GROWTH-CLIMATE RELATIONSHIPS

OF SUGAR MAPLE (*Acer saccharum* MARSH.)

ALONG A LATITUDINAL CLIMATE GRADIENT IN ITS WESTERN RANGE

A THESIS

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Introduction

Anthropogenic climate change is predicted to modify the precipitation and temperature regimes in eastern North America. Even small changes in the climate could have the potential to change forest habitats and overstory tree composition of forests in eastern North America (Iverson and Prasad 1998). Changes in overstory tree communities from historical norms are already being observed (McEwan et al. 2011). One consequence of climate change currently being seen is regeneration failure of ecologically and commercially valuable oak species. Many foresters and ecologists accept that oak regeneration failure is already changing the composition of forests west of the Appalachian Mountains (Elliot et al. 2015). Factors such as climate change, fire suppression, and loss of American chestnut (*Castanea* dentate [Marsh.] Borkh.) are several of the proposed explanations for the current oak regeneration problem (McEwan et al. 2011).Many of these stands are predicted to shift in composition to maple dominated hardwood stands that are characteristic of later successional forests. Oak regeneration failure is likely to heavily impact the ecological role of oaks as habitat and food sources, and its economic importance in the fine lumber industry (McEwan et al. 2011). Some ecologists attribute this regeneration failure to wet and mild climate conditions in recent decades, and the reproductive success of later successional sugar maples (McEwan et al. 2011). It is important to understand how climate change may affect the growth of individual tree species, as many trees provide both ecological and economic benefits. By studying individual tree species, ecologists can better understand forest ecosystems as a whole. One way to study the effects of climate change on forests is dendroecology. The past growth responses of individual tree species to variation in climate is one way to learn how species compositions may respond to future anthropogenic climate change.

Dendroecological studies are used as one way for understanding how climate affects the radial growth of trees. Radial growth response to variations in precipitation and temperature can be determined through measuring tree rings and observing correlations between radial growth and variations in temperature and precipitation. These variables are often correlated with radial growth in the late spring/early summer period (Speer et al. 2009; LeBlanc and Terrell 2009, 2011; LeBlanc and Stahle 2015 Lockwood and LeBlanc 2017). Prior research has primarily focused on ring-porous species due to ease of annual ring measurements. However, it is also possible to use diffuse-porous tree species in dendroecological research (Elliot et al. 2015).

Sugar maple (Acer saccharum Marsh.) is a tree species native to eastern North America that is valuable for its use in fine lumber products and maple syrup (Burns and Honkala 1990). It also plays a defining role in mature forests of the Eastern United States. Sugar maple is prominent east of the Appalachian Mountains, and tends to be outcompeted by drought tolerant species west of the Appalachian Mountains (Burns and Honkala 1990). Sugar maple is capable of producing large numbers of seedlings, a characteristic that has been shown to be a contributing factor in oak regeneration failure (Cleavitt et al. 2011; Graignic et al. 2014; McEwan et al. 2011). Apart from a couple of spatially limited sugar maple dendroecological studies done in southern Indiana (Miller 1951; Gaffney 1995), no dendroecological research has been conducted on sugar maple in the western parts of its range. Because this species is both ecologically and economically important, more sugar maple research is needed to understand how it may be affected by climate change.

Prior dendroecological research on sugar maple has studied populations in the eastern and northern parts of the species range. These studies have found weak correlations between radial growth and precipitation and temperature variables (Abrams et al. 1998; Lane et al. 1993;

Takahashi & Takahashi 2016; Tardif et al. 2001). However, these studies worked with sugar maple populations in low stress climates. Climate in these study areas is typically characterized by moderate temperatures and ample precipitation (Bryson and Hare 1974). These studies did not sample a large portion of the sugar maple range that is characterized by higher temperatures and lower precipitation, which may be more stressful to sugar maple growth. Sugar maple is distributed over a large geographical range that spans two major climate gradients. Temperature becomes warmer as one moves north to south, and climate becomes drier from east to west (Bryson and Hare 1974). Hence, sugar maple populations in southern and western parts of its range may show different correlations between radial growth and past variation in temperature and precipitation variables when compared to eastern populations. By studying sugar maple populations in the western part of its range, evidence of radial growth-climate correlations can be gathered in a region where little research has been done.

The objectives of this dendroecological study on sugar maple are three-fold: 1) Characterize correlations between sugar maple radial growth and the climate variables of temperature, precipitation, and Palmer Drought Severity Index (PDSI) at sites in Michigan, Indiana, Kentucky, and Missouri; 2) Determine differences in growth-climate correlations with temperature and precipitation along a latitudinal climate gradient in the western range of sugar maple; and 3) Characterize how the strength of sugar maple growth-climate correlations has changed over the last century. I predicted that radial growth-climate correlations for the variables of temperature and precipitation will be stronger in the western part of the range when compared to eastern populations. Furthermore, populations located more south and west along the latitudinal climate gradient will show stronger correlations between radial growth and climate variables.

Literature Review:

Climate change in the coming decades will likely become a major factor affecting the habitats of eastern North American tree species. In North America, increased seasonal temperatures, more frequent instances of drought, and more frequent extreme weather events will likely lead to shifts in distributions of tree species, and therefore forest ecosystems as a whole through the 21st century (Swanston et al. 2017; Iverson et al. 2008). The impacts of drought and drought-related stress events due to climate change are predicted to be a driver of tree mortality, habitat change, and range shifts (Iverson and Prasad 1998; 2001; Iverson et al. 2008). Studies of the effects of past droughts have found measureable impacts on forest ecosystems including lower site water balances, increased wildfires, and increased pest activity (Williams et al. 2013; Allen et al. 2010). Several tree species in North America are already being impacted by climate change, which has the potential to alter their habitats and eventually their ranges. For example, oak regeneration failure in the 20th century has resulted in oak species becoming less prominent in many eastern forests. This has been attributed to several factors including wetter growing seasons and changes in fire regimes that have altered the competitive balance of trees in eastern North America (McEwan et al. 2011). Wetter growing seasons combined with less frequent fires have created an environment in which maple species can outcompete oak species. This has led to a greater abundance of maples and a lower abundance of oak (Iverson and Prasad 2001; McEwan et al. 2011). Another example is the lower abundance of western conifer species as higher temperatures have allowed insect pests like pine bark beetle and spruce budworm to decimate populations of their host species (Iverson et al. 2008). As climate induced stresses are predicted to potentially increase, species abundance, diversity, structure, and function of forest ecosystems are likely to change. (Williams et al. 2013; Allen et al. 2010; Iverson et al. 2008). While it is

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impossible to predict exactly how forest ecosystems will respond to climate change, studying individual species responses to climate stresses in the past can allow scientists to better predict how these species will respond to climate stress in the future. Dendroecology is one such way of studying historical tree species responses to climate induced stresses.

One application of dendroecology is correlating the radial growth of trees with yearly variations in temperature and precipitation to observe how variations in climate may be affecting the radial growth of trees. A majority of this work in eastern North America has been conducted on species in the genus *Quercus*, an ecologically and economically important ring-porous species.

LeBlanc and Terrell (2009 and 2011) and LeBlanc and Stahle (2015) conducted dendroecological studies on several oak species over a sub-continental scale in the eastern deciduous forest. LeBlanc and Terrell (2009) studied white oak (*Quercus alba* L.) at 149 sites across its range in eastern North America. The radial growth of white oak was positively correlated with May-July precipitation at a majority of the sample sites. Negative correlations were also observed between radial growth and June-July temperature at a majority of sites (LeBlanc and Terrell 2009). This research was followed by a study comparing red oak (*Quercus rubra* L.) and white oak radial growth responses to climate at 82 sites across eastern North America. LeBlanc and Terrell (2011) found similar radial growth-climate correlations as the 2009 study for white oak. Red oak was found to have a positive correlation between radial growth and early summer precipitation and negative correlations with early summer temperature, albeit at fewer sites (LeBlanc and Terrell 2011). These results suggested that similar tree species may have similar growth-climate associations in similar environments.

A multi-species dendroecological study by LeBlanc and Stahle (2015) included *Quercus prinus* L., *Quercus velutina* Lam., *Quercus macrocarpa* Michx., and *Quercus stellata* Wangenh. Data was collected at 24, 29, 33, and 55 sites, respectively for each species. Like the previous two studies, precipitation correlated positively with radial growth for the species in the May-July period at most sites. Temperature also correlated negatively with radial growth during the same time period at most sites, except for *Q. prinus* (LeBlanc and Stahle 2015). A similar explanation was presented in all three studies regarding the strength and timing of the growth-climate correlations. Variation in site water balance due to temperature and precipitation during the early growing season, when radial growth is prioritized, was identified as the main driver of strong growth-climate correlations (LeBlanc and Terrell 2009,2011; Leblanc and Stahle 2015).

Speer et al. (2009) conducted a dendroecological study of five oak species including *Quercus alba* L., *Quercus velutina* Lam., *Quercus montana* Wiild., and *Quercus coccinea* Münchh. Oak was sampled at sites in Tennessee, North Carolina, and Georgia. As in previous studies, radial growth was positively correlated with precipitation and negatively correlated with temperature at most sites during the early summer period, particularly June (Speer at al. 2009). Drought during the growing season was put forth as the primary reason for the strength of growth-climate correlations, and increases in drought may upset forest compositions in eastern North America (Speer at al. 2009).

Similar climate-growth associations to oak have also been seen in other ring-porous species. Lockwood and LeBlanc (2017) studied white ash (*Fraxinus americana* L.) at 12 sites. There was a positive correlation between radial growth and precipitation at nearly all sites during the early growing season. Temperature was negatively correlated to radial growth, albeit at less than half of the sites (Lockwood and LeBlanc 2017). Like the previous studies, site water

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balance during the early growing season was proposed as the reason for strong growth-climate correlations, as most radial growth occurs during this period (Lockwood and LeBlanc 2017). While white ash radial growth-climate correlations were not the same as those of the oak species, the pattern of associations was similar.

Radial growth of diffuse-porous species in eastern North America has also been correlated to yearly temperature and precipitation, despite increased difficulty associated with measuring annual rings with indistinct ring boundaries. Orwig and Abrams (1997) found that tulip poplar (*Liriodendron tulipifera* L.). radial growth was negatively correlated with drought in northern Virginia. Maxwell et al. (2015) also observed negative correlations between tulip poplar radial growth and summer drought. Radial growth of tulip poplar, red maple (*Acer rubrum* L.), and sweet birch (*Betula lenta* L.) was positively correlated with summer precipitation (Elliot et al. 2015). Martin-Benito and Pederson (2015) performed a dendroecological study that also included tulip poplar and red maple. Tulip poplar radial growth was negatively correlated with summer drought and summer temperature. Red maple growth was also negatively correlated to drought and temperature during the summer months, but to a lesser degree than tulip poplar (Martin-Benito and Pederson 2015). Abrams et al. (1998) studied the redial growth response of red maple on xeric and mesic sites. Red maple radial growth on both sites was negatively correlated with summer drought. Even though these studies had different aims, they had similar conclusions. They all agreed that variations in precipitation and temperature had the potential to impact radial growth. This was mainly be seen in the form of negative effects on tree growth due to more stressful climate in the form of increased drought (Orwig and Abrams 1998; Maxwell et al. 2015; Elliot et al. 2015; Martin-Benito and Pederson 2015, Abrams et al. 1998).

