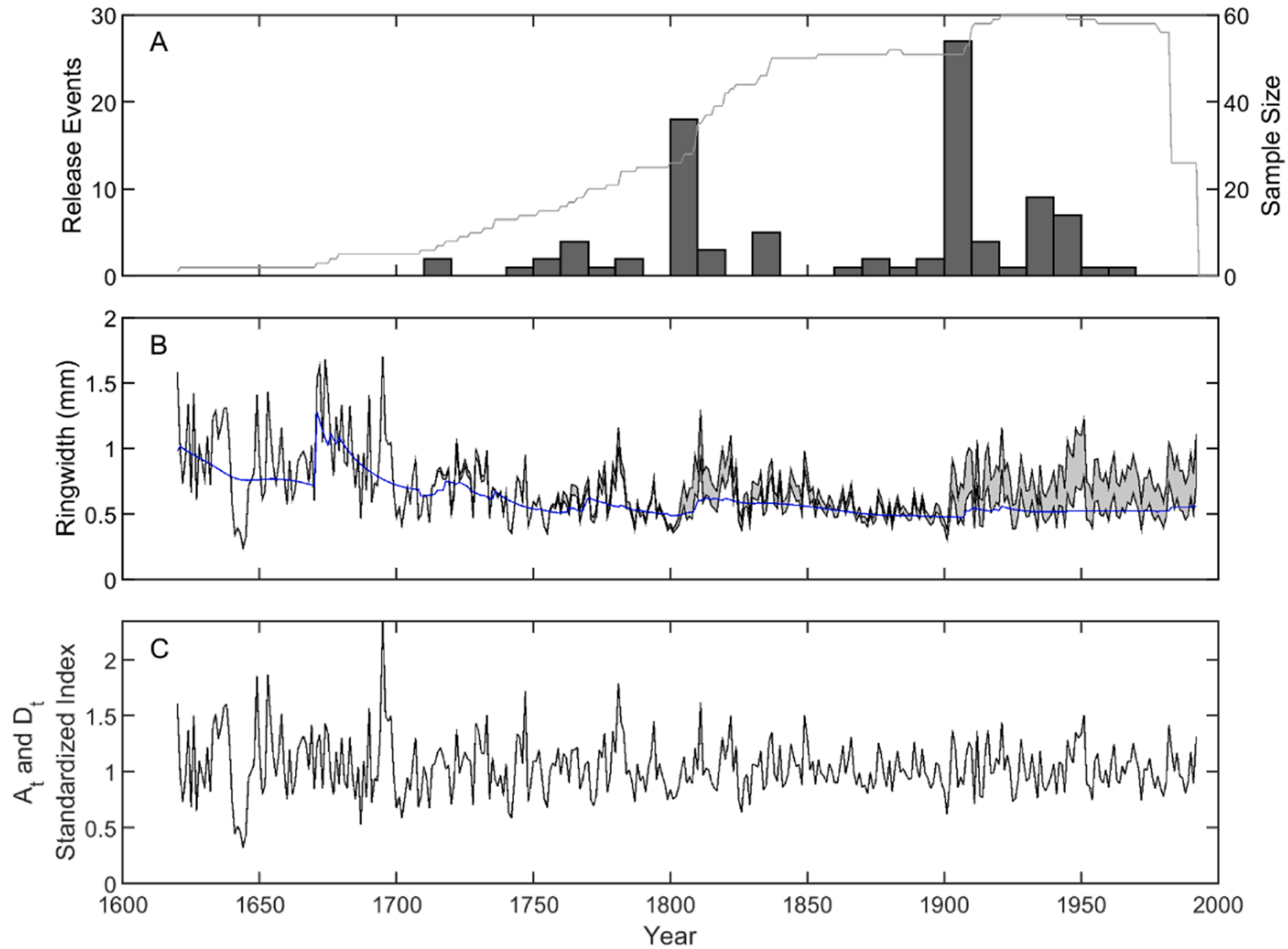

Fig. 3. Example *Quercus stellata* chronology from Democrat Ridge, Missouri, USA using the canopy disturbance detrending method with decadal histograms of canopy release events and gray line showing series sample size (A). Disturbance history chronology showing the difference of the initial average series values and the average disturbance-detrended ring widths with the gray shading representing the average disturbance growth increment across all series and an average age trend (blue line) fit to the disturbance growth series (B). Resulting climate index after removing age trends from the disturbance-detrended series for all post oak series (C).

