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RESEARCH ARTICLE

Using dendroclimatic analysis of exotic deciduous conifers in an arboretum to document tree growth in response to climate change, Northeast Ohio, USA

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Societal Impact Statement

Rising temperatures and wetter conditions in the Midcontinent of North America are influencing climate responses in trees. Dendroclimatological analyses of four exotic deciduous conifer species from Secrest Arboretum, Northeast Ohio help identify past, present, and future climate-tree interactions. Analyses suggest that two larch species have changed their response to climate, whereas dawn redwoods and bald cypress trees are well suited for the present and future climate. This study elucidates tree responses to climate gleaned from a largely untapped source of tree growth in arboreta that can be more broadly applied at other sites as well as facilitate forest management decisions.

Summary

- Dendroclimatic analysis of arboretum grown trees is an underutilized tool that can yield vital information on the climate response of exotic tree species. Four species of exotic deciduous conifers growing in Secrest Arboretum, Wooster, Northeast Ohio (NEO), USA, over the past century offer a unique opportunity to examine the climate response of trees growing in climates outside their natural ranges.
- This dendroclimatic study of well-replicated ring-width series coupled with comparisons of tree growth with monthly climate records provides information into those exotic species that may be well suited for plantings in NEO.
- Results show that the two larch species from Asia and Europe (*Larix decidua* and *Larix gmelinii* [Rupr.] Kuzen) have been limited primarily by summer precipitation, although this relationship is fading since a wetting trend began in the mid-1970s. Exotic stands of bald cypress from the American Southeast (*Taxodium distichum*) and dawn redwood from China (*Metasequoia glyptostroboides*) maintain a positive robust precipitation response that persists through the present, in contrast to the larch. Dawn redwood are also limited by maximum summer temperature, which could intervene to limit their growth in the future. Bald cypress' positive

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temperature and precipitation response makes it adaptive to NEO climate trends consistent with the native range of the species.
- Taken together, this study on deciduous conifers is an example of tree response to climate gleaned from a largely untapped source of tree growth in arboreta that can be more broadly applied at other sites.

KEYWORDS
arboretum, climate change, deciduous conifers, ecosystem services, tree rings

1 | INTRODUCTION

Arboreta and botanical gardens are laboratories uniquely set up to examine the relationship between tree-growth and climate change (Cedro et al., 2021; Chrobak, 2016; Moore et al., 2007; Primack et al., 2021; Schulman, 1944; Vargo et al., 2020; Westwood et al., 2021; Wilczyński & Skrzyszewski, 2003). However, despite significant advances in research, these collections are still underutilized in climate change studies (Hirons et al., 2021; Primack et al., 2021). Given that arboreta have a growing part in securing plant diversity for adaptation and resilience (Mounce et al., Smith, 2019), investigating tree-climate relationships for maximizing forest management is increasingly vital and within the concept of "climate-smart forests" (Bonan, 2008, 2023). This relatively new concept seeks to evaluate and optimize the ecosystem services provided by trees, including identifying the mechanisms that mitigate: (1) heat islands in developed areas, (2) global warming through carbon sequestration, and (3) stormwater runoff in urban settings (Andresen et al., 2012; NEORSD, 2019). An evaluation of ecosystem services (i.e., c-sequestration, shade, habitat, and stormwater management) of trees from Northeast Ohio (NEO) necessitates a knowledge of the interactions among variables such as climate, pathogens, management, as well as forest and land use history (Pederson et al., 2015; Swanston et al., 2018; Thom et al., 2018).

Generally, researchers compare the relative roles of either broadleaf angiosperms or evergreen conifer species when investigating ecosystem services in forests (Bonan, 2023). These studies include the deciduous conifers as part of the larger ecosystems, and this is understandable as few stands of extant deciduous conifer-dominated forest are represented on the planet today (Taggart & Cross, 2009). The deciduous conifer genera considered here (*Larix*, *Metasequoia*, *Taxodium*) were a major part of the high latitude Northern Hemisphere (>80°N) forests during the Eocene Epoch (40 to 50 million years ago; Jahren, 2007; Eberle & Greenwood, 2012). This geological interval was a time of elevated carbon dioxide levels (more than two times the present levels of ~425 ppm; CenCO2PIP [2023]). Eocene paleoforests from Axel Heiberg Island, Nunavut Territory, Canada, were dominated by the dawn redwood with tree heights estimated as high as 40 m (Williams et al., 2003). In these far northern sites, trees experienced a remarkable range of seasonal variations in day length and insolation, suggesting the taxa are resilient and that future plantings could similarly persist and thrive in a warmer, higher CO_2 future greenhouse world. Furthermore, the carbon sequestration of these paleo-forests has been estimated to be comparable to modern old growth forests of the Pacific Northwest of the US and coastal Cordillera forests of southern Chile (Williams et al., 2003), as well as comparable to swamp-cypress forests of modern southeastern USA (Eberle & Greenwood, 2012). Today, large sections of the boreal forest in Asia and, to a lesser extent, in Europe and North America are composed of a significant population of *Larix* species (Mamet et al., 2019).

Deciduous conifers have received less attention despite their wide range of useful attributes, including their ability to thrive in marginal habitats (wetlands, rocky soils, arid locations, and mine reclamation sites), their minimal contribution to seasonal leaf biomass in urban settings, their unique esthetic in landscapes, and resilience to wind (Qu et al., 2022; Salisbury et al., 2025). Bald cypress and dawn redwoods are widely planted, whereas the two larch species included here have received relatively less attention in North America (Qu et al., 2022).

1.1 | Study area

Secrest Arboretum in Wooster, Ohio is located on the Wooster campus of the College of Food, Agricultural, and Environmental Sciences (CFAES) of the Ohio State University (Figure 1). Established in 1909, in part, to reforest Ohio after it had lost over 90% of its forest cover during European settlement (Deines et al., 2016; Trautman, 1977), the Arboretum was dedicated to and named after Edmund Secrest in 1950, who was the first director of the then Agricultural Research Station in Wooster and the first Forester of the State of Ohio. The College of Wooster Tree Ring Lab (WTRL) has been working at the arboretum for the past several years (Moore et al., 2007; Vargo et al., 2020; Wiles et al., 2025), and here, we summarize the climatic response of four deciduous conifer tree species, all four are exotic, two of which are larch species from Asia and Europe (*Larix decidua* (EL) and Larix gmelinii (Rupr.) Kuzen (DL)), one from China (dawn redwood [DR]; *Metasequoia glyptostroboides*), and one from the American Southeast, Bald Cypress (BC; *Taxodium distichum*). The trees were planted between 1909 and 1953, and the sample size of each tree-ring series in the ring-width chronologies generated here is determined by the trees originally planted (Table 1). The soils in the arboretum are dominated by silty loams formed on glacial topography capped by loess as the parent material. The DR, DL, and BC stands

were all planted at the base of slopes and are fed, in part, by natural springs, whereas the EL sites are located in a more dry, upland setting (Figure 1).

1.2 | Species background

European larch is one of the most economically important coniferous species in Europe and is commonly found in mountainous regions of Central Europe (the Alps, Sudetes, and Carpathians). Its natural range spans 40–60° N, 5–30° E (European Forest Genetic Resources Programme (EUFORGEN), 2019, Qu et al., 2022) and grows best at altitudes generally between 1000 to 2000 m; however, it can be found as higher than 2000 m, where it can grow beyond the natural range of its competitors (Matras & Pâques, 2008). As a pioneer species, it is one of the first trees to colonize open land after disturbance and thus, it is often considered in reforestation projects and has been widely planted across Europe (Matras & Pâques, 2008; Pietrzykowski, 2019). It is an important species for climate reconstruction (Frank & Esper, 2005) and in documenting insect outbreaks (Büntgen et al., 2009; Esper et al., 2009). The species has also been planted in North America in Pennsylvania, Ohio, and West Virginia for revegetation of surface mine sites (Sullivan, 1994).



FIGURE 1 (a) Map showing the location of the Secrest Arboretum and the location of individual tree sites in Secrest arboretum (EL = European larch, DL = Dahurian larch, DR = Dawn redwood, BC = bald cypress). The location of the College of Food, Agriculture and Environmental Sciences Weather Station is also shown.