Studies with European and Asian maple species have also documented growth-climate correlations. A dendroecological study of sycamore maple (*Acer pseudoplatanus* L.), was performed in the alpine areas of the Tatra Mountains in Poland (Bednarz 1981). This area is characterized by cooler and wetter mountain conditions. Negative correlations between radial growth and high levels of precipitation, and positive correlations between radial growth and temperature were observed for sycamore maple (Bednarz 1981). Bednarz proposed that in cold mountain climates, warmer air temperatures during the growing season could promote radial growth. This is opposed to high levels of growing season precipitation that prevents radial growth as cold, cloudy, and rainy mountain weather can reduce photosynthesis (Bednarz 1981). A dendroecological study of Persian maple (*Acer velutinum* Boiss.) in the hot and dry environment of northern Iran found a positive correlation between radial growth and August precipitation (Kiaei and Bakhshi 2011). While the environments and climate variables associated with these maple relatives are quite different, radial growth of maple species has been shown to reliably correlate with climate factors.

Most sugar maple dendroecological research in North America has been performed in the northern and eastern parts of the species range. Abrams et al. (1998) performed a dendroecological study on a variety of species in central Pennsylvania, including sugar maple. Radial growth was negatively correlated with known drought years (Abrams et al. 1998). Tardif et al. (2001) sampled three tree species in southwestern Quebec, including sugar maple, to analyze associations between radial growth and climate. Radial growth of sugar maple was found to be negatively correlated with temperature in the June-July period, and positively correlated with precipitation in the same months. Water stress was proposed as to the physiological mechanism for these correlations. However, cool growing season temperature in Quebec,

Canada, likely creates a low stress environment (Tardif et al. 2001). Takahashi and Takahashi (2016) conducted a dendroecological study on sugar maple in Mont. St. Hilaire, Quebec, Canada. Radial growth was positively correlated with June precipitation, and a negatively correlated with June and December temperature. Similar to other studies, climate stress induced by drought was proposed as the reason for restricted radial growth among sugar maple (Takahashi and Takahashi 2016). These studies provide evidence that sugar maple radial growth is sensitive to variations in precipitation and temperature, even in areas with cooler climates where drought stress is less common. In both studies, growth-climate correlations during the growing season were relatively weak, with coefficients in the range of 0.2 to 0.4 (Tardif et al. 2001; Takahashi and Takahashi 2016).

Limited dendroecological research has been conducted with sugar maple in the western part of its range. A dendroecological study of sugar maple was performed in a remnant old-growth forest near Alamo, IN (Miller 1951). Radial growth was correlated with yearly local precipitation from 1911-1940. Despite crude measuring procedures and statistical methods, radial growth was found to be positively correlated with precipitation for June-July (Miller 1951). Gaffney (1995) conducted a dendroecological study of sugar maple at two adjacent sites in southern Indiana. Sugar maple radial growth was found to be positively correlated with summer precipitation and negatively correlated with summer temperature. Radial growth of trees on western, southern, and upper slopes was found to be better correlated with temperature and precipitation compared to trees on eastern, northern, and lower slopes, but the differences among slope positions were not large (Gaffney 1995). Sugar maple radial growth-climate correlations were attributed to variations in site water balance associated with yearly variation in early growing season temperature and precipitation (Gaffney 1995). From the few dendroecological

studies of sugar maple in its western range, evidence points to positive correlations between radial growth and June-July precipitation and negative correlations between radial growth and June-July temperature. This evidence is similar to other sugar maple studies in the eastern part of the species range. With a limited amount of dendroecological research on western sugar maple populations, more research is warranted.

Study Sites

Study sites were chosen over a latitudinal-temperature gradient in the western part of the range of sugar maple in Michigan, Indiana, Kentucky, and Missouri (Figure 1). While study sites were not randomly chosen due to budgetary and time constraints, these study areas spanned much of the climate gradient from North to South of the western sugar maple range. Sites were selected based on information provided by land managers and US Forest Service foresters regarding sugar maple abundance, size and age in specific stands. Ease of access and permissions to sample limited possible study sites.

Specific criteria were required to choose suitable study sites. Each site had to have at least 20 sugar maples old enough for use in a dendroecological study as heart rot was a pervasive problem and many individuals could not be sampled. Trees dating back to at least 1930 were preferred to be able to analyze growth-climate relationships over a majority of the previous century. Study sites were also selected based on the abundance of large sugar maple to ensure an adequate sample size could be collected. Because large old sugar maples often contain heart rot (personal observation), it was necessary to have many large sugar maples at a site to collect cores from at least 15 trees per site. With constraints of budget and time, several sites were sampled in close spatial proximity. This was done to insure a representative sample of the area and to prevent too small of sample sizes if a large number of cores in the sample were later considered

unusable for dendroecological analysis. This was important in sites with potentially young trees, and areas where environmental stresses and site quality may lead to poor core qualities.

Alpena, Michigan: The Alpena, Michigan site (44.976, -83.584) is a privately owned 7 hectare sugar maple farm. All large trees are tapped for syrup production, with plans to harvest for timber in the future. The stand is dominated by sugar maples in all layers of the forest. Many individuals present on the property were larger than 50 cm DBH. The stand's slope ranged from 0 to 6% and is located 220 m above sea level. The dominant soil types in the stand are Ossineke fine sandy loam, and Morgonlake loamy sand (USGS Web Soil Survey 2017).

Huron-Manistee National Forest, Cadillac District, Michigan: The Manistee NF of western Michigan in the Lower Peninsula covers 218,000 hectares of land with the Cadillac district covering slightly less than half. Sampling occurred in two areas (44.371, -85.663) and (44.339, -85.703). These sites were last harvested from 1912-1920 and contained enough sugar maples of useable age. This is the northern most district of the Manistee NF. Elevation in this area ranges from 260 to 300 m and is characterized by a Beech-Maple-Birch community (personal observation). The sites were hilly with slopes ranging from 0-40%. Land use includes timber production, but sampling occurred in older areas set aside for conservation. Soil types in this area are dominated by Kalkaska-East Lake sands, Kalkaska sand. And Kalkaska sand banded substratum (USGS Web Soil Survey 2017).

Ginn Woods, Delaware County, Indiana: This is a 64 hectare remnant old-growth forest located in northern Delaware Country, Indiana (Badger et al. 1998). This area is located at (40.349, -85.438) and elevation is 270 m above sea level with flat topography (0-1% slopes) and dotted with water-collecting depressions. The overstory is characterized by a Beech-Maple-Basswood climax community. Soils in this forest are occasionally flooded in the spring and are

predominately Blount-Del Rey silt loam and Pewamo silty clay loam (USGS Web Soil Survey 2017). This site has also been characterized with having a high water table and shallow impervious soil layer which is thought to result in a shallow rooting zone (Kemuel Badger, per. Comm.)

Phyllis and Frank Yuhas Woods, Indiana: This is a 33 hectare upland and palustrine forest located at (40.101, -85.089) and is 300 m above sea level in Farmland, Indiana. The stand is a high quality woodland in east-central Indiana with a diversity of overstory and understory species including oaks, hickories and maples (Baltzer et al. 2007). Sugar maple is not a dominant species in the overstory, but large individuals are present. The forest has small hills with slope ranging from 0-18%. The most common soil types are Patton silty clay loam and Losantville silt loam (USGS Web Soil Survey 2017).

Daniel Boone National Forest, Sterns District, Kentucky: The Daniel Boone National Forest spans Kentucky from North to South along the east central part of the state. The Sterns District is the southernmost district in the National Forest covering 69,200 hectares. Sampling was done in the vicinity of (36.628, -84.222). This area in the Appalachian Mountains is at 300-480 m in elevation and characterized by 0-75% slopes. The forest is composed of a diverse group of tree species, and would be considered Mixed-Mesophytic (David Taylor USFS, Per. Com.). Sugar maple is found throughout the area, but large individuals are primarily located at higher elevations. Major soil types in this area include Shelocta-Bouldin complex and Shelocta-Sequoia complex (USGS Web Soil Survey 2017).

Mark Twain National Forest, Ava and Cassville Units, Missouri: Mark Twain National Forest is a collection of forested areas in southern Missouri. Sampling was done in the Ava and Cassville Units where local foresters reported populations of sugar maple dating back to the last

timber harvests in the early 20th century (John Nelson USFS, Per. Com.). Sampling occurred in the vicinity of (36.695, -92.783) and (36.537, -93.845) for Ava and Cassville respectively. The areas of interest have slopes ranging from 3-100% with sugar maple present on sloped and bottomland areas with elevations between 350-450 m above sea level. The forest type is classified as Oak-Hickory in both units, but large maples are a component in some areas (John Nelson USFS, Per. Com.). Major soil types in the Ava unit include Rueter-Gasconade-Rock outcrop complex, Moko-Rock outcrop complex, and Ocie-Gatewood complex. Major soil types for the Cassville unit are Hailey-Rock outcrop-Moko complex and Clarksville-Noark complex (USGS Web Soil Survey 2017).
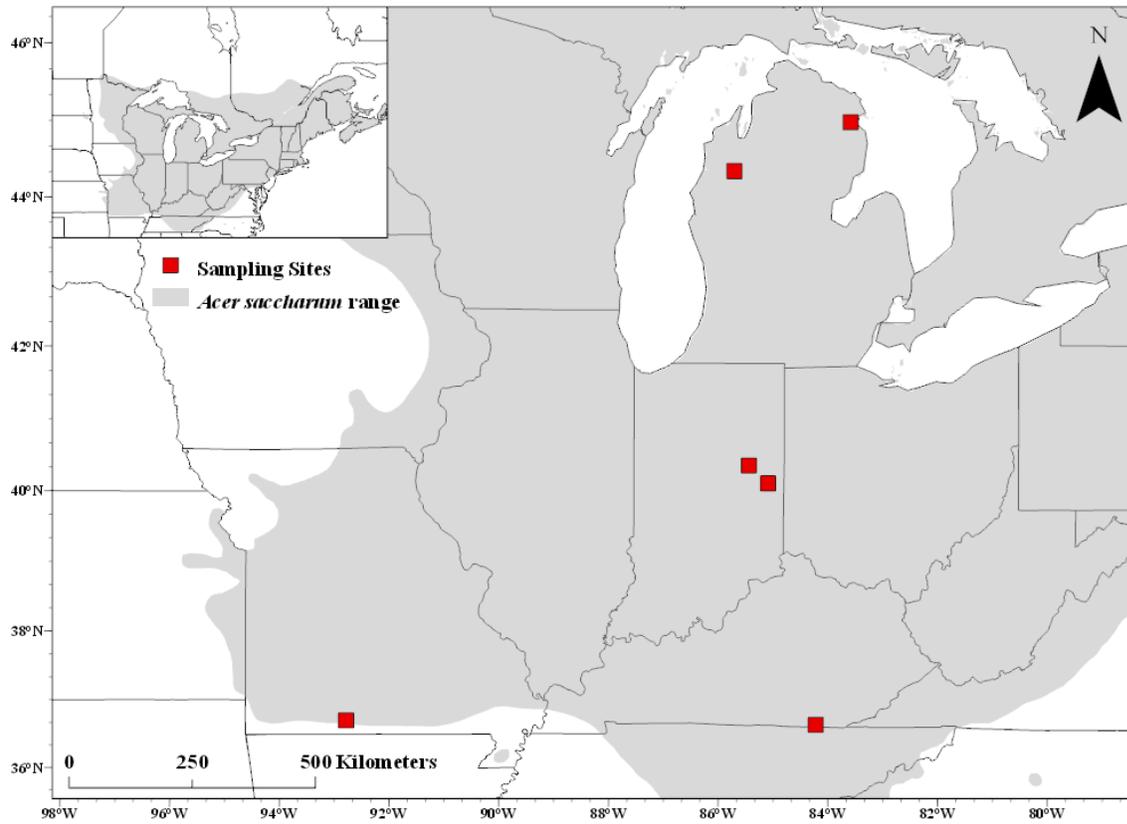
Figure 1: Map of sugar maple (*Acer saccharum* L.) study sites (red squares).
Dark gray area represents the natural range of sugar maple, adapted from
Little (1971).