3.2. Effect of detrending methods on climate-growth correlations

Both eastern hemlock and post oak ring-width chronologies using traditional negative exponential detrending, two-thirds spline, and our canopy disturbance detrending method showed significant correlations with monthly temperature or precipitation (Table 2. Current and prior year correlations are presented in Appendix Table A2 and time series comparison in Appendix Fig. A2). For the hemlock chronology, temperatures during March correlated significantly using all three detrending methods; however, higher magnitude correlations occurred with the disturbance detrended chronology whether considering months independently or averaged from January through March.

For the post oak chronology, the highest magnitude correlations occurred with May and June precipitation totals across all three detrending methods, but the canopy disturbance detrending method also correlated more strongly with these months than the other two methods. The canopy disturbance detrending method also had the strongest negative correlation with June temperatures.

Descriptive statistics of ring-width indices from both chronologies show that while the average interseries correlation (rbar) and estimated population signal (EPS) across the entire chronology is slightly lower using the modified negative exponential detrending, mean first-order autocorrelation is lower in the canopy disturbance detrending method (Table 3). Considering just the common interval with the climate data, rbar and EPS were both slightly higher with the canopy disturbance detrending method.

Wavelet coherence of the eastern hemlock chronology with and January-March mean monthly temperature showed an increase in significant correlations at periods between 8 and 32 years for the canopy disturbance detrending method compared with the other two detrending methods (Fig. 4). For the post oak chronology, wavelet coherence showed significant correlations at periods between 8 and 32 years across all three detrending methods (Fig. 5) with only a slight increase using the canopy disturbance detrending method. At both study sites, this correlation increase occurred more recently in the chronology, when more release events are also detrended using this method.

Table 2
Selected simple correlations between detrending methods and primary seasonal climate variables (sensu, Meko, 2011). showing significant relationships with total precipitation for a *Q. stellata* (1896–1992) ring-width chronology and with mean temperature for a *T. canadensis* ring-width chronology (1896–2004). *p ≤ 0.05.

	Total Precipitation			
***Q. stellata* Chronology**	**May**	**Jun**	**May-Jun**	
Modified Negative Exponential	0.303*	0.383*	0.443*	
Two-Thirds Spline	0.292*	0.412*	0.456*	
Canopy Disturbance	0.310*	0.475*	0.510*	
	Mean Temperature			
***T. canadensis* Chronology**	**Jan**	**Feb**	**Mar**	**Jan-Mar**
Modified Negative Exponential	0.161	0.180	0.224*	0.295*
Two-Thirds Spline	0.165	0.095	0.226*	0.253
Canopy Disturbance	0.249*	0.201	0.334*	0.409*

Table 3
Descriptive statistics of detrended ring-width indices from two study sites compared by detrending methods showing mean correlation between all series (rbar), estimated population signal (EPS), and mean first-order autocorrelation (AR1) for either the entire years of the chronology or for the interval in common with the climate data.

		Entire Chronology			Climate Interval	
Species	**Detrending Method**	**mean AR1**	**rbar**	**EPS**	**rbar**	**EPS**
Tsuga canadensis	Mod. Neg. Exp.	0.774	0.267	0.960	0.272	0.961
Tsuga canadensis	Two-Thirds Spline	0.650	0.286	0.963	0.290	0.964
Tsuga canadensis	Canopy Disturbance	0.518	0.286	0.963	0.298	0.966
Quercus stellata	Mod. Neg. Exp.	0.567	0.378	0.974	0.365	0.972
Quercus stellata	Two-Thirds Spline	0.425	0.430	0.979	0.453	0.980
Quercus stellata	Canopy Disturbance	0.241	0.432	0.979	0.457	0.981

