

RADIAL GROWTH CLIMATE ASSOCIATIONS OF WHITE ASH (*FRAXINUS AMERICANA*

L.) IN INDIANA, U.S.A.

A THESIS

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BENJAMIN R. LOCKWOOD

DR. DAVID C. LEBLANC – ADVISOR

BALL STATE UNIVERSITY

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## Chapter 1

### LITERATURE REVIEW

#### INTRODUCTION

Ash species (*Fraxinus*) are ecologically and economically important components of forests in eastern North America (Burns and Honkala 1990). Ash populations in North America are under attack by the emerald ash borer (*Agrilus planipennis* Fairmaire, EAB), an invasive beetle from Asia that is causing widespread ash mortality. Recovery of ash species after the current EAB outbreak, likely decades in the future, will occur under an altered climate regime. Forest managers will need better information than currently exists about the responses of ash species to climate stresses to guide their efforts. Analyses that relate historical variation in width of tree annual growth rings to past variation in climate variables provide a direct means to improve simulation models that are used to predict tree and forest responses to potential climate change (LeBlanc and Foster 1993, LeBlanc and Terrell 2009, 2011). While much of this research has been done for oak species, virtually no research has been done to document the climate responses of ash species in the eastern United States. Unfortunately, millions of large and mature trees that are required for these analyses have succumbed to attack by the EAB. Hence, there is a relatively narrow window of time in the next few years to learn what we can about white ash responses to climate stresses before mature trees are gone.

## WHITE ASH ECOLOGY

The native range of white ash spans from Nova Scotia to northern Florida in the east, and from Minnesota to Texas in the west (Burns and Honkala 1990). A wide variety of soil types can support white ash, most of which are in the orders of Alfisols, Spodosols, and Inceptisols. White ash is particularly sensitive to soil moisture content. Moderately well drained soils in which roots can penetrate to a depth of 40 cm provide for the best growth. While it is rarely found in swamps, white ash is considered an intermediately flood-tolerant species. In the Central States it is most commonly found on slopes along major streams.

White ash is a temperate zone, ring-porous hardwood species. Research suggests that such species produce annual earlywood vessels prior to leaf formation and support this production with energy stores from prior growing seasons (Dougherty et al. 1979; Foster and LeBlanc 1993; Barbaroux and Breda 2002; LeBlanc and Terrell 2009). This is necessary because earlywood becomes nonfunctional over the winter and new vessels must be produced before the tree can support leaf-out. After leaves have emerged, cambium activity switches to latewood production which is supported by photosynthesis during the current growing season. During the late growing season latewood production stops, however photosynthesis is still occurring and metabolites are stored within the tree for future season's earlywood production (Zweifel et al. 2006).

## EMERALD ASH BORER

Emerald ash borer was first identified as the cause of severe ash mortality in Michigan in 2002; however recent studies suggest that it was present in the area as early as 1997 (Siegert et al. 2014). Authors of the study used dendrochronological methods to reconstruct the epicenter

and spread of the outbreak. They found that ash mortality began in 1998 in southeastern Michigan and spread at a rate of 3.84 km per year, but by 2001 spread rate had increased to 12.97 km per year. The authors also documented that satellite colonies emerge at a rate of 7.4 per year with an average dispersal distance of 24.5 km. Seigert et al. documented the ability of emerald ash borer (EAB) to spread at rapid rates across large distances.

Recent research suggests that complete mortality of native ash due to the EAB may be unavoidable (Knight et al. 2010). Knight et al. documented that healthy stands of ash can progress from healthy to nearly 100% mortality in as little as 6 years, regardless of initial ash density, size, habitat, or diversity. The extremely high rate of ash mortality due to the EAB means that ash will likely need to be re-established in some areas if extinction is to be prevented. Forest managers will need accurate information about ash climate tolerances to implement a reintroduction after decades of climate change.

## DENDROECOLOGY OF *FRAXINUS* GENUS

Tree growth is frequently affected by variations in climate, and the response to this variation is recorded in the annual rings of the tree (Fritts 1976). Fritts describes the possible biological mechanisms responsible for climate factors leading to variation in the annual rings. For example, under conditions of low precipitation and high temperature a tree is subjected to an increase in water stress. This can lead to less net photosynthesis and an overall decrease to carbon translocation and storage throughout the tree. Water stress can also lead to decreased transpiration, which results in heat stress, leaf damage and premature leaf drop resulting in

reduced net photosynthesis. Ultimately the overall result of an increase in water stress is that there is less potential for cambial growth.