Methods:

Sampling: In each study location, a total of 15 sugar maple trees were sampled. Individuals were cored at breast height (1.4 m) using a Haglof increment borer with two cores taken per tree for a total of 30 cores per site. Cores taken from the same tree were no less than 90 degrees apart from each other. All trees sampled were measured for DBH and height. GPS locations were also recorded for all sampled individuals.

Core Preparation: All cores were air dried prior to mounting on wooden rails with the transverse face of the core facing upwards. Mounted cores were sanded starting at 220 grit sand paper and progressing up to 1200 grit and were then buffed.

Cross-dating and Ring-width Measurement: All cores were initially crossdated via skeleton plotting for marker rings (Stokes and Smiley 1968) to accurately assign each growth ring to its year of formation. Ring widths were then measured with a Velmex measuring table, which records ring widths with a precision of 0.01 mm. Quality of ring width measurements and cross-dating were then verified using the program COFECHA (Holmes 1983). With this program, a master chronology was created by averaging ring widths of all the cores from a specific site by year. The ring width chronology for each core was then correlated against this master chronology in 20 year increments with 10 year overlapping time spans. This reduced time period from the standard 50 year interval with a 25 year overlap is due to the younger ages of the trees, and to allow for more detail to be resolved between cores and the master chronology.

When the COFECHA analysis indicated dating errors, accurately dated chronologies from nearby locations with other species, obtained from the International Tree-Ring Data Bank, were used in some instances to locate the most probable areas of missing rings in order to properly date cores. Cores that could not be cross-dated were removed from the database.

Site Quality Assessment: Site quality for sugar maples at each site was assessed by comparing

tree size versus age among the study sites. First, all trees with cores that allow for accurate

estimates of tree age were identified. This was defined as cores missing the pith by no more than

2-3 annual rings. For all trees accurately aged within each site, average DBH, height, ring width,

and age were calculated. Average height and age were plotted to approximate a site index curve.

A simple linear regression projecting expected height with age was placed to evaluate potential

site quality for sugar maple.

Calculation of Mean Site Chronologies: Residual ring-width chronologies for each site were

created using the program ARSTAN (Cook 1985). A smoothing spline (-67, 50%) that reduced

50% of the variance over 67% of the series lengths was fitted to reduce the effects of age and

stand dynamics on the series to create ring indices. Then ARSTAN modeled and removed

temporal auto-correlation in individual ring index chronologies. This process left the effects of

inter-annual variation in climate on ring-width as the primary cause for temporal variation in ring

index values. A bi-weight mean was used to average ring indices by year across all the cores

from each site. This process is important to reduce the effects of stand disturbance and

exceptionally large or small rings on the site average chronology. These bi-weighted means were

used to create the mean residual ring-width chronology for each site. These residual ring-width

chronologies primarily represent the year to year variations in ring widths common to trees at a

site that are most likely due to the effects of climate. These site residual chronologies were then

correlated with the climate variables of interest.

Climate Data: Climate data were sourced from the National Climate Data Center (NCDC 2018).

Data values come from weighted averages of weather recording stations within state climate

divisions. The climate variables that were tested for correlation with radial growth indices of

sugar maple were monthly mean temperature, maximum temperature, and minimum

temperature, total monthly precipitation, and Palmer Drought Severity Index (PDSI). PDSI

integrates temperature and precipitation in a measure of soil water balance. However, PDSI is

standardized around a mean of 0 for an individual site, and cannot be used to compare water

balance between sampling sites. Precipitation: maximum temperature ratios were created as a

non-standardized measure of water balance that combines the influence of temperature and

precipitation that can be compared between sites. Data values come from weighted averages of

weather recording stations within state climate divisions. Seasonal variables reflect those used in

Leblanc and Terrell (2009) and included past summer (pJJA), past autumn (pSON), past winter

(pDJF), spring (MA), early summer (MJJ), summer (JJA), and the period of May-August that

encompasses the bulk of the productive growing season. Annual climate was calculated from

monthly values for June of the year prior to annual ring formation through the September of the

year the ring was formed. Seasonal/annual temperature and PDSI variables were calculated as

averages of the relevant months. Seasonal/annual precipitation variables were calculated as sums

of the relevant months.

Statistical Methods: Each climate variable was tested for correlation with the mean site

chronologies using Pearson's correlation. For each variable, mean site chronologies were

correlated with climate variables for current year months, prior year months, seasonal periods,

and an annual period. Because this analysis included hundreds of tests of significance for

growth-climate correlations, the likelihood of a Type 1 error occurring greatly increased. A

simple Bonferroni adjustment was used to determine the p-value needed to claim that a growth-

climate correlation was significant. Each climate variable was considered independent and

composed of 16 separate months (previous June-current September). The adjusted Type 1 error rate was determined as $\alpha = 0.05 / 16 = 0.003$.

Pearson's correlation was also used to analyze the temporal stability of sugar maple growth climate correlations beginning from 1901-1904, depending on site, to the most recent year of ring formation (2017-2018). Correlations between the mean site chronology and June-August maximum temperature, precipitation, and PDSI were computed for 50-year shifting windows, incremented in 1 year steps (e.g. 1901 – 1950, 1902 – 1951, etc.), to see how the strength of growth-climate correlations changed over time. These three climate variables during the June-August months were chosen specifically for temporal analysis as they resulted in the strongest growth-climate correlations.

Results

Seventeen of sixty cores and eighteen of sixty cores could not be crossdated at Cadillac and Mark Twain, respectively. After deleting these cores, data for the remaining cores sampled from the two sites in each of these national forests were combined and treated as a single Cadillac site and a single Missouri site. The combined sites were in close proximity to each other and in the same state climate division.

Site Quality and Climate: Measured characteristics of sampled sugar maples did not differ in a way that would suggest some study sites had lower site quality than others. The sites with the tallest trees were also the sites with the oldest trees (Figure 2). Mean DBH and average ring width (presented in Table 3) also did not indicate substantial differences among the study sites that were unrelated to differences in stand age (Table 1).

Averaged climate variables for the summer portion of the growing season (June-July for MI and IN, May-July for KY and MO) showed a progression of increasing temperature and

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increasing precipitation from North to South, and decreasing precipitation from East to West (Table 2). Precipitation: Maximum Temperature (P:T) ratio also increased from Alpena to Sterns District, indicating lower water stress in Kentucky compared to northern Michigan. (Table 2).

Alpena, Michigan, Ginn Woods, Indiana, and Yuhas Woods, Indiana had higher percent variance in the first principle component, and higher between tree correlations than the other sites. At all sites except for Cadillac Michigan, only the first principle component was significant; the second component was also significant at the Cadillac site. There was little difference in average ring-width (Table 3). Only expressed population signal in Kentucky was noticeably lower than the other sites.

Table 1: Mean DBH, height, and age of sampled sugar maple at each site for comparing site quality.

Site	DBH (cm)	Height (m)	Approx. Age
Cadillac, MI	60.1	31.5	106
Alpena, MI	55.2	32.7	119
Ginn Woods, IN	77.5	35.8	145
Yuhas Woods, IN	61.9	30.5	113
Sterns District, KY	53.1	27.5	100
Ava/Cassville, MO	43.1	22.5	86
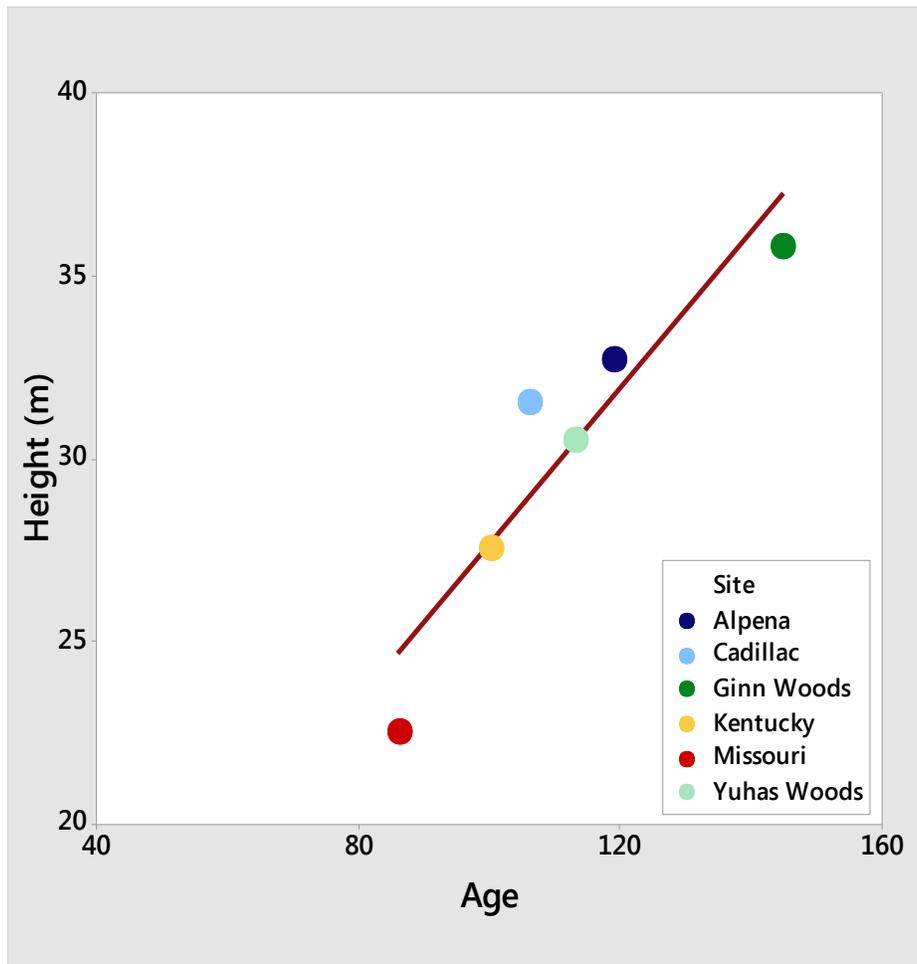
Figure 2: Age and height scatter plot to compare site quality of sampled sites.