4. Discussion

4.1. Advantages of canopy disturbance detrending

Climate correlations indicate that our new approach isolates climate signals from both a coniferous and a deciduous ring-width chronology as well as if not slightly better than previous methods. Canopy disturbance detrending shows a lower mean first-order autocorrelation and higher common signal (rbar and EPS) among ring-width indices than the other detrending methods suggesting that it is removing persistence from release events that obscure the underlying climate signal. Wavelet analyses show that our approach still retains low frequency variation in growth that is significantly correlated with low frequency variation of past climate. Wavelet coherence of the eastern hemlock population at the Palmaghatt Ravine revealed greater information at periods between 8 and 32 years than prior methods. Retention of a greater range of past climatic variation over varying time-scales is the predominant motivation of detrending methods in tree-ring analysis (RCS, modified negative exponential, etc). Here, in perhaps one of the more challenging forest types, disturbance regimes, and climatologies for the extraction of past climatic variation, the diverse and dense mixed-mesophytic forest, we find reasonable improvement from prior approaches. Notably, the Palmaghatt Ravine experienced a wide range of canopy disturbances and disturbance intensities over the last 140 years, a period upon which the entire calibration of tree rings into climatic information are made. This suggests that for the near term, past few decades, and prior century, our method made substantial improvements. For the post oak population in the drier region containing Democratic Ridge, we see only a slight improvement in the recovery of past growth variation as all three methods contain significant correlations with climate at periods between 8 and 32 years. The reasons for this are not clear, but could potentially be explained by environmental or species-specific differences. First, the more open-grown post oak canopy at Democratic Ridge might lessen the impact of changes in competition on climate signals (*sensu* Phipps, 1982). Second, temperature data may have more red-noise information than precipitation (Pelletier and Turcotte, 1997).

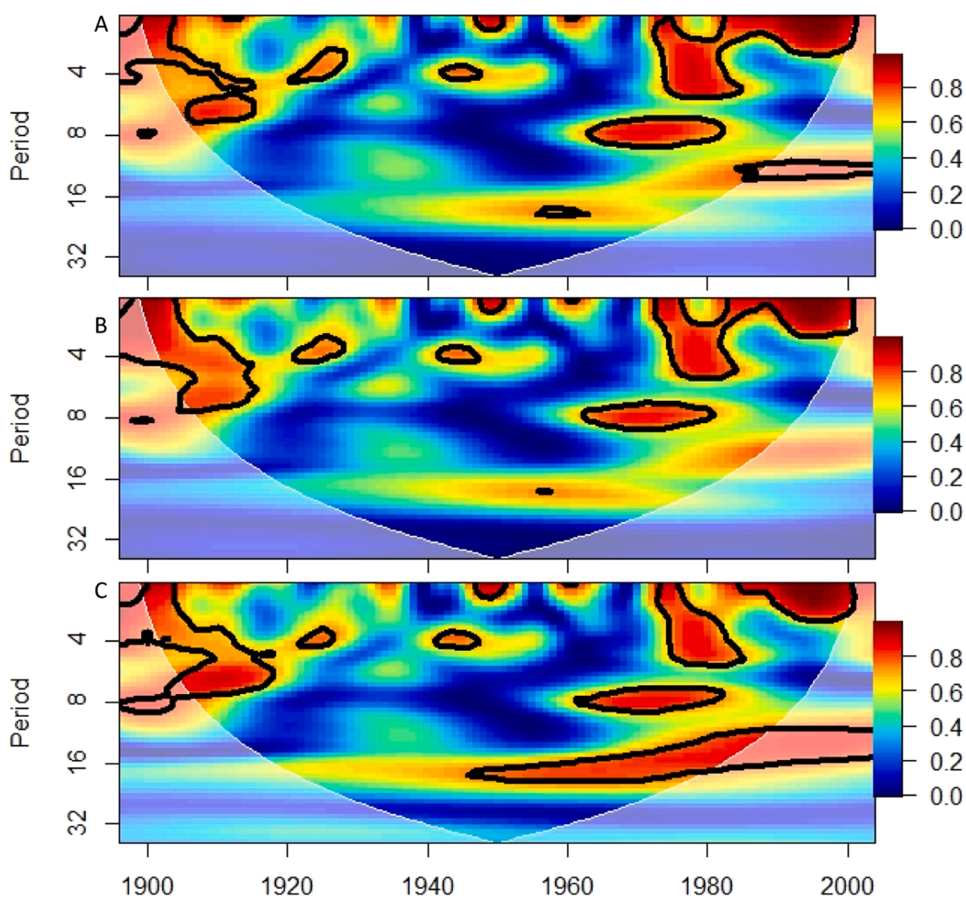

Fig. 4. Wavelet coherence between the *Tsuga canadensis* ring-width chronology and January-March mean monthly temperature from 1896 to 2004 using three detrending methods: Modified Negative Exponential (A), two-thirds spline (B), canopy disturbance detrending (C). After 1940, the correlation increases with the disturbance and age standardized chronology over periods of 8–32 years.