European larch is generally slow growing in its native range as the climate is cooler and drier than conditions in NEO (Obojes et al., 2018). However, montane sites within its native range are warming and, in some cases, becoming wetter (Obojes et al., 2018). Thus, the climate response of this species based on the comparison with the local NEO monthly precipitation can yield insights into the future of the native population, in assessing how climate change might affect this species, and in informing its utility in reforestation and land reclamation in North America.

The natural range of Dahurian larch extends from Siberia's Yenisei Valley east to the Kamchatka Peninsula in the Russian Fareast and into neighboring Mongolia and China (40–73°N, 90–150°E). In its natural range, Dahurian larch is a keystone species of the Boreal forest in Eurasia, the second largest biome in the world. It is a dominant tree of the Chinese boreal forest, which is distributed primarily in northeast China. Dahurian larch forests are also the predominant timber source in China, occupying 55% of Chinese boreal forest area and accounting for 75% of Chinese boreal forest volume (Jia & Zhou, 2018; Qu et al., 2022). Understanding the climate response of this species is critical for forestry management and for anticipating future forest growth in the region (Berner et al., 2013).

Dawn redwood is of interest, in part, because of its remarkable history of its new scientific discovery and planting in North America. Many scientists thought the tree only existed in the fossil record, which dated back to the Late Cretaceous (LePage et al., 2005) and subsequently was "discovered" (Hu & Cheng, 1948; Ma, 2003) living in China, which was then followed by significant plantings across Europe and North America. Less than 6000 individuals are thought to comprise the native population in Hunan, Hubai, and Sichuan provinces in south-central China (Tang et al., 2011). They occur between 800 and 1500-m elevation in their native range, growing in mesic

TABLE 1 Four ring-width chronologies and their attributes, Secrest Arboretum (Corr. = interseries correlations; Sens. = sensitivity; auto. = autocorrelation; EPS = expressed population signal).

Site	Species	Cores/trees	Span (years)	Corr.	Sens.	Auto.	Interval (EPS > 0.85)
EL	*Larix decidua*	121/72	1915–2019	0.55	0.36	0.80	1915–2018
DL*	*Larix gmelinii*	25/7	1931–2005	0.70	0.36	0.66.	1935–2005
DR	*Metasequoia glypt*.	32/19	1955–2010	0.62	0.38	0.60	1957–2009
BC	*Taxodium distichum*	31/28	1914–2020	0.55	0.44	0.72.	1917–2020

*This stand of trees was lost to storm damage.

temperate climates. Plantings in North America resulted in thriving populations from Montreal, Canada, to New Orleans, to Sitka, Alaska, in the United States. In some cases, they grow 30 m within 50 years (Williams, 2005). This introduced species not only has a novel history, but provides ecosystem services that include carbon sequestration, stormwater management, and it also has an esthetic value as a deciduous conifer (Salisbury et al., 2025; Tang et al., 2011).

Bald cypress (BC) trees are a slow-growing, long-lived species native to the southeastern United States, which favor humid regions with intermittent flooding. They thrive in areas that receive high amounts of precipitation, between 1120 and 1630 mm (Wilhite & Toliver, 1990). They also exhibit novel structures in their root zone in the form of knees that may serve, in part, to stabilize the trees, exchange gases, store carbohydrates or serve some other purpose, although their function remains enigmatic (Briand, 2000). These trees effectively absorb water and have been planted to prevent the spread of pollution by anchoring soils to prevent loss to erosion (Conner et al., 1986).

Growing in and along flowing water such as river floodplains, stream banks, and lake shores, these tree species are well suited for settings designed for wetland remediation, wildlife habitat, recreation areas, wastewater recycling, flood control, and groundwater recharge areas. Furthermore, BC have a strong potential role in stormwater management and carbon sequestration. The species is windfirm, able to resist high winds associated with hurricanes in part because of their strong buttressed structure. Additionally, it has a strong commercial value due to the natural rot resistance of the wood; however, it has been labeled "the forgotten opportunity" with respect to timber (Williston et al., 1980) in part due to the swampy areas in which it is found and the relative inaccessibility of sites for timber extraction.

Somewhat counterintuitive with BC growing in wet lowland riparian settings, it also has a strong response to precipitation variability as is well documented by the extensive paleoclimate work (Stahle & Cleaveland, 2000). Individual trees live for greater than 1000 years, and this longevity along with its precipitation sensitivity has made it a crucial species for paleoclimate studies and drought reconstruction in the south and southeast (Cleaveland, 2010; Cook et al., 1999; Stahle & Cleaveland, 2000).

1.3 | Objectives

In Ohio the ongoing and future climate conditions include warming, increased precipitation, and storminess (Anderegg et al., 2020). Although these deciduous conifer species from Secrest Arboretum are specific to these climate conditions, our aims in this study are more general. First, we aim to show that dendroclimate analyses in arboreta can be more widely applied to other sites, each with unique climates and species assemblages. Second, we emphasize that such dendroclimatic studies are natural experiments given that the exotic species will experience future climate change in their present natural ranges and thus tree response can be better anticipated; and finally, we explore which of these exotic species growing in Ohio are best suited for anticipated climate change in the region.

2 | MATERIALS AND METHODS

Tree-ring records are exactly dated records with annual resolution that integrate a range of environmental information in their widths (Speer, 2010). These time series can be statistically evaluated by comparing ring-width time series with meteorological climate records to identify the climatic variables important for tree growth (Cook & Kairiukstis, 1990). Results can then be interpreted as (1) an evaluation of forest health and an assessment of future response of trees to anticipated climate changes, (2) an estimation of forest carbon capture and storage (Evans et al., 2022), and (3) a record of past environmental and climate change (Speer, 2010) among other inferences.

In Secrest Arboretum, trees were cored at breast height using a standard 5.1-mm increment borer, taking 2–3 cores from each tree. Cores were glued into wooden mounts and sanded to a high polish so individual cells in the rings were visible (Figure 2). Ring-widths were then measured to the nearest 0.001 mm manually using a Velmex stage Quick Check counter and the program MeasureJ2X, or digitally using high-resolution scans uploaded to the computer program CooRecorder 9.8.1 (Cybis, 2022, http://cybis.se/forfun/dendro/index.htm; Maxwell & Larsson, 2021). Ring-width series were then cross-dated using standard dendrochronological procedures (Stokes &

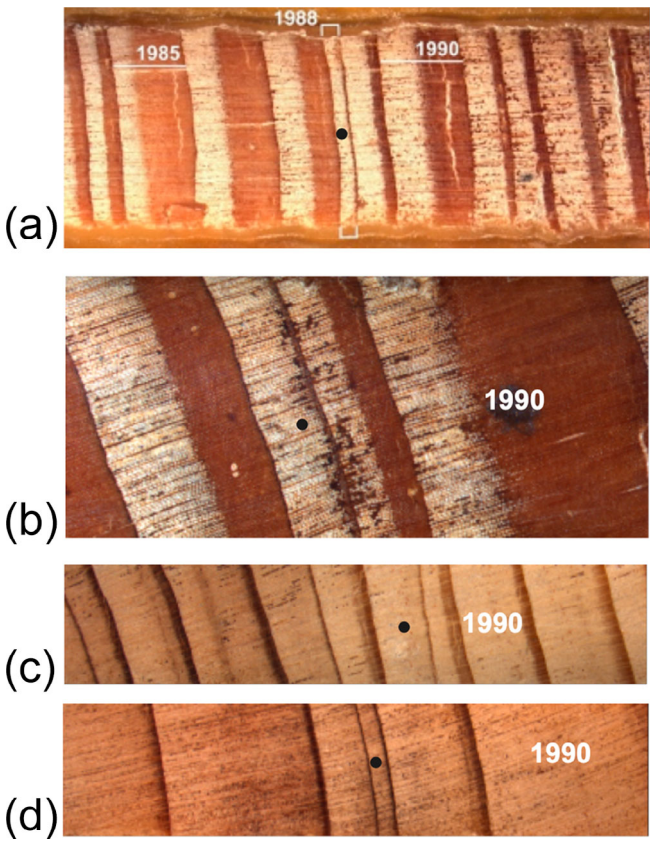


FIGURE 2 Photomicrographs of (a) Dahurian larch (DL), (b) European larch (EL), (c) Dawn redwood (DR). (d) Bald cypress (BC), note the false rings. All show the 1988 drought marker year (black dots), which are narrow rings and/or light density latewood years. The outer (more recent) rings are toward the right.