Table 2: Summer growing season (June-August) mean temperature (T), minimum temperature, maximum temperature, precipitation (Precip), and precipitation: maximum temperature ratio (P:T). Values were calculated from the climate data over the period (1901-1904) to (2017-2018) depending on length of site chronology.

Site	Mean T (C°)	Min T (C°)	Max T (C°)	Precip (mm)	P:T
Cadillac, MI	18.2	11.5	24.9	228	10.1
Alpena, MI	18.2	11.2	25.1	230	9.05
Ginn/Yuhas Woods, IN	21.9	15.7	28.2	295	10.5
Sterns District, KY	22.1	16.6	29.3	337	11.5
Ava/Cassville, MO	24.4	18.0	30.7	309	10.6

Table 3: ARSTAN descriptive statistics for each site. R-Bar represents the mean between-tree correlation among residual chronologies for trees at a site. EPS is the expressed population signal showing agreement of the sample mean chronology with the population chronology during common interval of years when most cores contributed data. Asterisks next to values in the percent variance accounted for by the 1st and 2nd principal components indicate statistical significance at p≤0.05 level.

Site	1st PC % Variance	2nd PC % Variance	r-bar (between tree)	Mean sensitivity	EPS	Avg. Ring Width (mm)
Cadillac, MI	31.12*	17.85*	0.272	0.180	0.870	2.441
Alpena, MI	45.02*	8.440	0.414	0.206	0.914	2.152
Ginn Woods, IN	43.83*	7.451	0.373	0.300	0.886	2.604
Yuhas Woods, IN	43.37*	7.403	0.377	0.233	0.876	2.367
Sterns District, KY	22.93*	8.892	0.157	0.220	0.696	2.475
Ava/Cassville, MO	25.57*	8.873	0.203	0.194	0.836	2.170

Growth-Climate Correlations

Maximum Temperature: Temperature correlated negatively with sugar maple radial growth during the growing season from June-August across most sites (Figure 3). Correlations with temperature during the previous growing season, dormant season of October-May, and the current year September-October were not significant. Correlations with maximum temperature were stronger and showed similar patterns to correlations with mean temperature. Therefore only maximum temperature correlations will be discussed further. Radial growth at Alpena in northwestern Michigan correlated strongest with maximum temperature during the months of July and August (Figure 3). Radial growth at the Cadillac site was not correlated with maximum temperature. At sites in Indiana, Kentucky and Missouri, correlations with maximum temperature were stronger during the June-July period. There was little difference between May-June seasonal growth-climate correlations and June-August seasonal growth-climate correlations at Indiana. Alpena, Michigan had stronger June-August seasonal growth-climate correlations compared to May-July. (Figure 3). Annual maximum temperature was significantly correlated with radial growth only at the Missouri site (Figure 3).

Precipitation: Positive radial growth-precipitation correlations were significant only during the June-July period for all sites (Figure 4). Growth-precipitation correlations for the previous growing season, October-May dormant period, and current year September-October were not significant. At the Alpena site, correlations were significant only in July; monthly correlations were not significant at the Cadillac site. The Indiana and Kentucky sites had stronger correlations in June, while monthly correlations were not significant in Missouri. May-July seasonal correlations were stronger at Kentucky, while June-August seasonal precipitation correlations were stronger at the Cadillac site. Differences in the May-July versus June-August correlations at

the remaining sites were small (Figure 4). Only annual precipitation in Missouri significantly correlated with radial growth (Figure 4).

Palmer Drought Severity Index: Positive radial growth-PDSI seasonal correlations also peaked in the May-August period for all sites (Figure 5). The only significant correlations outside of the May-August period were April PDSI in Missouri and September PDSI in Alpena, Michigan. All other growth-PDSI correlations outside of this period were not significant. Seasonal correlations with growing season PDSI peaked later in the summer for all sites (Figure 5). Radial growth in Alpena, Michigan correlated strongest with PDSI in July, while radial growth never correlated with PDSI at the Cadillac site. Radial growth at Ginn Woods correlated strongest with PDSI in July, while August PDSI correlated strongest at Yuhas Woods. Growth-PDSI correlations at Kentucky were strongest from June-July, while growth-PDSI correlations in Missouri were of similar strength from May-August (Figure 5).
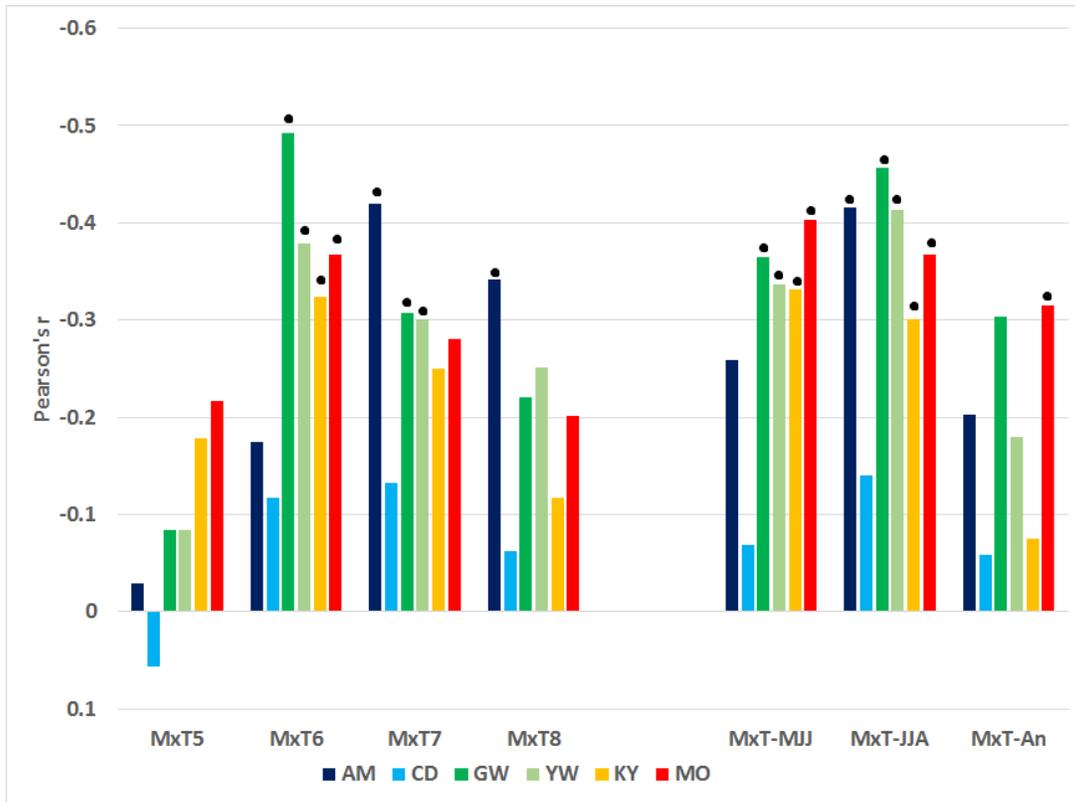
Figure 3: Radial growth-Maximum Temperature correlations (Y-axis inverted) for all 6 sites during the individual months of May-August, the growing season period of May-July, June-August, and annual maximum temperature (previous year June-current year September). Significant correlations are signified with a black dot. Site codes refer to the followng; AM: Alpena, MI, CD: Cadillac District, MI, GW: Ginn Woods, Delaware County, IN, YW: Yuhas Woods, Randolph County, IN, KY: Sterns District, Kentucky, MO: Ava/Cassville Units, MO.
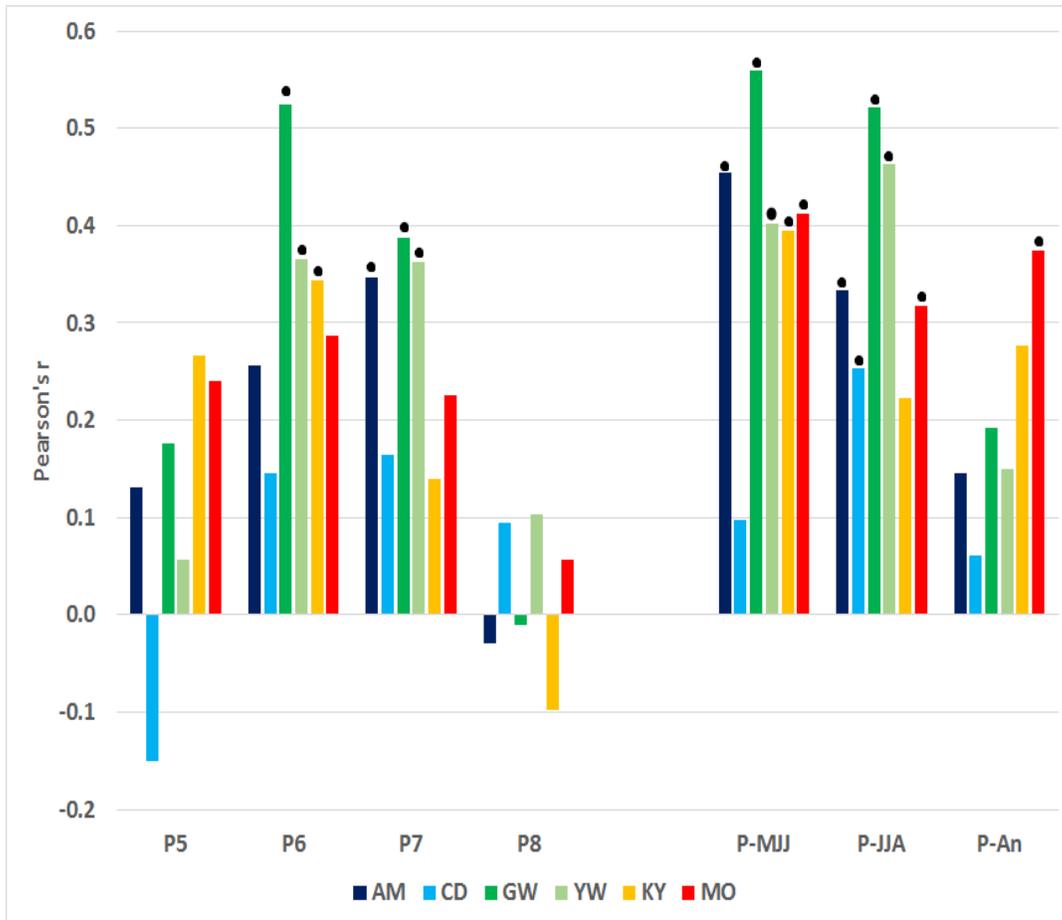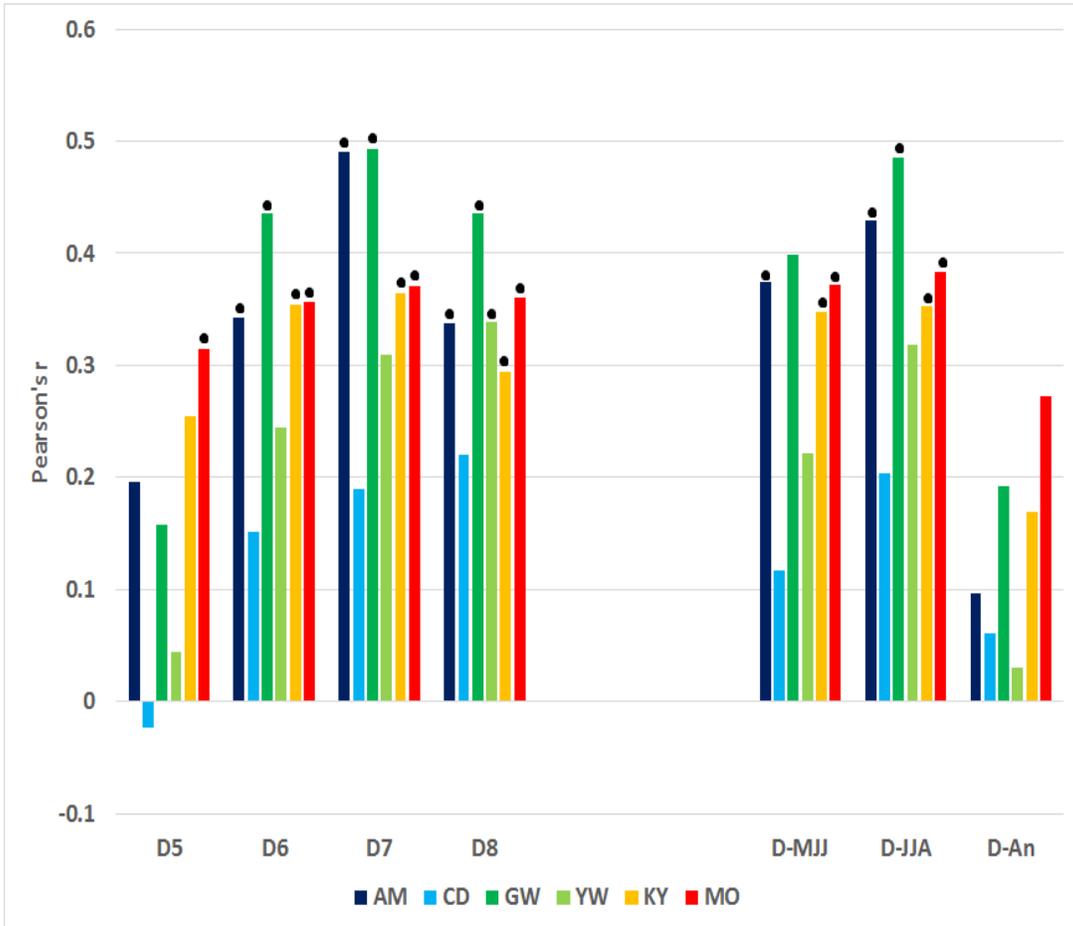
Figure 4: Radial growth-Precipitation correlations for all 6 sites during the individual months of May-August, the growing season period of May-July, June-August, and annual precipitation (previous year June-current year September). Significant correlations are signified with a black dot. Site codes the same as in