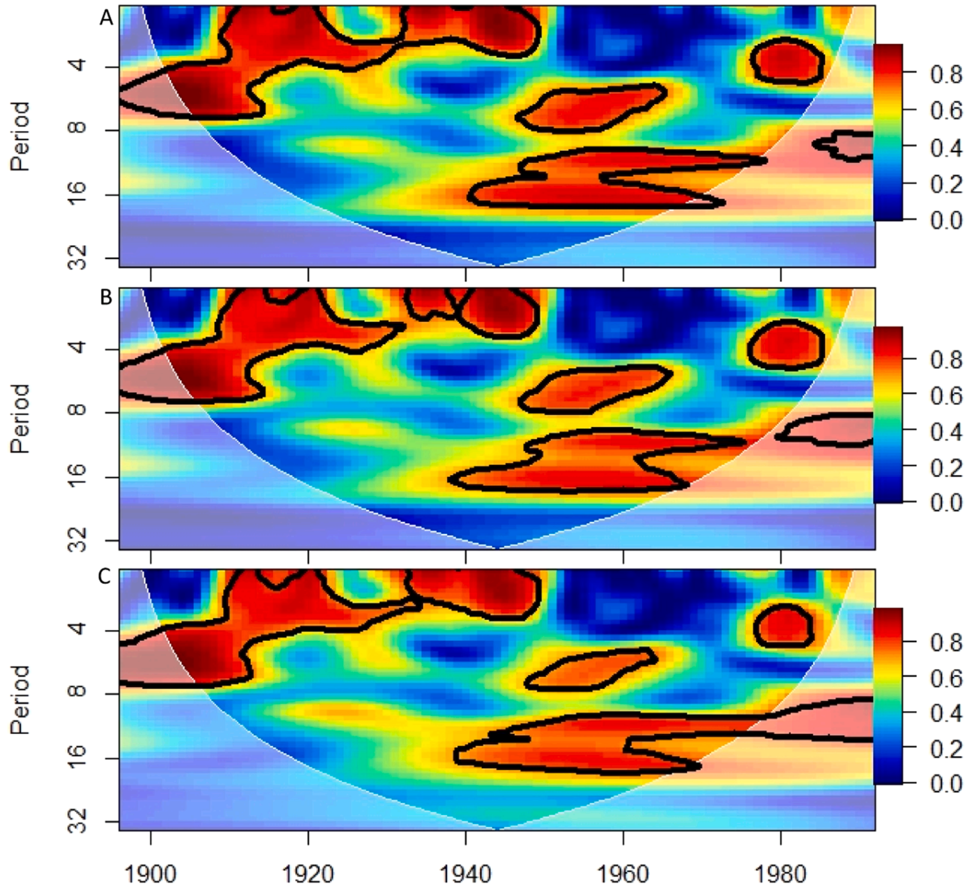

Fig. 5. Wavelet coherence between the *Quercus stellata* ring-width chronology and June-July total monthly precipitation from 1896 to 1992 using three detrending methods: Modified Negative Exponential (A), two-thirds spline (B), and canopy disturbance detrending (C). Correlations are similar between the three detrending methods with only a slight increase after 1940 over periods of 8–32 years with the disturbance and age standardized chronology towards the present.

Third, shade tolerant tree species, including eastern hemlock, have also been shown to respond more positively to canopy disturbance events (Jones et al., 2009) and canopy disturbance events were more frequently observed at Palmaghatt Ravine than at Democrat Ridge. We cannot be sure, but can envision experiments to determine the utility of our method in different forests with different densities, species compositions, and forest histories or testing using pseudoproxies with known disturbances. At this point with these data, we recommend our approach for the recovery of climatic signals and variations of growth patterns over a range of periodicities in closed-canopy forests.