Smiley, 1996). Visual and statistical cross-dating was checked using COFECHA (Holmes, 1983), a cross-dating quality control computer routine. Unique marker years in the tree-ring series were also identified and used in cross-dating (i.e., Figure 2).

Once cross-dated, individual tree-ring series were compiled into ring-width chronologies (Figure 3) by first standardizing each series, converting ring-width measurements to dimensionless ring-width indices using ARSTAN (Cook, 1985) before calculating a robust estimate of the mean value function. For the Arboretum sites, the standardization involved the removal of a biological growth trend using primarily an age-dependent spline and, in the case of a poor fit, for about 2% of the series, we used a Friedman super smoother

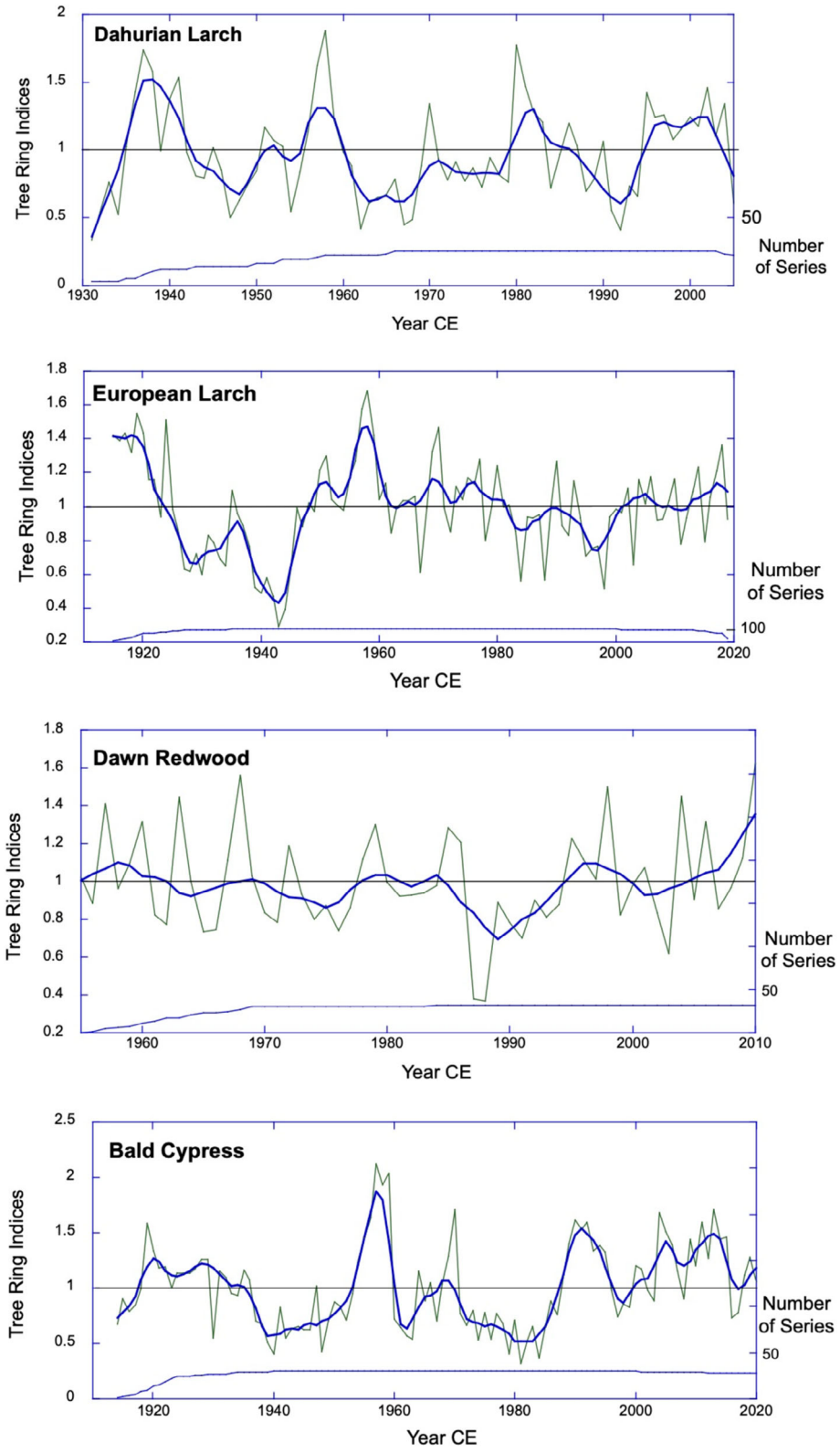


FIGURE 3 Plots of tree-ring-width indices and sample size from Secrest Arboretum. EL = European larch, DL = Dahurian larch, DR = Dawn redwood, BC = bald cypress.

function (Friedman, 1984; Friedman & Silverman, 1989) with an alpha of 5. This latter function was used primarily in the case of larch ring-width series that have released their growth in response to the loss of adjacent trees.

The climate datasets used are monthly precipitation and maximum, minimum, and mean temperature records from the Wooster station (Applequist et al., 2024), which is located within 1 km of the tree sites in the Arboretum (Figure 1). This meteorological station (Figures 1 and 4) was established in 1866 and records show that the mean, minimum temperatures, and precipitation in most months, and the frequency of large precipitation events have all increased, while maximum summer temperatures have decreased (Basso

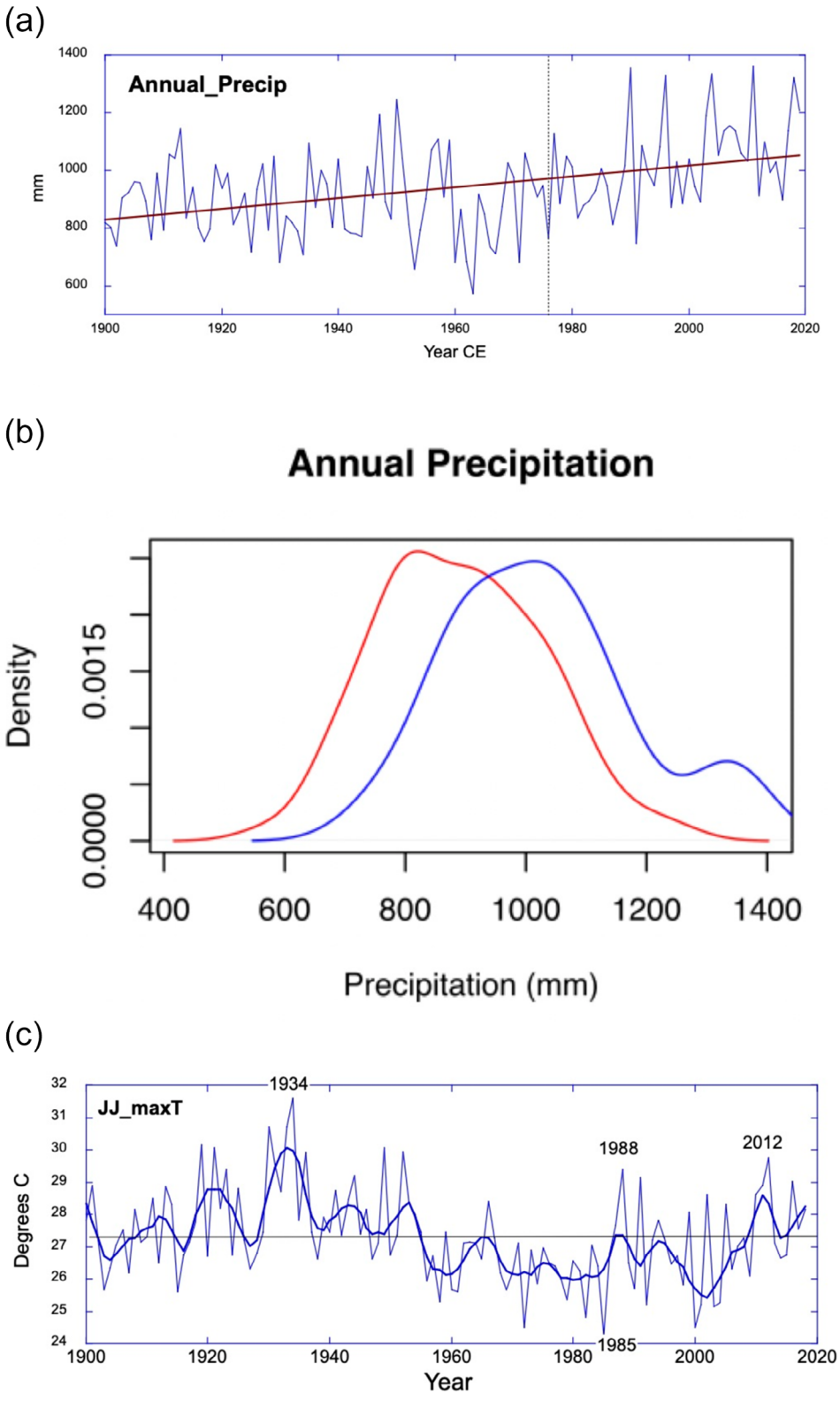


FIGURE 4 Selected climate parameters from the Secrest station since 1900. (a) Mean annual precipitation, note how the increase in annual precipitation is almost 300 mm in the past 120 years and with the largest gains occurring since 1975. (b) Density plots for the interval before 1976 (red) and after 1976 (blue) showing the change in mean and distribution before and after this interval. (c) Average June/July maximum temperatures (JJ_maxT) showing an overall decrease since 1900 and the decadal variability in the record. Years with high maximum temperatures (1934, 1988, and 2012) correspond with the largest droughts in the region. Comparisons of these datasets are made with tree-ring sites.