Figure 5: Radial growth-PDSI correlations for all 6 sites during the individual months of May-August, the growing season period of May-July, June-August, and annual PDSI (previous year June-current year September). Significant are correlations signified with a black dot. Site codes the same as in Figure 3.

Temporal Stability of Radial Growth-Climate Correlations

Sugar maple radial growth-seasonal climate correlations have changed over the past century, but the patterns of change over time in the correlations differed among sites. *Michigan:* Despite differences in the strength of growth-climate correlations between the northwest Cadillac site and the northeast Alpena site, the manner in which these correlations have changed over the last century was similar. At both sites growth-maximum temperatures correlations during the June-August period were either not significant or have weakened since 1990. Maximum temperatures for this period have changed little over the last century (Figures 6a,b and 7a,b). June-August growth-precipitation correlations at both sites weakened over the last century, and precipitation over this time period has noticeably increased (Figures 6a,c and 7a,c). Growth-PDSI correlations for the June-August period have also weakened over time. PDSI during these months has increased over the last century (Figures 6a,d and 7a,d). *Indiana:* At both Indiana sites, growth-climate correlations have also changed over the last century. At Ginn Woods, growth-maximum temperature correlations for June-August have weakened over the last century. At Yuhas Woods, the correlations have remained relatively stable. At both sites maximum temperature during June-August has changed little (Figures 8a,b and 9a,b). At Ginn and Yuhas Woods positive growth-precipitation correlations have remained relatively stable over time for June-August. This is in spite of an increase in June-August precipitation at the sites (Figures 8a,c and 9a,c). Positive growth-PDSI correlations for June-August have stayed stable for Ginn Woods, but strengthened for Yuhas Woods. This coincides with increasing PDSI values over the past century (Figures 8a,d and 9a,d).

Kentucky: All growth-climate correlations with growing season climate variables strengthened over the past century at the Kentucky site (Figure 10a). Maximum temperature and precipitation has changed little over the past century while PDSI has increased (Figure 10).