4.2. *Comparing documentary and tree-ring forest disturbance histories*

The documented history of the Palmaghatt Ravine forests is broadly reflected in the eastern hemlock reconstruction of canopy disturbance history (Fig. 2). Extraction of hemlock for tanning likely led to the pronounced release events and subsequent recruitment beginning in the 1870s and continuing into the 1880s (Knickerbocker, 1937); chestnut blight and subsequent salvage logging to the releases in the 1920s and 1930s (Thompson and Huth, 2011; Huth and Smiley, 1985). Spongy moth defoliation may have led to the releases in the 1980s for hemlocks (Thompson and Huth, 2011), which may have been less impacted than oaks and thus able to increase their subsequent growth rate.

Conversely eastern hemlock trees as evergreens were likely severely impacted from the arrival of the Hemlock Woolly Adelgid and the November 2002 ice storm. The pronounced growth suppression during the subsequent growing season led to negative detrended growth values when re-expressed as ring-widths. Retaining transformed ring-width residuals in climate analyses would avoid this artifact in detrended series in addition to the advantages of residuals outlined in Cook and Peters (1997). The complexities of sequential canopy release events and canopy suppression within this forest make it challenging to detrend, but a useful example for evaluating our canopy disturbance detrending method.

Other studies of eastern hemlock in northeastern North America have found similar responses in release events and recruitment to canopy disturbance events (Abrams et al., 2000; Abrams and Orwig, 1996; Black and Abrams, 2005), particularly considering that eastern hemlock often lags in its growth response to canopy disturbance events. Carter et al. (2021) detected releases in 74–86% of hemlock trees within two years of a known harvest with a maximum growth rate occurring 6.8 ± 0.3 years after harvest. In a separate experiment, hemlock responded with a maximum growth rate within 5 years of harvest and most species responded with maximum growth rates within 3–15 years post-harvest (Jones et al., 2009).

In the post oak chronology, the ca. 1900 canopy disturbance recorded also aligns with intensive forest logging in the region (Cleaveland and Stahle, 1989). The ca. 1800 event is not documented and may have resulted from a natural disturbance event. These two canopy disturbances are the most pronounced events over the duration of this chronology. While the earlier canopy disturbance appears to have had more of a transient growth release on the chronology, the ca. 1900 event led to a sustained growth release in the chronology suggesting that these sampled trees obtained a dominant canopy position after this logging event.

4.3. Comparing tree-ring climate reconstructions from three detrending methods

This canopy disturbance detrending method isolated climate signals from both a coniferous and a broadleaf tree-ring chronology removing the effect of disturbances on tree growth and increasing its correlations with monthly climate variables at least as well as previous methods such as negative exponential curves and smoothing splines (Table 2). The climate signal of eastern hemlock at Palmaghatt is similar to a previous analysis using this species within the Shawangunk Mountains with a positive correlation with March temperatures but unlike that previous sampling, this chronology did not express a correlation with precipitation across prior and current months (Blasing et al., 1984; Cook and Jacoby, 1977). This difference may arise from the use of partial correlations in this analysis with the secondary precipitation variable, which reduce the influence of collinearity across climate variables (Meko et al., 2011). The post oak climate signal from Democrat Ridge with its positive correlations to May-June precipitation and negative correlations to June-Sept. temperatures aligns with other climate reconstructions from this species in the Ozarks (Cleaveland and Stahle, 1989; LeBlanc and Berland, 2019; Prolic and Goldblum, 2016).

Conceptually, these results also align with previous research showing that tree-ring series with release events had stronger climate reconstructions if the series was split into pre and post release segments that were separately detrended with splines (Blasing et al., 1983). However, this method detects and detrends the response of tree growth to canopy disturbance events by explicitly targeting adaptive splines to account for these aperiodic events within a time series.

4.4. Application of method

Intervention detection methods have shown the ability to minimize canopy disturbance events in climate reconstructions based on tree-ring widths (Rydval et al., 2017, 2016). Adding to this, we hope that this method will be more accessible to other existing tree-ring resources such as the dplR and TRADER packages in the R programming language (Altman et al., 2014; Bunn et al., 2022), which will broaden the applicability of this approach to explicitly quantifying disturbance and climate time series from closed-canopy forests.