et al., 2021). Since the trees were planted between 1908 and 1954 (Table 1), we truncated the climate datasets at 1900 CE after which there are no missing values in the monthly datasets. These datasets have been vetted in our previous dendroclimatic studies (Wiles et al., 2025).

Mean annual precipitation has increased more than 20 cm over the past century (Figure 4a,b). Mean annual temperature also has a positive trend of about 0.5°C, with the increase in minimum temperatures accounting for most of the warming in the region. There is an overall cooling since 1900 in the maximum temperatures for the summer months (June–July maximum temperatures [JJ_maxT]) (Figure 4c). Superimposed on this downward trend is a strong decadal variability (Figure 4c) that ranges by more than 6°C. The highest JJ_maxT occurred in 1934, the driest year in the past several hundred years for much of the continental United States (Cook et al., 2014). Other notable high JJ_maxT years include the marked drought of 1988 (Rogers, 1993; Figure 2) and 2012 (Figure 4c); the coolest maximum summer temperature value on record is also one of the wettest in 1985 (Figures 2 and 4c). For the Wooster climate station data, the JJ_maxT and JJ_Precip are correlated at −0.27 ($p < 0.004$) with one another over the full 118 years of record. This negative relationship is well documented (Zhao & Khalil, 1993) with high temperatures generally accompanying lower summer precipitation and cooler summers associated with higher rainfall.

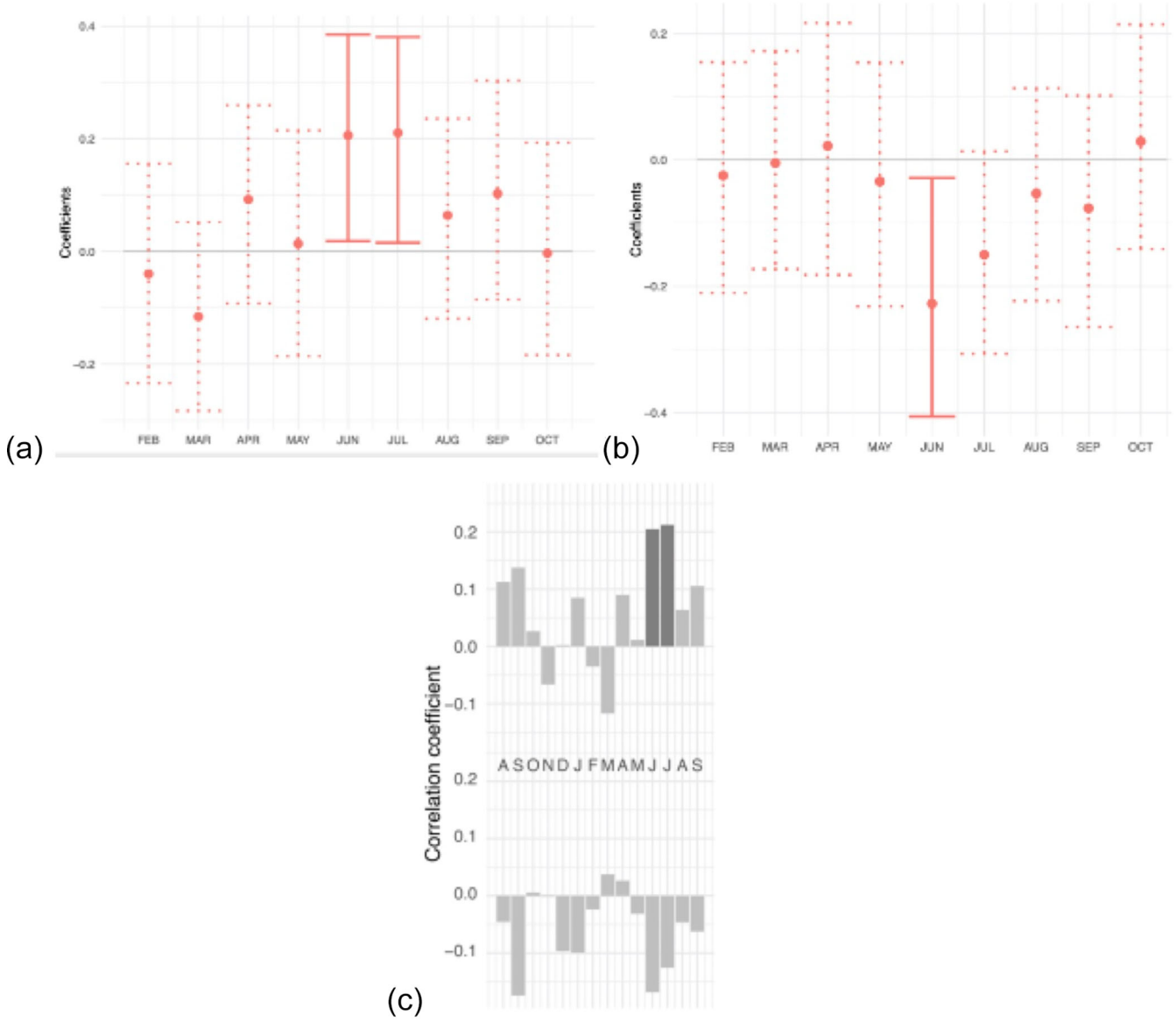


FIGURE 5 Climate response diagrams for European larch. For each series the upper histograms (a,b) show the monthly correlations with precipitation (a) and temperature (b), solid bars are significant at the 95% confidence level. The ranges shown are 1000 bootstrapped runs for each month. Because of the intercorrelation between the maximum temperatures and precipitation partial correlations for each of the sites are also shown. Partial correlations (c) are also shown based on SEACORR analysis (Meko et al., 2011) as translated in R code (Zang & Biondi, 2015). Bold bars on the histograms are significant at the 95% confidence level.

For the climate analyses we examined the portion of the tree-ring intervals in each chronology with an EPS of >0.85 (Wigley et al., 1984; Table 1) a conventional measure of sufficient sample size to provide a robust representation of the overall population. We used the *dplR (v.1.7.8), Treeclim (v.2.0.7.1)* packages in R-Studio (Bunn, 2008, 2010; R-Core Team, 2020; Zang & Biondi, 2015). Monthly bootstrapped correlations (Figures 5–8a, b) for each series are presented along with moving correlations (Figure S1). Due to the intercorrelation of summer precipitation and maximum temperatures, we also used the *seascorr* function in *Treeclim* for partial correlation analyses (Figures 5–8c) to analyze the relative roles of these climate parameters in tree growth (Meko et al., 2011). Moving correlations between ring-width and targeted monthly climate data help to identify the timing of changes and to detect nonstationary climate responses in the trees (Figure 9).