Missouri: All growing season growth-climate correlations in southwest Missouri have weakened over the past century (Figure 11). Maximum temperature and precipitation have changed little while PDSI has increased during that time (Figure 11). Only at the Missouri site were annual climate variables significantly correlated with radial growth (Figures 3, and 4). Annual-growth climate correlations have strengthened over time (Figure 12). This occurred as precipitation and PDSI increased while temperature changed little.
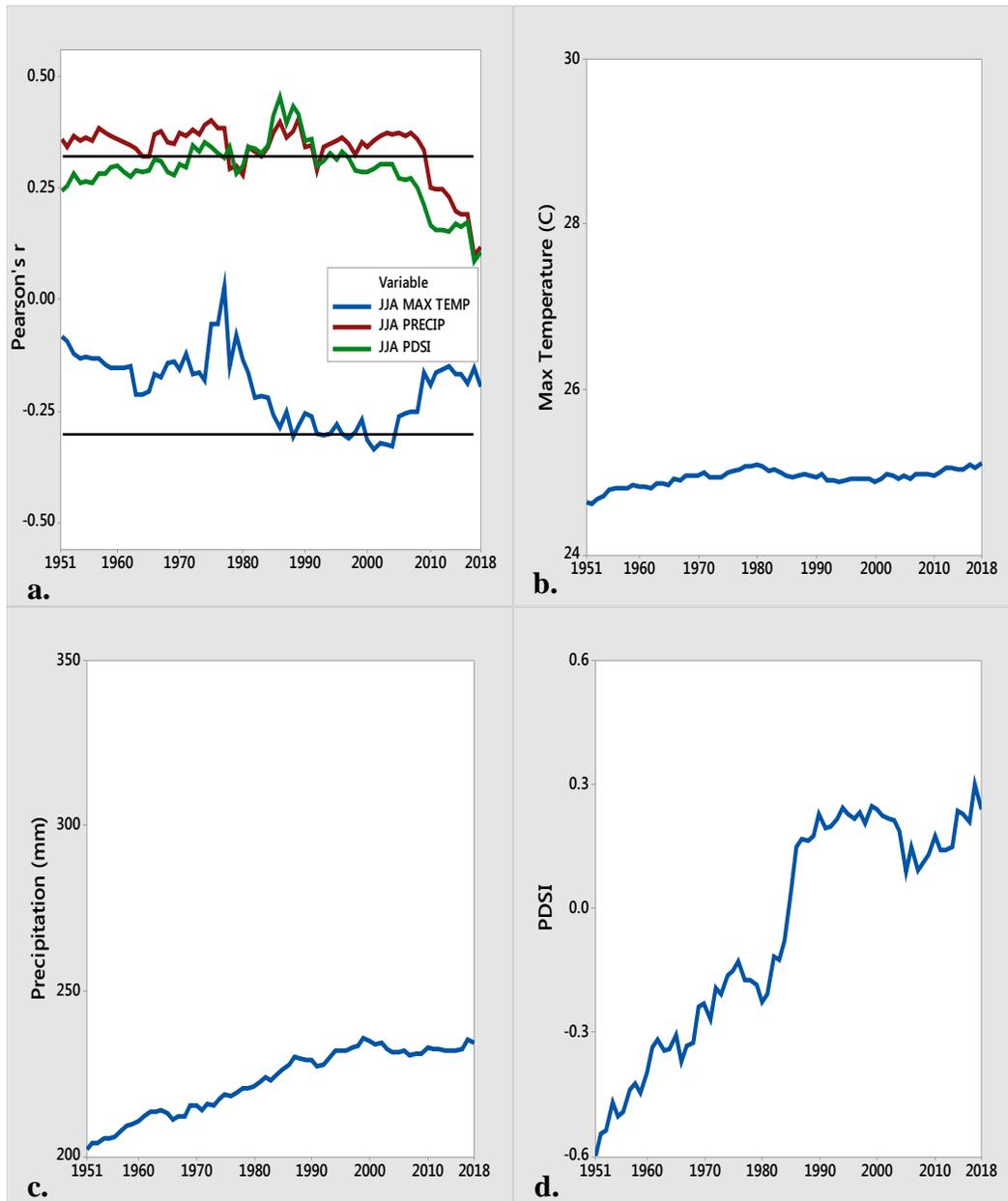
Figure 6 **a.)** Change in radial growth-climate correlations for June-August maximum temperature, precipitation index, and Palmer Drought Severity Index in Cadillac District, Michigan. **b.)** Change in average June-August maximum temperature. **c.)** Change in June-August precipitation. **d.)** Change in June-August Palmer Drought Severity.
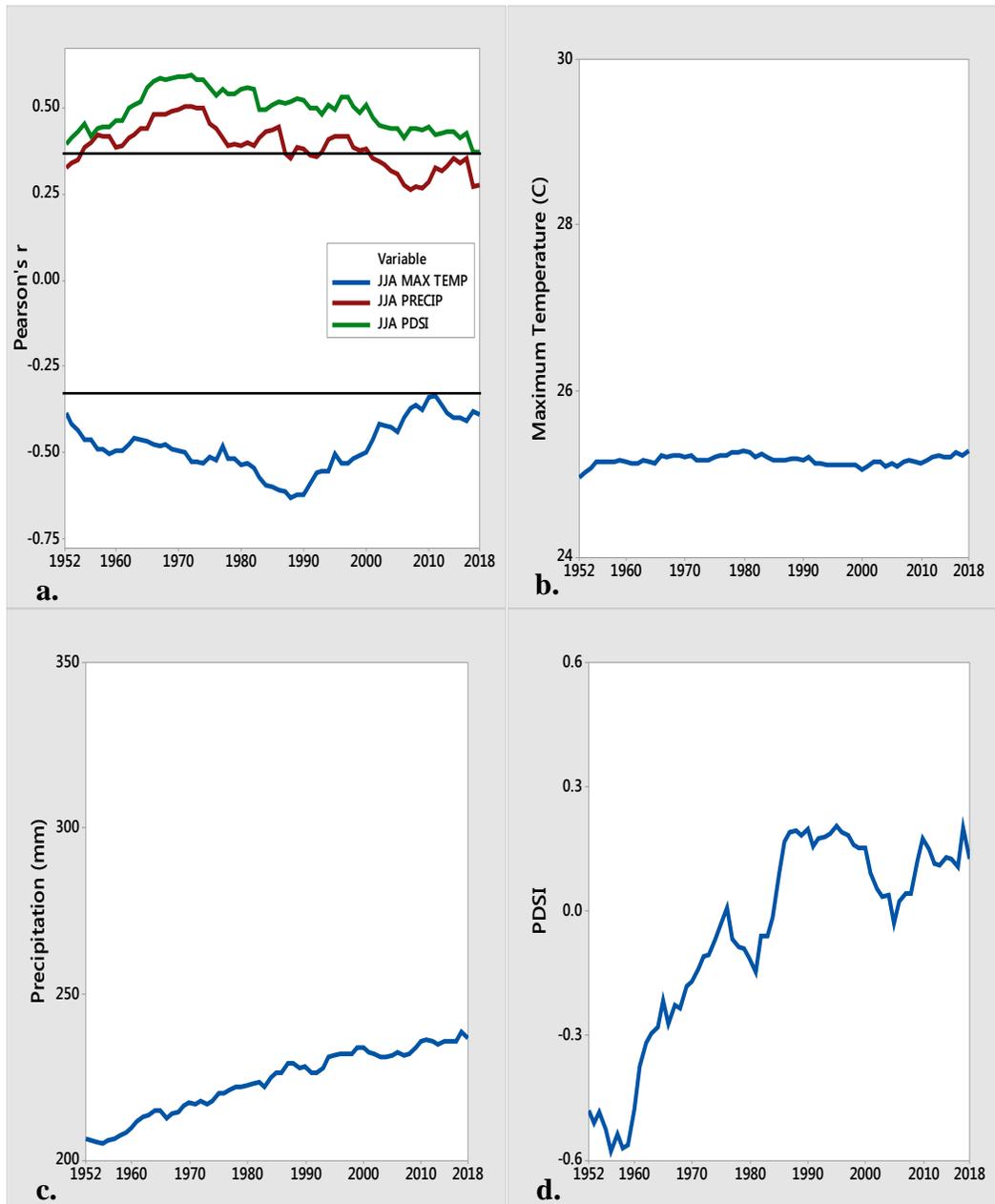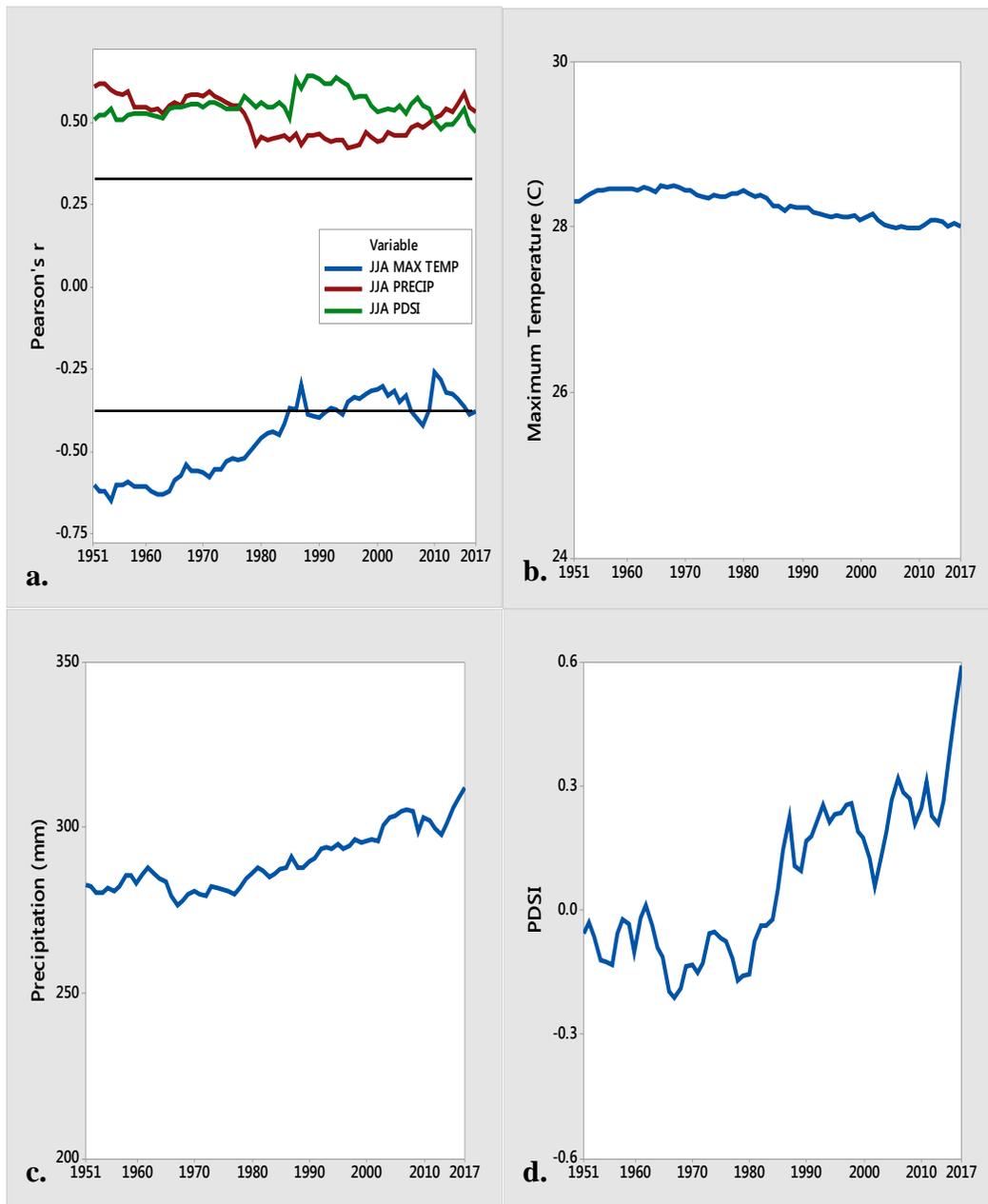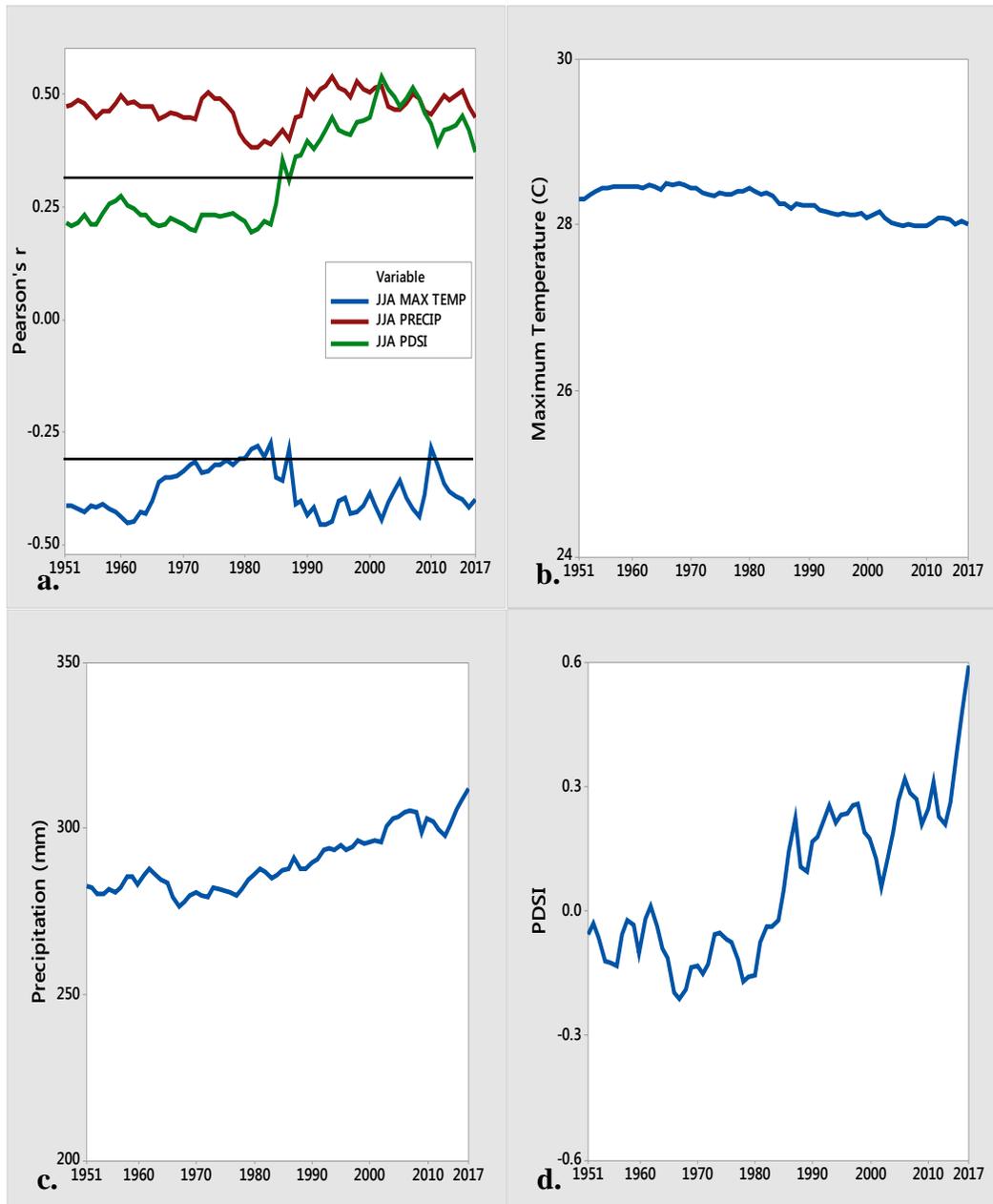
Figure 7: **a.)** Change in radial growth-climate correlations in Alpena, Michigan for June-August maximum temperature, precipitation index, and Palmer Drought Severity Index. **b.)** Change in average June-August maximum temperature. **c.)** Change in June-August precipitation over a 50 year shifting window. **d.)** Change in June-August Palmer Drought Severity Index.