Our method also has the flexibility to incorporate other canopy release detection methods and detrending methods for climate analysis. The Lorimer and Frelich (1989) settings could be adjusted or replaced with other release detection approaches as reviewed by Altman (2020). Similarly, canopy suppression events could also potentially be detected and detrended, assisting with estimating the impacts from ice storms as shown with the eastern hemlock chronology. Other detrending or growth increment functions could also replace an age-dependent spline for removing canopy disturbance or age trends. For example, regional curve standardization (Helama et al., 2017), could also be considered for removing age trends from disturbance-detrended series as they may more likely approximate growth patterns of open-canopy forests after removing the canopy disturbance signal.

Tree-ring widths respond to multiple external environmental forcing events including climate and canopy disturbance events. Quantifying the responses from these independent drivers of tree growth remains as important now (e.g., Anderson-Teixeira et al., 2022) as it did when Cook (1987) proposed the conceptual growth model. This method provides an integrative approach to partitioning tree growth that incorporates previously separate advances from dendroclimatology and forest ecology.

5. Conclusions

We present a canopy disturbance detrending method that combines radial-growth averaging with data-adaptive power transformation and age-dependent splines to detrend ring widths into explicit time series quantifying the effect of canopy disturbance and climate on tree growth. Building from previous research on intervention detection methods in tree-ring width series, this more straightforward and accessible approach disentangles canopy disturbance and climate signals from trees in closed canopy forests. Comparing with traditional dendroclimatic detrending methods of a negative exponential curve and a two-thirds spline, this method not only effectively resolves a past climate signal, but it also detects release events and generates time series of disturbance growth increments. Results from eastern hemlock and post oak chronologies indicate that this method should have potential applications in studies within closed canopy forests of either past climate or ecological interactions or studies that consider both of these factors that influence tree growth.

CRediT authorship contribution statement

Dario Martin-Benito: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology. **Edward R. Cook:** Writing – review & editing, Writing – original draft, Software, Methodology, Funding acquisition, Formal analysis. **Neil Pederson:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Data curation. **Daniel L. Druckenbrod:** Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A