3 | RESULTS

The four ring-width series from the Arboretum have strong common signals within each of the chronologies with correlations

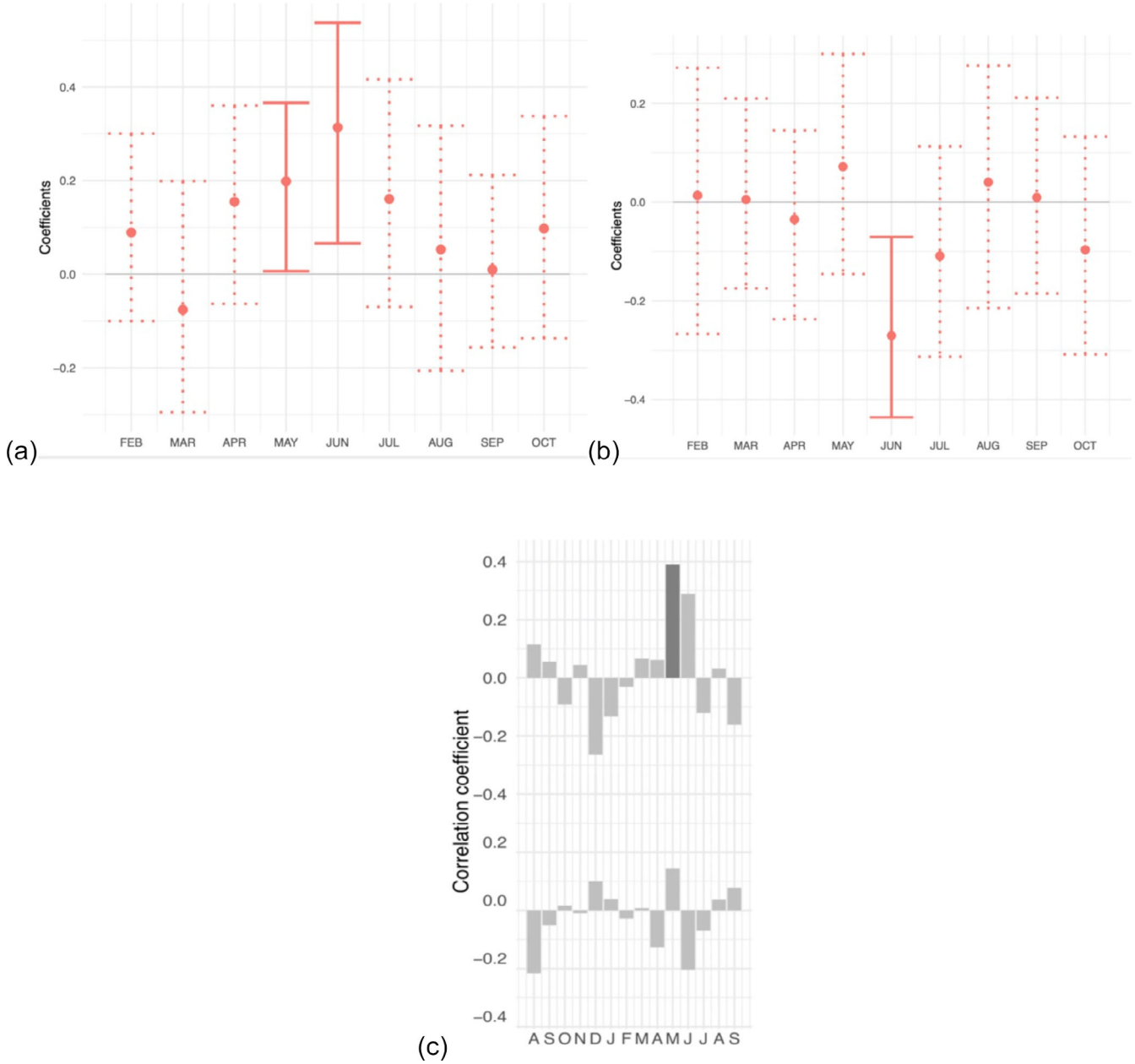


FIGURE 6 Climate response diagrams for Dahurian larch. For each series the upper histograms (a,b) show the monthly correlations with precipitation (a) and temperature (b), solid bars are significant at the 95% confidence level. The ranges shown are 1000 bootstrapped runs for each month. Because of the intercorrelation between the maximum temperatures and precipitation partial correlations for each of the sites are also shown. Partial correlations (c) are also shown based on SEACORR analysis (Meko et al., 2011) as translated in R code (Zang & Biondi, 2015). Bold bars on the histograms are significant at the 95% confidence level.

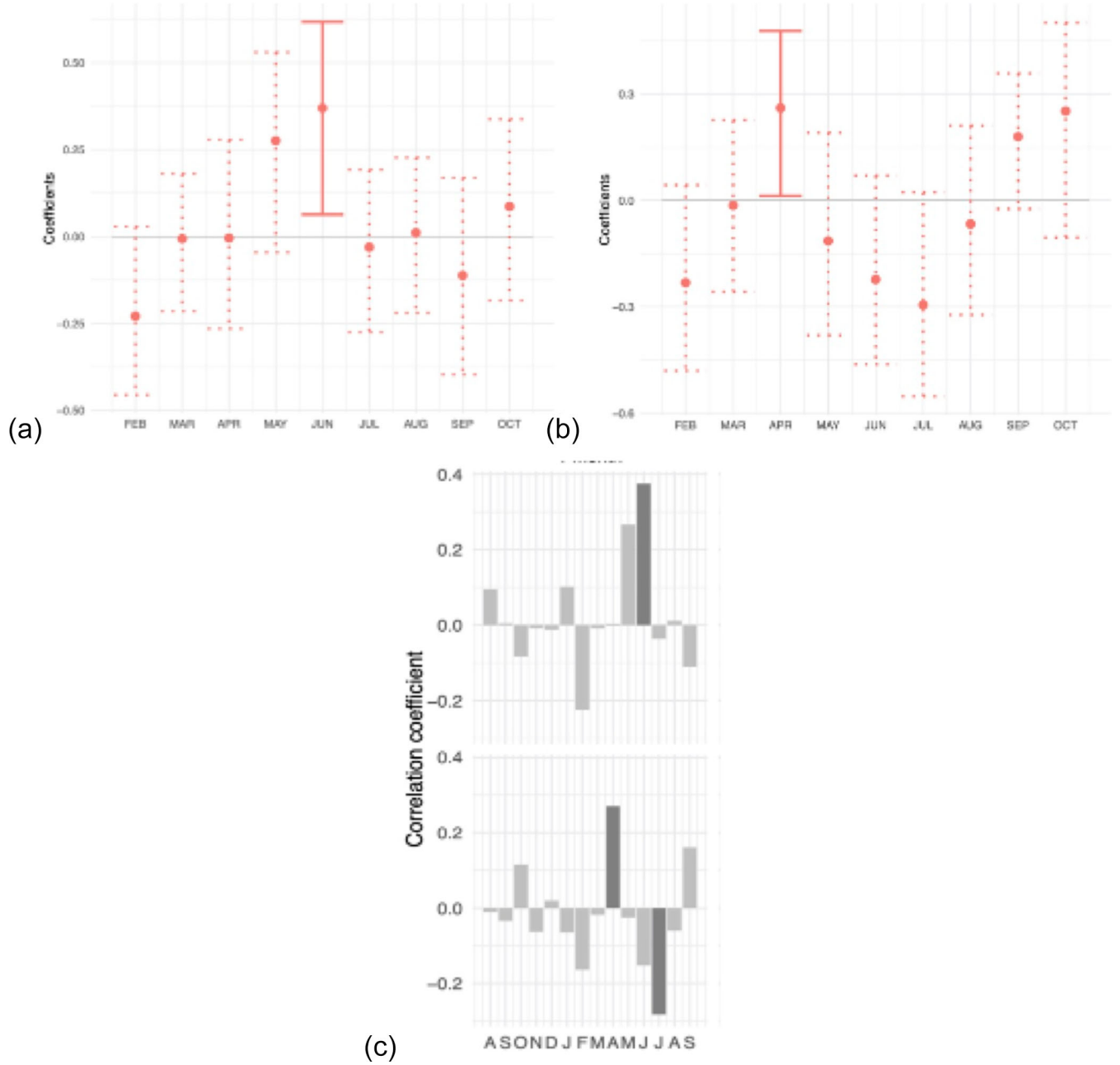


FIGURE 7 Climate response diagrams for dawn redwood. For each series the upper histograms (a,b) show the monthly correlations with precipitation (a) and temperature (b), solid bars are significant at the 95% confidence level. The ranges shown are 1000 bootstrapped runs for each month. Because of the intercorrelation between the maximum temperatures and precipitation partial correlations for each of the sites are also shown. Partial correlations (c) are also shown based on SEACORR analysis (Meko et al., 2011) as translated in R code (Zang & Biondi, 2015). Bold bars on the histograms are significant at the 95% confidence level.

ranging from 0.55–0.70 (Table 1). When comparing the four ring-width series with one another, correlations range from 0.07–0.43 (Table S1) between the species with the two larch species correlating at 0.43, The relatively low correlations between series suggest tree species are responding to different climate parameters. The following section presents individual climate analyses for each of the species in turn, building on the brief background on their ecology and utility in ecosystem services from Section 1.2.