Figure 8: **a.)** Change in radial growth-climate correlations at Ginn Woods, Indiana for June-August maximum temperature, precipitation index, and Palmer Drought Severity Index. **b.)** Change in average June-August maximum temperature. **c.)** Change in June-August precipitation. **d.)** Change in June-August Palmer Drought Severity Index.
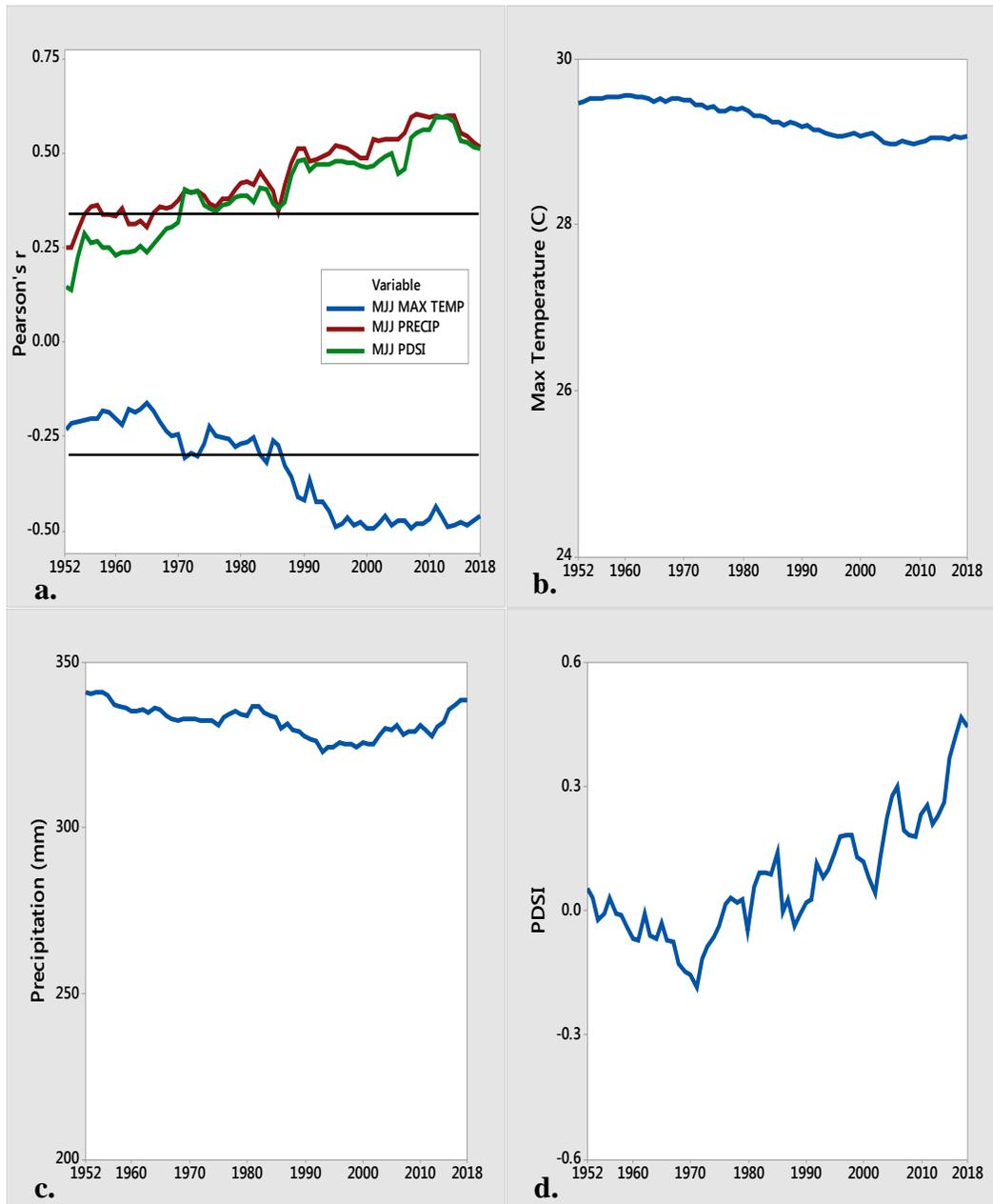
Figure 9: **a.)** Change in radial growth-climate correlations at Yuhas Woods, Indiana for June-August maximum temperature, precipitation index, and Palmer Drought Severity Index. **b.)** Change in average June-August maximum temperature. **c.)** Change in June-August precipitation. **d.)** Change in June-August Palmer Drought Severity Index.

Figure 10: **a.)** Change in radial growth-climate correlations in Sterns District, Kentucky for June-August maximum temperature, precipitation index, and Palmer Drought Severity Index. **b.)** Change in average June-August maximum temperature. **c.)** Change in June-August precipitation. **d.)** Change in June-August Palmer Drought Severity Index.
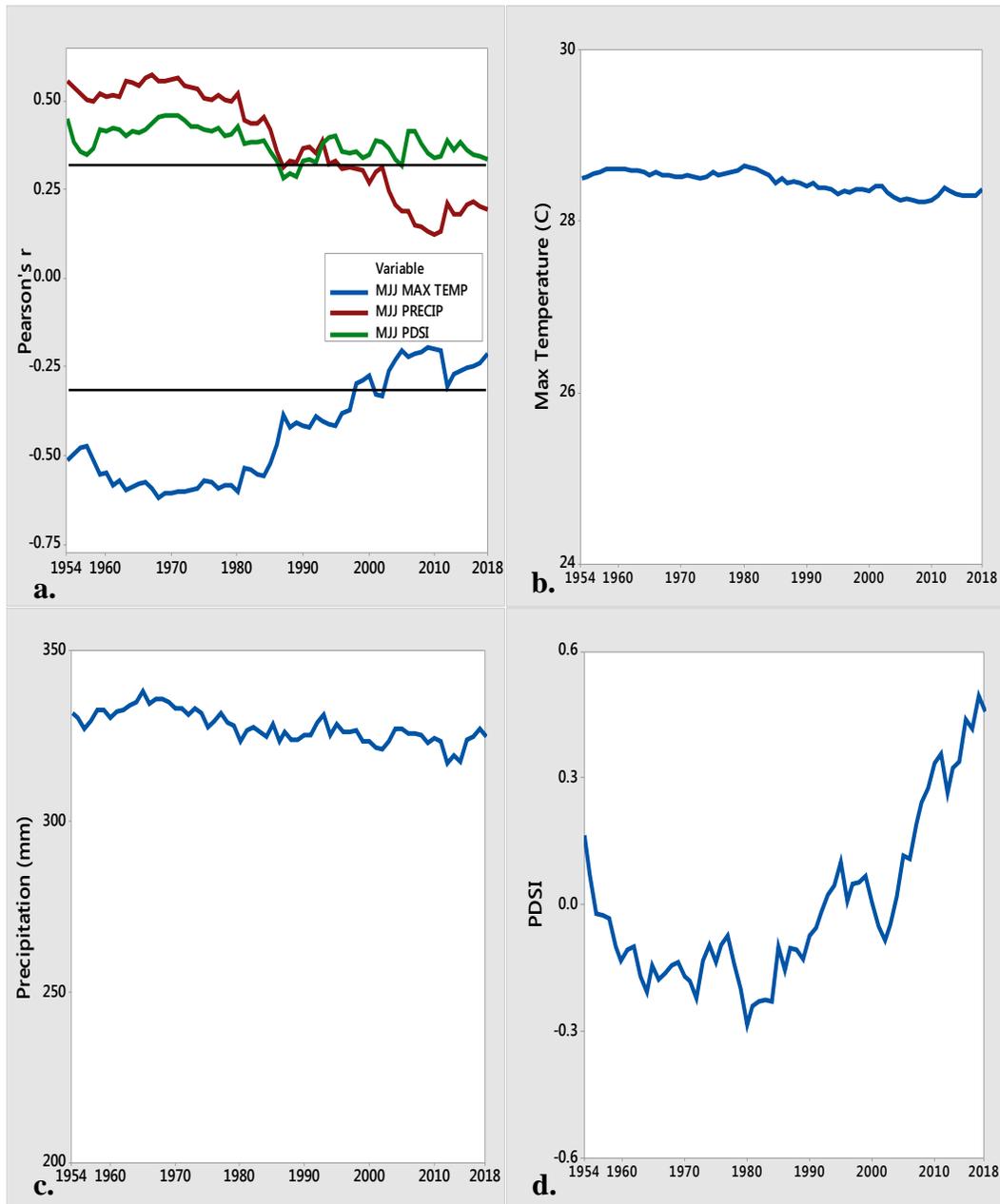
Figure 11: **a.)** Change in radial growth-climate correlations in Ava/Cassville units, Missouri for June-August maximum temperature, precipitation index, and Palmer Drought Severity Index. **b.)** Change in average June-August maximum temperature. **c.)** Change in June-August precipitation over a 50 year shifting window. **d.)** Change in June-August Palmer Drought Severity Index.
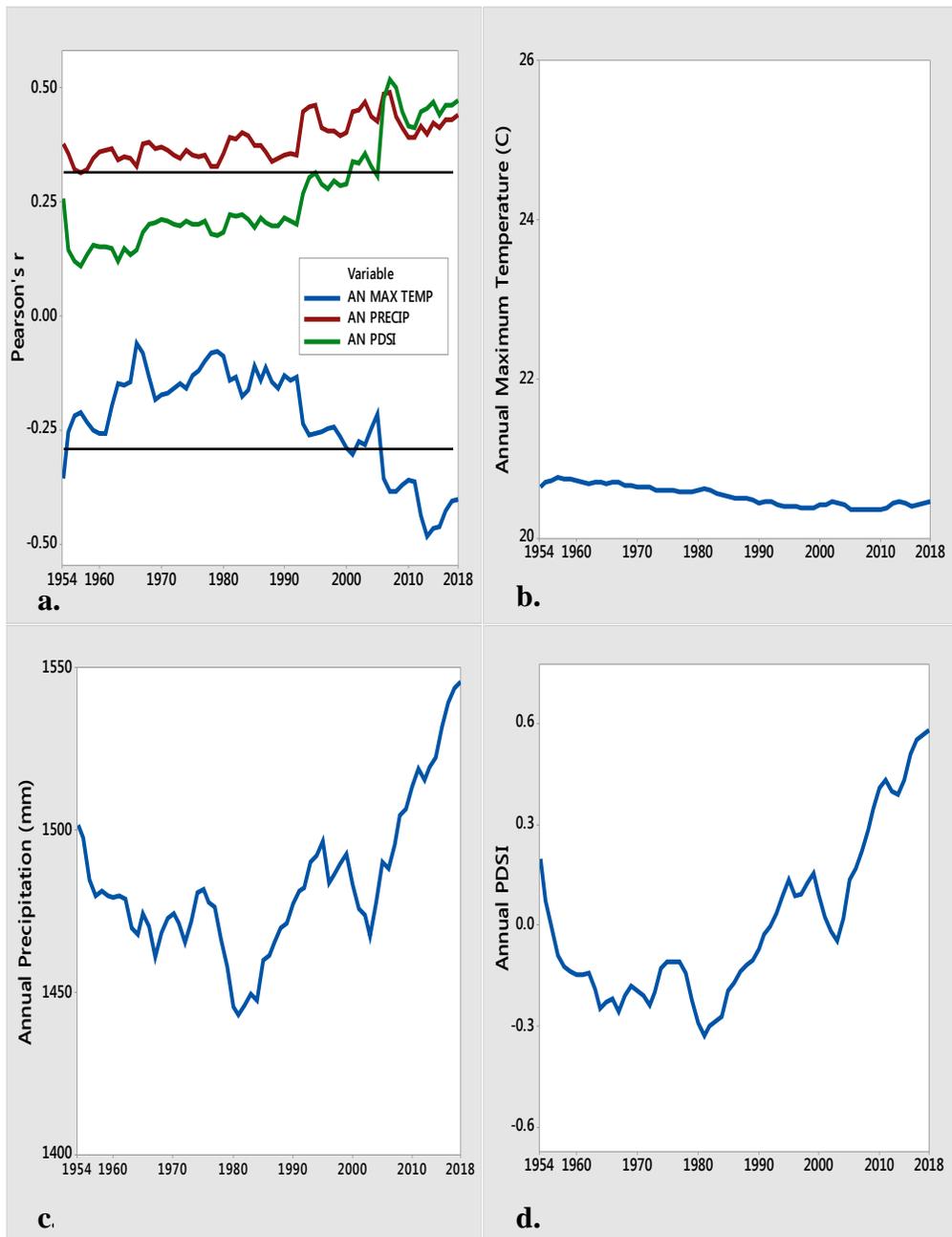
Figure 12: **a.)** Change in annual radial growth-climate correlations in Ava/Cassville units, Missouri for maximum temperature, precipitation index, and Palmer Drought Severity Index. **b.)** Change in average annual maximum temperature. **c.)** Change in annual precipitation. **d.)** Change in Annual Palmer Drought Severity Index. Annual period defined as previous year June to current year September.