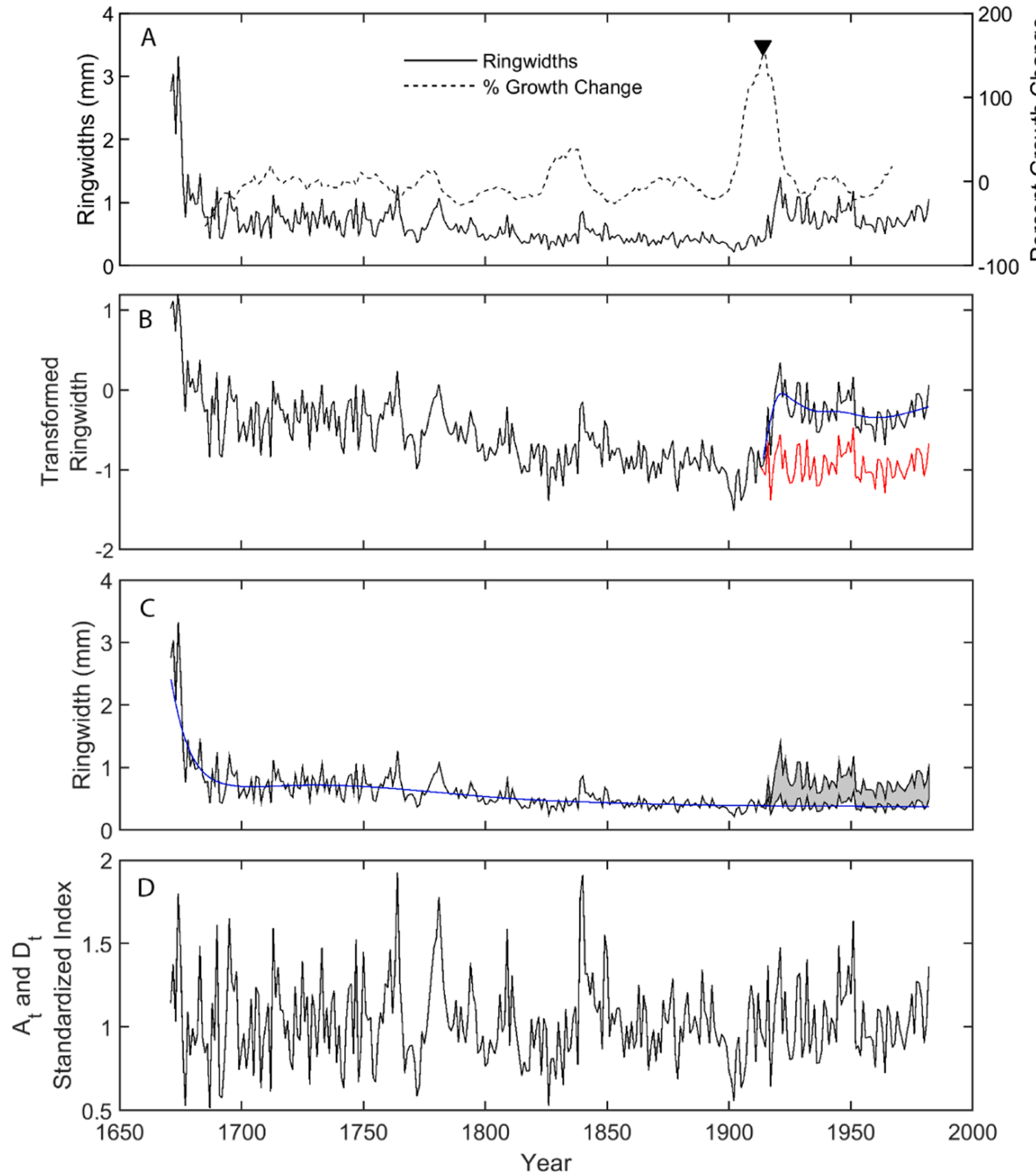

Figure A1. Canopy disturbance detrending of a post oak (*Q. stellata*) series from Democrat Ridge, Missouri, USA, with a release (triangle) detected in 1914 (A). Detrending using an age-dependent spline on power-transformed ring widths (B). Ring widths re-expressed in original units with initial ring widths shown by the upper line and the disturbance-detrended series represented by the lower line. Gray shading depicts the disturbance growth increment beginning after 1914 and fitting an age-dependent spline to the entire series (blue line) represents the age-trend (A_t) for this tree (C). Dividing the disturbance-detrended series by the age trend produces a series that is both age and disturbance standardized index values (D).

Table A1
Descriptive statistics of both ring-width chronologies.

Species	No. trees	No. series	Timespan (yrs)	Av. series length (yrs)
Tsuga canadensis	26	67	1683–2013	125
Quercus stellata	26	61	1620–1992	186

Table A2
Climate correlations extending from prior year through current year growing season for two example ring-width chronologies using the seascorr function in R package treeclim (Zang and Biondi, 2022) based on Meko et al. (2011). Significant months ($p \leq 0.05$) shown in bold. Eastern hemlock chronology shown by detrending method with av. temperature as primary response variable using simple correlations. Partial correlations with precipitation totals were not significant for any month with any method at this site.

		Prior Year Months					Current Year Months								
Method	**Var.**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
ModNegExp	TEMP	-0.042	-0.069	0.084	0.034	0.014	0.161	0.180	**0.224**	0.055	-0.068	0.124	0.102	0.025	0.035
2/3 Spline	TEMP	-0.150	-0.105	0.045	-0.019	-0.019	0.165	0.095	**0.226**	0.012	-0.125	0.048	0.036	-0.093	-0.009
Canopy Dist.	TEMP	-0.211	-0.151	0.058	0.091	0.061	**0.249**	0.201	**0.334**	0.054	-0.161	0.087	-0.003	-0.090	0.029

Post oak chronology shown by detrending method with precipitation totals as primary response variable using simple correlations and av. temperature as secondary partial correlations.

		Prior Year Months					Current Year Months								
Method	**Var.**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
ModNegExp	PRCP	**0.273**	0.000	0.058	0.026	0.003	0.205	0.148	0.051	0.082	**0.303**	**0.383**	0.006	0.180	-0.016
Spline	PRCP	**0.305**	0.020	0.030	0.001	-0.024	**0.257**	0.148	0.087	0.112	**0.292**	**0.412**	0.014	**0.209**	0.007
Canopy Dist.	PRCP	**0.287**	-0.008	0.043	0.047	0.004	**0.281**	0.147	0.162	0.098	**0.310**	**0.475**	-0.005	0.179	-0.025
ModNegExp	TEMP	-0.188	-0.198	0.119	0.048	-0.015	-0.075	0.165	0.027	-0.119	-0.027	**-0.334**	**-0.275**	**-0.260**	**-0.317**
2/3 Spline	TEMP	-0.161	-0.171	0.127	0.119	-0.016	-0.039	0.115	0.084	-0.138	-0.022	**-0.349**	**-0.283**	**-0.225**	**-0.266**
Canopy Dist.	TEMP	**-0.201**	-0.182	0.178	0.065	-0.032	-0.063	0.103	0.043	-0.162	-0.002	**-0.391**	**-0.274**	**-0.259**	**-0.279**