3.1 | European larch (*L. decidua* Mill.)

Seventy-eight increment cores were extracted from 38 trees at three individual stands (EL; Figures 1 and 3a) within Secrest Arboretum. One of the EL stands consisted solely of larch; the other two are partially mixed with Norway spruce. Limited undergrowth and the even spacing between the trees allowed for relatively little competition from surrounding vegetation. European larch tree rings have well-defined earlywood and latewood structure (Figure 2a) with marked

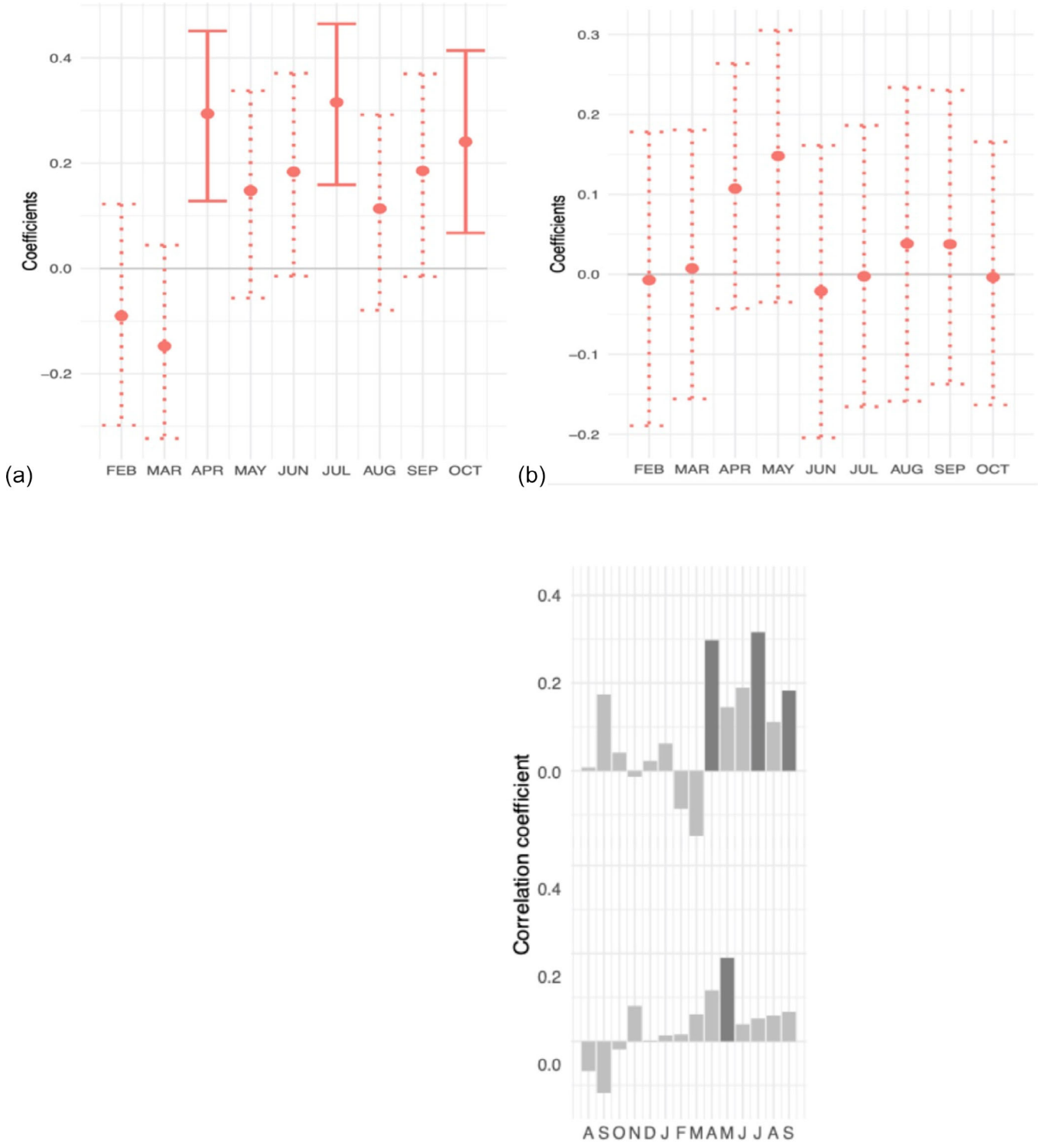


FIGURE 8 Climate response diagrams for bald cypress. For each series the upper histograms (a,b) show the monthly correlations with precipitation (a) and temperature (b), solid bars are significant at the 95% confidence level. The ranges shown are 1000 bootstrapped runs for each month. Because of the intercorrelation between the maximum temperatures and precipitation partial correlations for each of the sites are also shown. Partial correlations (c) are also shown based on SEACORR analysis (Meko et al., 2011) as translated in R code (Zang & Biondi, 2015). Bold bars on the histograms are significant at the 95% confidence level.

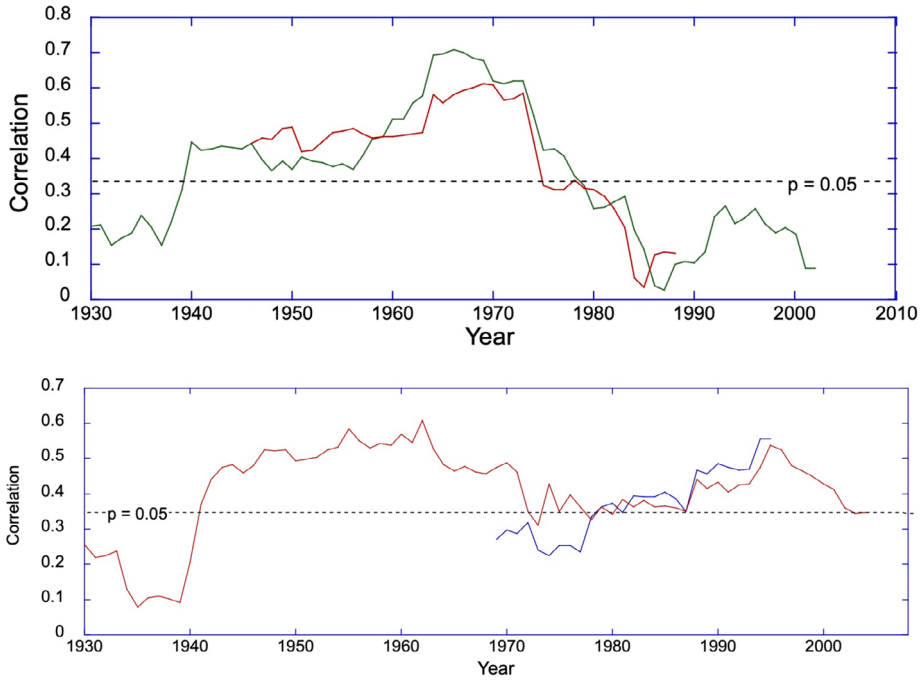


FIGURE 9 Upper panel is the response of the two larch sites (red = Dahurian and green = European) to June–July precipitation records. Note there is a marked loss of correlation after the 1976–1977 shift in climate. Lower panels show the steady precipitation response to precipitation of the DR (dawn redwood; blue) to May–June precipitation, and BC (bald cypress; red) to average April–October precipitation. The dotted lines indicated the 95% significance level.

variability in density and color. A profoundly narrow ring with light latewood occurs at 1988, recording a short but severe, summer drought associated with a rapid decline in streamflow, and depressed groundwater and reservoir levels (Sherwood et al., 1991; Soulé & Meentemeyer, 1989). This was also one of the warmest summers (June–July maximum temperatures; JJ_maxT) on record (Figure 4c). In contrast, the wider, more strongly colored latewood ring of 1985 formed in the year of the coolest JJ_maxT temperatures on record (Figures 2a and 4c).