Discussion:

The ARSTAN statistics indicated that the influence of climate on radial growth differed among the study sites. The Cadillac, Michigan, Sterns District, Kentucky, and Ava/Cassville, Missouri had the lowest values in the first principal component, r-bar, mean sensitivity, and EPS. These sites also had the weakest growth-climate correlations. This may signify that climate was not as stressful at these sites, or that other factors such as stand dynamics may be degrading the growth-climate signal. Likewise, Alpena, Michigan, and the Indiana sites showed the strongest growth-climate correlations. With the higher values for the first principal component, r-bar, mean sensitivity, and EPS, the effect of climate on radial growth is more easily seen. The significant first and second principal components and low r-bar at the Cadillac, Michigan site may be the result of combining samples from two different sampling areas in. Despite proximity and location in the same state climate division, other factors such as stand history or local site factors may have attributed to these results.

Growth-climate correlations for maximum temperature, precipitation, and PDSI were strongest during the summer period of the growing season at all six sites. These correlations are likely strongest during these months as carbon allocation in sugar maple prioritizes radial growth during this period (Wong et al. 2003). Beginning in August/early September, carbon allocation shifts to dormancy preparation (Wong et al. 2003). Similar patterns have been observed in white oak (McLaughlin et al. 1980), a species that shares much of the same range as sugar maple. This shift in carbon allocation in the late summer also corresponds to lower growth-climate correlations. Climate stress during the May-August period is likely to be reflected in reduced radial growth, resulting in the strongest growth-climate correlations. A similar phenology of

growth-climate correlations was also observed in oak and ash at Midwestern sites (LeBlanc and Terrell 2009, 2011; LeBlanc and Stahle 2015; Lockwood and LeBlanc 2017).

Sugar maple radial growth is likely influenced by site water balance across the western part of its range. Site water balance during the summer portion of the growing season has been proposed as the main factor impacting tree radial growth in the Midwest for other species like oak and ash (LeBlanc and Terrell 2009, 2011; LeBlanc and Stahle 2015, Lockwood and LeBlanc 2017). Drought stress throughout the growing season has also been documented restricting sugar maple radial growth (Brzostek et al. 2014; Abrams et al. 1998). The balance of water inputs due to precipitation and outputs due to evaporative cooling determines water stress for trees as sustained high summer temperatures deplete the soil water reservoir. In this scenario, water stress during the early summer growing season restricts the rate of secondary growth in sugar maple (Wong et al. 2003). Negative temperature correlations and positive precipitation correlations during this period indicate that site water balance is the most likely factor impacting sugar maple radial growth.

Evidence of stronger growth-climate correlations among the sites from North to South along previously described climate gradients was not clearly observed. Precipitation over the growing season infiltrates soils and replenishes the soil water pool. Maximum temperature then influences the potential evapotranspiration at a particular site. When high maximum temperatures causes high potential evapotranspiration, a low amount of soil moisture would result in increased water stress. However, observing maximum temperature or precipitation alone does not allow for direct comparisons between sites. The ratio of precipitation: maximum temperature integrates the effect of these two variables on water stress of sugar maple in a single variable. Using this ratio, water availability and drought stress can be compared among sites with

different climate. Maximum temperature was used in this case, as it better reflects daytime temperatures when evapotranspiration is occurring. Despite the highest average summer temperatures in Missouri and Kentucky, these sites also exhibited the higher precipitation due to closer proximity to the Gulf of Mexico (Bryson and Hare 1974). Higher summer precipitation in Missouri and Kentucky likely kept soil water balance high enough to support radial growth and evaporative cooling despite increased heat stress associated with higher summer temperatures. The opposite was the case in Michigan where lower summer precipitation was seen in conjunction with lower summer temperatures. This may explain why distinct patterns of spatial variation in P:T ratio and increasing growth-climate correlations were not observed over the latitudinal gradient. Increased stress due to higher summer temperatures is likely mitigated in the southern extremes of the western sugar maple range by higher levels of precipitation, resulting in a less stressful environment due to sufficient site water balance. In the northern extremes of the western sugar maple range, stress due to lower precipitation levels is likely mitigated by lower summer temperatures. Again, this resulted in a lower stress environment for sugar maple radial growth due to sufficient site water balance. The east-central Indiana sites had summer temperatures and precipitation higher than the northern sites, but lower than the southern sites. P:T ratios indicated that water stress at the Indiana sites is similar to Cadillac, Michigan and Ava/Cassville, Missouri. Despite some higher growth-climate correlations at the Indiana sites, there is no indication that Indiana climate is more stressful compared to the other sites.

More stressful climate due to stronger impacts of low site water balance for sugar maple in its western range likely explains why growth-climate correlations documented in this study were stronger than reported by studies done at sites in the eastern part of the range. Compared to the eastern portion of the sugar maple range, the western portion experiences greater water stress,

and more prolonged instances of water stress during the growing season (Bryson and Hare 1974). The Appalachian Mountains are known to act as a barrier to the amount of precipitation that occurs west of their range. That combined with lower amounts of precipitation as one moves inland as climate is less affected by the oceans contributes to greater water stress in the western half of the sugar maple range (Bryson and Hare 1974). Previous dendroecological studies of sugar maple in southeastern Quebec, Canada, produced growth-climate correlations with precipitation and temperature during the June-July period no greater than 0.4 or -0.4, and in most cases correlations were around 0.2 or -0.2 (Tardif et al. 2001; Takahashi and Takahashi 2016). In Indiana, Michigan, and Missouri, growth-climate correlations during the June and July months were greater than 0.4. At Ginn Woods, Indiana, correlations with these monthly variables approached 0.5 and 0.6. In the eastern studies, growth-climate correlations peaked in June and July (Tardif et al. 2001; Takahashi and Takahashi 2016). Precipitation and PDSI correlations in Michigan were on par with or higher than June and July correlations for the eastern studies (Tardif et al. 2001; Takahashi and Takahashi 2016).

The strength of sugar maple growth-climate correlations during summer period of the growing has changed over time across all sites, but not in the same manner across all the study sites. A pattern of weakening growth-climate correlations for other tree species in the Midwest has previously been tied to an increase in summer precipitation and a decrease in summer drought for the region that results in less environmental stress due to site water balance (Ficklin et al. 2015; Maxwell et al. 2016). Growth-climate correlations in Michigan, Indiana, and Missouri were observed getting weaker over the last century. Particularly in Michigan and Indiana, this is likely similar to other studies as increased precipitation and little change in summer temperature has resulted in greater site water balance during the summer, and

consequently less environmental stress. However, growth-PDSI correlations at Yuhas Woods, Indiana, and all climate variables in Kentucky for the summer period showed a pattern of strengthening correlations over the last century. In Kentucky, precipitation was not found to increase over the past century. It is not understood why growth-climates correlations at these sites have increased over time, while the other sites showed the opposite pattern with nearly identical changes in climate.

Changes in growth-climate correlations in Missouri weakened over time, but summer precipitation was not observed to be increasing over the past century. Also, growth-climate correlations for annual climate variables were significant and observed getting stronger over time. LeBlanc and Stahle (2015) showed that oak radial growth in the south-central Great Plains correlated strongest with annual climate variables, while correlations with growing season and annual climate variables were equally strong at northern sites in that region. This may be the case of sugar maple in southwestern Missouri. Changes in growth-climate correlations for annual and summer variables over the past century showed opposite patterns. While summer correlations weakened, annual correlation strengthened. In both cases the shift happened in the 1990's. This change is unexpected and a reasonable mechanism has not been identified.

Unexpected patterns in changing growth-climate correlations and low correlations at some sites may be explained by the influence of other environmental factors that could be degrading the growth-climate signal. Site quality may influence the ability to detect growth-climate correlations as tree growth on poor stands may be responding to the local environment rather than climate (Long et al. 2009; St. Clair et al. 2008). However, site quality is unlikely to change over time for these sites and is not a likely explanation for changes in growth-climate correlations over time.

Stand dynamics and tree maturation may play a role in degrading sugar maple growth-climate correlations both among sites and through time. Sugar maple is a shade tolerant species that can quickly take advantage of gaps after decades of suppression, which would be reflected in ring widths release (Burns and Honkala 1990). However, no apparent periods of suppression or release were observed in ring width chronologies at any of the sites during the past century. With site quality and stand dynamics being unlikely to heavily influence the growth-climate signal in this data, changes in correlations over time do not have a casual mechanism that can be explained within the bounds of this study. Weak growth-climate correlations at sites like Cadillac, Michigan may simply be due to climate not being stressful at that location. More research is warranted to understand both spatial and temporal patterns in sugar maple growth-climate correlations.

Conclusions:

Overall, it has been found that sugar maple radial growth is sensitive to climate in the western part of its range. Radial growth-maximum temperature correlations were significant and strongest from June-July in Indiana, Kentucky, and Missouri, while strongest from July-August at Alpena, Michigan. Precipitation correlations were strongest in Indiana, Kentucky, and Alpena, Michigan, from June-July, while Missouri and Cadillac, Michigan, were only significant for summer seasonal precipitation. PDSI correlations were strongest in Indiana, Kentucky, and Alpena, Michigan, from June-August, while correlations were strongest in Missouri from May-August. These correlations were found overall to be stronger than correlations reported in dendroecological studies of sugar maple in the eastern and northern parts of its range. Sugar maple growth-PDSI correlations in its western range were also found to be significant for a longer portion of the summer growing season compared to studies in the eastern portion. This is

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likely due to the western range of sugar maple having a more stressful climate, resulting in lower site water balance during the summer portion of the growing season. Radial growth-climate correlations were also observed becoming weaker over the last century at most sites, and is likely due to increases in summer precipitation, resulting in less drought related stress and an overall less stressful environment during the growing season. However, there is disparity in these results as growth-summer climate correlations in Kentucky and growth-annual climate correlations in Missouri were observed becoming stronger over time. However, the casual mechanism for this disparity cannot be evaluated in this study.

Despite difficulties associated with finding quality sites and sugar maple individuals for this dendroecological study, the results still provide valuable information on past sugar maple growth responses to climate. Climate in the Midwest has become less stressful in the past few decades (Ficklin et al. 2015). This is likely one reason for the increase in sugar maple in many areas of the Eastern Deciduous Forest, and has already been proposed as one of many reasons for oak regeneration failure (McEwan et al. 2011). However, climate in the Midwest is expected to become more stressful in the coming decades. Recent trends in sugar maple growth-climate correlations could potentially change to reflect a more stressful environment as summer precipitation may no longer be able to effectively support radial growth and evaporative cooling in the face of increased summer temperatures (Iverson and Prasad 2001; Iverson et al. 2008). More research is warranted into the dendroecology of sugar maple and other diffuse porous species, as they are an important part to understanding how climate affects the diverse forests of eastern North America.

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