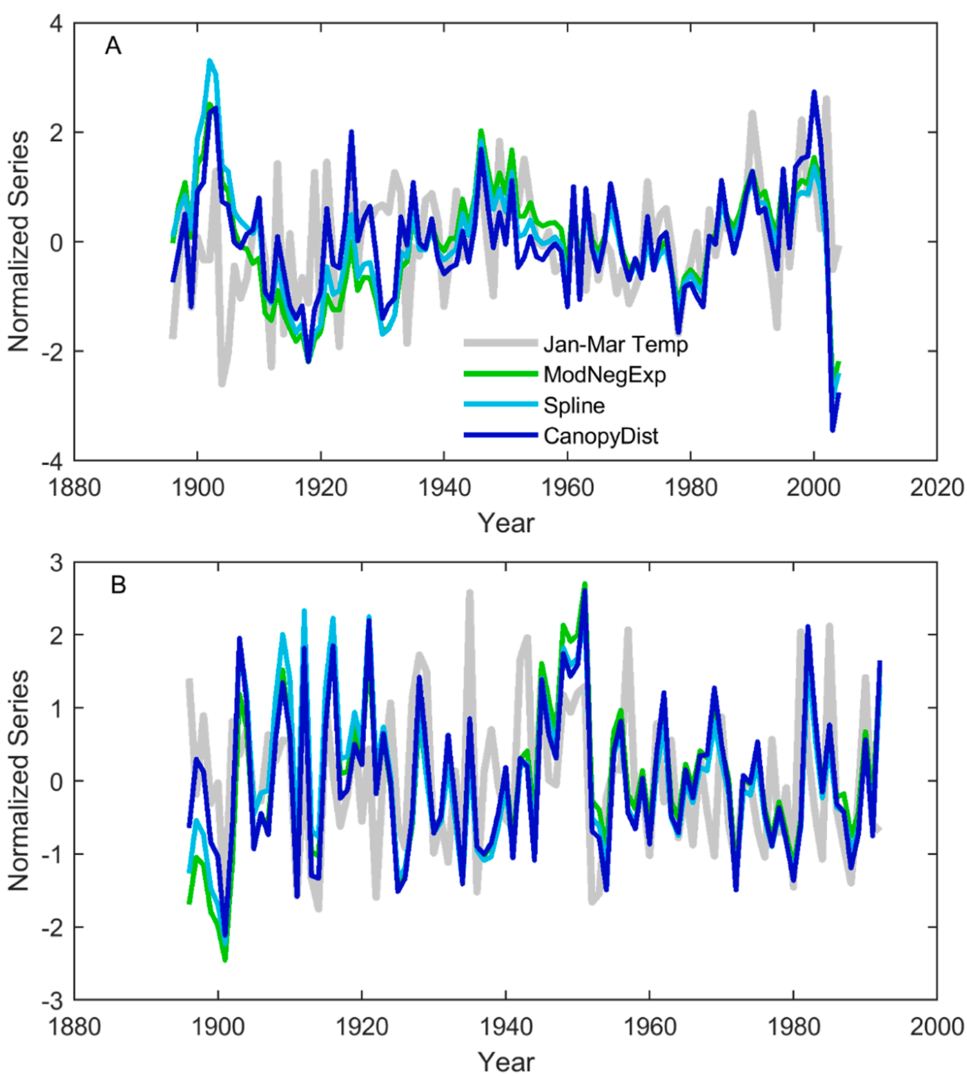

Figure A2. Normalized time series of detrended ring-width chronologies and seasonal climate variables: eastern hemlock with January-March average temperature (A) and post oak with May-June total precipitation in gray (B).

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