Comparing the monthly June–July precipitation (JJ_Precip) series with the ring-width tree-ring chronology yields a positive correlation of 0.27 for the full common period (1915–2019), which is significant ($p < 0.05$; Figure 5a). From 1915 to 1975, JJ_Precip and ring-width correlate at $r = 0.34$ ($p < 0.007$; $n = 61$) and after 1975, the precipitation-tree growth relationship drops off sharply and is not significant ($r = 0.20$, $p = 0.19$; $n = 44$; Figure 9).

In addition to the summer precipitation response, the trees negatively respond to summer maximum temperatures (Figure 5b) when evapotranspiration and moisture stress is high. The loss of sensitivity with JJ_Precip identified above since the mid-1970s (Figure 9) is coupled with a weakening of the negative JJ_maxT signal. This again occurs about 1975 when the correlation is −0.33 ($p < 0.012$; $n = 61$ years) prior to 1975 and then drops to $r = -0.005$ ($p = 0.98$, $n = 44$ years) after 1976. Taken together, EL has lost its sensitivity to summer (JJ) precipitation and maximum summer temperature after the mid-1970s. Partial correlations (Figure 5c) show that when the influence of monthly JJ_Precip is removed, maximum summer temperatures are not significant; thus, precipitation is the primary limiting factor in EL growth at least prior to the mid-1970s.

In Secrest Arboretum, increasing summer precipitation appears to be a benefit for tree growth for the European larch and furthermore, the increasing moisture minimizes its maximum temperature sensitivity. The majority of dendroclimatic studies on European larch have been conducted in the tree's native range, which includes the Alpine regions of Europe, in colder and drier regions relative to NEO. Here, temperature-sensitive signals in the ring-width records have yielded climate reconstruction (Büntgen et al., 2009; Huesken, 1993; Kress et al., 2009; Serre, 1978; Vitas, 2015), and, in general, cool summer temperatures have resulted in narrower tree rings (Büntgen et al., 2009; Carrer & Urbinati, 2004, 2006; Serre, 1978; Vitas, 2015). However, in Poland, at low elevations near the eastern edge of its native range, an inverse effect was found with temperature, where lower summer temperature and higher precipitation were both factors in the generation of greater ring-widths (Koprowski, 2012; Oleksyn & Fritts, 1991; Vitas, 2015). At lower elevations where temperatures are warmer, precipitation is a greater factor in determining the annual growth rate of European larch, which is consistent with our findings at Secrest Arboretum.

3.2 | Dahurian larch (*L. gmelinii* (Rupr.) Rupr.)

Twenty-five cores were taken from seven trees in 2006 (Table 1) in the Arboretum. These trees were planted in 1929 and the inner ring of the chronology is 1931; for the climate analysis we started in 1935 when the series an EPS > 0.85 (Wigley et al., 1984; Table 1). All the trees at the Secrest site were blown over in various storms after the initial Moore et al. (2007) study was published and before the 2010 and 2017 tornados in the Arboretum (Notes S1). Moore et al. (2007) detected a shift in the strength of correlation with the precipitation signal changing from a dominant June–July signal before 1980 to a May/June precipitation signal after 1980 (Figures 6a, S1; Moore et al., 2007).

Here, we report a modification of this interpretation based on more recent work that has linked shifts in climate and tree response to the 1976–1977 shift in the North Pacific. When 1976 is chosen as the time of the shift in response to JJ_Precip, from 1931 to 1975 correlates at 0.45 ($p < 0.002$; $n = 45$; Figure 9). After 1975, the correlation is not significant; however, the May–June precipitation signal after 1976 is strong ($r = 0.43$, $p < 0.02$; $n = 30$). This shift may be related to changes associated with an earlier initiation of growth as shifting seasons and increased growing degree days (Bonta & Barker, 2011). Partial correlations (Figure 6c) show that for the entire period (1935–2005), once the strong June precipitation signal is removed, maximum temperatures are not significantly correlated with tree growth (Figure 6c). Taken together, these results suggest a shift in response to an earlier spring precipitation signal and a loss of sensitivity to later summer moisture.

As noted above, the entire stand of Dahurian larch was lost prior to 2009 from windstorms likely due to a combination of winds and the high-water tables at the base of a major slope in the Arboretum. Notably, the immediate adjacent dawn redwood stand (Figure 1) has remained windfirm over the same interval.

3.3 | Dawn redwood (*M. glyptostroboides*)

Planted in Secrest Arboretum as a symmetric grid in 1953, there are 19 trees remaining of the original 20 trees in the stand. Thirty-two cores were sampled and cross-dated into the ring-width series that spans 1955–2009. The work of Vargo et al. (2020) compared the Secrest DR ring-width series with the Wooster Station meteorological records showing a strong sensitivity with May–June precipitation 0.36 ($p < 0.007$) for the 56-year period of growth (Figure 7a) with a recent increase in correlation between 1976 and 2009 to 0.48 ($p < 0.004$, $n = 35$; Figure 6). A negative relationship with July_maxT is also strong ($r = -0.35$; $p < 0.002$, $n = 55$; Figure 6b) and appears to be strengthening, $r = -0.39$ ($p < 0.002$, $n = 34$), after the 1976 shift in climate and coinciding with the recent decadal increase seen in the July_maxT record (Figure 3c). Partial correlation analyses show that when the effect of precipitation is removed, the July_maxT maintains its significant negative relationship (Figure 7c). Consistent with this observation, Vargo et al. (2020) pointed out that the 1988 ring is one of the most-narrow rings in the record, which corresponds to the severe 1988 drought (Figure 2c), a year that recorded one of the highest JJ_maxT (Rogers, 1993; Figure 3c). In addition, April maximum temperatures are also significant and positively related to tree growth when the influence of precipitation is removed (Figure 7c), suggesting warmer Aprils favor dawn redwood tree growth.

Tree-ring studies on dawn redwood (DR) outside of the Secrest Arboretum include work in Krakow, Poland (Wilczyński et al., 2014). They analyzed a ring-width series from planted trees growing for 40 years and were concerned with tree health and air quality, concluding that the city's pollution had little effect on tree growth. This analysis also found that there was a positive correlation with April through August precipitation and a negative correlation with April and May temperatures (Wilczyński et al., 2014), similar to our findings for the summer months.

DR is a strong candidate to consider for plantings because of its unique natural history and ability to thrive in warm and wet climates quickly putting on significant biomass. Due in part to its strong buttressed trunk morphology, the stand studied here is at a prominent topographic location yet appears to be unaffected by the storms and recent tornados (Notes S1) that have removed many of the other trees in the area (Figure 1).

3.4 | Bald cypress (*T. distichum* [L.] Rich.)

The Secrest BC stand receives water from natural springs and a culvert and the stormwater basin in which it resides has a berm that regulates the water level. The soils are highly organic and a shallow sediment core taken at the site yielded 0.66 m of clay and silt with an organic-rich upper 30 cm, which has accumulated at the site since it was installed in 1914. The combination of the relatively high-water table and its closed basin has thus sequestered a significant amount of organic material as well as sediment.

Forty-eight cores were extracted from 31 trees, which together span from 1914 to 2020. Through cross-dating, we were able to identify both missing and false rings which are abundant in this stand (Figure 2d). False rings usually indicate favorable growing conditions in the late summer or early fall, and their formation indicates late summer precipitation (Copenheaver et al., 2017; Therrell et al., 2020). When moisture is present during the late summer, mature bald cypress begin latewood production that leads to the formation of these false rings (Copenheaver et al., 2017).

April through October precipitation is significantly correlated with the ring-width data (0.48, $p < 0.0001$, $n = 106$; Figure 8a) and this positive relationship is uniform through the interval of growth (Figure 9). No other significant relationship with mean, maximum, or minimum temperatures was detected except for a positive correlation with May maximum temperature, which emerges as significant after the effect of precipitation is removed (Figure 8c). Taken together, the BC trees positively respond to wet conditions during the growing season and, at least for the month of May, are positively correlated with warm temperatures. The Secrest water retention basin site is clearly well adapted for this species and the likelihood that warmer temperatures and wetter conditions would benefit its growth all make it a strong choice for future plantings in similar settings.

4 | DISCUSSION

The long-term plantings of tree species in Secrest Aboretum, Northeast Ohio coupled with the onsite meteorological record provides a novel case study for investigating the response of trees to a changing climate that can be more broadly applied to similar arboreta. The two larch series are losing their sensitivity to summer precipitation presumably due to being less limited by summer moisture. This finding of

trees losing sensitivity to precipitation has been noted in other endemic species from the region (Maxwell et al., 2016; Wiles et al., 2025) and is considered a "nonstationary" climate response. Maxwell et al. (2016) and Matheus and Maxwell (2018), who studied a range of Midwest native tree species, pointed out a decline in moisture sensitivity as precipitation increases. This loss is also due, in part, to a lack of major droughts in recent decades (Matheus & Maxwell, 2018) and coincides, in our study, with a well-documented shift in climate in the mid-1970s.

The timing of the loss of moisture sensitivity detected in the two larch series is coincident with a mid-1970s shift in climate and may be linked to changes in the North Pacific decadal variability (Ebbesmeyer et al., 1991; Wiles et al., 2025). Wetter conditions in the Midwest and the resulting loss of correlation with tree growth may reflect shifts in storm tracks and the northward migration of the North American Westerly Jet (NAWJ) across the region bringing more moisture to the study site. Density plots of JJ_Precip prior to and after the 1976/1977 shift reveal there is a 160- to 220-mm precipitation increase at the Wooster station. This marked rise in precipitation, during an interval of relatively low maximum (daytime) temperatures, if it persists, will continue to be favorable to larch growth in the NEO region. Although summers, to which larch are sensitive, continue to become wetter in Northeast Ohio, recent modeling results suggest that future Midwest summers may also experience more severe drought due to a combination of Arctic Amplification (Preece et al., 2023) and an increasingly wavy NAWJ, which will be displaced northward (Zhou et al., 2022), and thus increased precipitation may stave off the negative effects of increased evaporative demand of warming summer months. Taken together, the nonstationarity of climate response in the larch is important to recognize given the increasingly unprecedented nature of climate change that can influence tree growth and health and, in turn, climate mitigation, biodiversity, and tree management practices (Tumajer et al., 2023).

The DR and BC species continue to be sensitive to and positively correlated with precipitation (Figure 9). Dawn redwoods show a change in precipitation sensitivity shifting from June to May, presumably as the growing season lengthens (Bonta & Barker, 2011). When the precipitation signal is removed, there is a significant negative relationship with July maximum temperatures and a positive response to April maximum temperatures. Together, these observations suggest a favorable relationship with early growing season temperatures; whereas during the summer months, higher evaporative demands are negatively related to tree growth. The climate of NEO is similar to that of the natural range of DR in China; however, there are no tree-ring records from its endemic range to compare with our results.

The much larger and persistent precipitation "window" April–October, to which BC are sensitive, is consistent with its natural range being much wetter with a longer growing season. Additionally, a positive temperature relationship with maximum monthly May temperatures detected here is also consistent with its warmer, wetter endemic region of the southeastern United States. Future, ongoing increases in precipitation and warming in early summer months should continue to favor the growth of BC in the NEO region.

The trees studied here have been growing for more than five decades outside their native ranges and thus provide insights into future climate response within their endemic range given it is likely that climate within their native ranges is also changing. For example, the Dahurian larch in its natural range will likely experience future wetter and warmer conditions in parts of Siberia and China, similar to what the population at Secrest has already experienced in NEO. This is another example of how the utility of this work can provide insights into the climate response of exotic species in arboreta and is informing paleoclimate studies. European larch is widely used in dendroclimatic reconstruction for Eurasia (Frank & Esper, 2005), and its study in Secrest Arboretum under novel climate conditions can be utilized to better define the range of tree response to climate, especially here for moisture response.

Our analyses are confounded by the negative intercorrelation of summer precipitation and maximum temperatures, and hence, we have used partial correlation analysis to separate the relative climate responses of the two climate inputs. In the greater Midwest, the decrease in summer maxT over the past century has received considerable attention as it is coupled with analyses of heat stress on crops (Basso et al., 2021; Partridge et al., 2018). Higher JJ_maxT, in general, come with increasing evaporative demands, but with its overall decline (Figure 2c) and at the same time, a rise in precipitation, the effect of drought is likely to be mitigated for the near future. In the Northeast United States, reforestation has been implicated in increased cloudiness coupled with increased canopy roughness during summer and trans-evaporative cooling which together likely have a role in overall summer maximum temperature decreases (Zhang et al., 2020). The possible role of reforestation and long-term cooling of maximum temperatures at the Arboretum and in the Midwest, in general, has not been fully investigated and its study is beyond the scope of this work; however, it may play a part. Additionally, our sites do not consider the interactions of species within forests and the dispersal of the various study species when considering the ranges under which these deciduous conifer species can grow (Laughlin & McGill, 2024).

Furthermore, given that tree species ranges, due to these factors and others, are often underestimated (Laughlin & McGill, 2024) and that climate changes the range of tree species, we might anticipate that exotic trees can be adapted to the present and changing climate of our study area. Similar ideas have been tested using information from arboreta (i.e., Bush et al., 2018). Taken together, these findings are relevant as we seek to better understand tree growth in a wetter and warmer NEO and seek to assess the possible roles trees can play in mitigating climate change and the impacts of climate in the coming decades to centuries. As the role of stormwater management and carbon sequestration become more crucial in planting decisions in NEO, some species will be chosen to act in the role of mitigating the impacts of climate change itself, through carbon sequestration, shading and cooling in urban settings, and for managing increasing stormwater runoff (Handler et al., 2014). Projections of future climate change anticipate continued warming and stronger pluvial conditions; thus, the analyses of these non-native deciduous conifer tree species in arboreta can help better target management and planting to maximize ecosystem services.

Additional advantages of deciduous conifers in this study include the relatively large heights of the four species that can introduce an increase in canopy roughness to the landscape and, along with the seasonal loss of needles, which increases albedo in the winter months relative to evergreen species, can together serve to mitigate heating. These two considerations taken together can lead to cooling (Bonan, 2023), although quantifying these influences is beyond the scope of the present study. However, one can envision a forested, warmer future dominated by deciduous conifers with larch species in the relatively better drained uplands and the swampy lowlands dominated by dawn redwoods and bald cypress echoing back to the Eocene when more than double present atmospheric carbon dioxide levels drove the northern treeline into the high Arctic (Eberle & Greenwood, 2012; Jahren, 2007). A comprehensive study by Mamet et al. (2019) suggests that for boreal *Larix* species, a northern expansion is underway and that with continued warming temperatures the greatest gains northward are seen in Russia with the strongest potential of northward migration in North America where the unforested northern land mass is greatest.

Given strong winds and storms associated with climate change and at Secrest Arboretum (Zeng et al., 2019), the deciduous conifer taxa studied here are considered to be among the most windfirm species (Salisbury et al., 2025). The observed complete loss of one entire study site (DL) to wind damage and the significant recent loss of 14 of the 72 individuals at the EL site since our sampling indicate a need to focus on studying and preserving information from these botanical resources. In this study, our archiving of the cores and the tree-ring data is an initial step, and larger efforts to archive cores and cross sections of fallen trees should be considered where possible. It is also notable that over the time of our almost 20 years of tree-ring work in Secrest Arboretum, few windfirm dawn redwoods or bald cypress were lost to storms, in contrast to the larch sites. Although these observations are largely anecdotal, they are consistent with both species being resilient to coastal storms including hurricanes (Gardiner et al., 2025) and new modeling studies of resilience with respect to wind (Salisbury et al., 2025).

Similar investigations can be done at other arboreta and botanical gardens to better understand the complex response of the biosphere to a changing climate (Primack et al., 2021; Primack & Miller-Rushing, 2009) and thus improve planting and management decisions for "climate-smart" forests (Bonan, 2023). In a world where CO_2 emissions continue to rise and we seek to limit planetary warming to 2°C, all tree species, including assemblages of deciduous conifers, will need to be considered to mitigate the effects of future climates.

AUTHOR CONTRIBUTIONS

Gregory Wiles led the writing of the manuscript, data analysis, and data collection. Nicholas Wiesenberg led the field sampling and development of tree-ring measurements and archiving. Srushti Chaudari, Mazvita Chikomo, and Wenshuo Zhao participated in the field, lab, and data analysis efforts. Benjamin Gaglioti assisted with the research design, writing, and revision. Meagen Pollock assisted in the research design and interpretation.

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CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

The tree cores used in this study are archived in the Wooster Tree Ring Lab, and the data are available at the International Tree Ring Databank (ITRDB) at the National Center of Environmental Information (NCEI) maintained by NOAA (https://www.ncei.noaa.gov/products/paleoclimatology/tree-ring).

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