Tardiff and Bergeron (1993) studied the principal environmental factors relating to radial growth of black ash (*Fraxinus nigra* Marsh.) in northwestern Quebec. Tree-ring samples were collected in 50 quadrats within five stands located on different topographic position (sandbar, along river, near bog, upland away from bog or river, and river delta). Redundancy analysis was used to compare the mean standardized chronologies of the 50 quadrats. Response of trees to climate factors was assessed using response function analysis. Four subgroups of quadrats were formed on the basis of the redundancy analysis: (1) Sandbar and river delta stands, (2) Near bog quadrats, (3) Near-river quadrats, and (4) All quadrats located in stands far from river or bog (upland sites). They found that trees in both groups 2 and 3 showed a positive correlation with April and July temperatures of the current year when the annual ring formed. Group 3 showed no correlation with summer precipitation in the current year. Radial growth of ash trees on upland (Group 4) sites had positive correlation with June precipitation. Tardiff and Bergeron concluded that the radial growth of black ash was influenced by weather conditions in the year prior and the year of growth. The results also suggest that the growth-climate associations of black ash are strongly influenced by topographic position.

Tardiff and Bergeron (1997) studied the effect of climate on black ash in northwestern Quebec, near the northern and western range limits of the species (Burns and Honkala 1990). Black ash tree-ring chronologies were developed for an upland site where black ash is not affected by flooding. Increment core samples in this study were processed using standard dendrochronological procedures detailed by Fritts (1976). Pearson correlation analysis was used to analyze the associations between climate and radial growth. They found that black ash on this

site showed negative association with August temperature of the previous year and a positive association with August precipitation of the previous year. This suggests that water stress during the previous year causes trees to produce less radial growth the following year. They also found that black ash radial growth was negatively correlated with regional temperature during May of the current year and to Canadian Drought Code during June of the current year. This suggests that limited water availability during the early growing season negatively affects the radial growth of black ash on upland sites. While the growth-climate associations for black ash on the upland site were weak, the results indicate that water availability is a primary influencer of radial growth of black ash on these sites.

## FUNCTIONAL GROUPING

Cook et. al (2001) introduced the hypothesis that functional groups of tree species comprised of species with similar biology will respond similarly to climate. They conducted a dendroclimatic study of trees species in Gulf Coastal Plain region of eastern Texas to test this hypothesis. The chronologies developed for this study were analyzed using rotated principal components analysis (RCPA) to determine phylogenetic groups. This analysis revealed three phylogenetic signals, which separated data into *Pinus* species, oak species in the black oak subgenus, and species in the white oak subgenus combined with *Fagus* species. Precipitation and maximum temperature data were then used to model the dendroclimate signals in the chronologies and the resulting correlations were subjected to RCPA. The phylogenetic groups that emerged from the climate correlations RCPA were the same as the RCPA results from the chronologies. The results suggest that similar genetics cause phylogenetic groups of trees to

respond similarly to climate. These results further suggest that functional groupings of tree species can be used in vegetation/climate models to realistically predict how forests will respond to future climate change.

LeBlanc and Terrell (2011) studied the growth-climate associations for northern red oak (*Quercus rubra* L.) and white oak (*Quercus alba* L.) at 82 sites across eastern North America. Samples were acquired from a combination of existing databases and field sampling, then cross-dated. ARSTAN was used to compute a mean residual tree-ring index chronology for each site. They used simple Pearson product-moment correlation analyses between each site residual ring index chronology and monthly, seasonal, and annual climate variables. No significant differences were found between white oak and northern red oak in the proportion of sites where significant correlations were observed. An average of 83% agreement was observed between the species with regard to whether a climate variable was significantly correlated with radial growth. LeBlanc and Terrell hypothesized that the high degree of similarity in growth-climate relationships between white oak and northern red oak suggest that other species with similar biology/ecology (temperate zone ring-porous hardwood species) may respond similarly to climate variation. Studying climate variation responses by functional groups rather than for individual species could simplify forest simulation models.

Research conducted by Cherubini et al. (2003) suggests that radial growth of members of the genera *Fraxinus* and *Quercus* may respond similarly to climate variation. The study analyzed annual growth rings of *Arbutus unedo* L., *Fraxinus ornus* L., *Quercus cerris* L., *Q. ilex* L., and *Q. pubescens* Willd. growing in Tuscany, Italy. *Fraxinus ornus*, *Q. pubescens* and *Q. cerris* are deciduous species with ring-porous wood that undergo a winter dormancy phase. The authors found that mean ring-width chronology patterns for these species are similar to

precipitation patterns during dry periods. In addition the authors found the highest between species correlation of mean chronologies of the five species analyzed was between *F. ornus* and *Q. pubescens* (0.88) and correlations between these two species and the other winter deciduous oak species (*Q. cerris*) were greater than or equal to 0.8. Between species correlations were much lower (0.46 to 0.66) when evergreen hardwood species or diffuse-porous species were compared to deciduous ring-porous oak and ash species. This study supports the hypothesis that species with similar biology and ecology may respond similarly to variation in climate.

## IMPLICATIONS

The information presented in this review focuses on several main points. A limited amount of existing literature documents the associations between climate variables and radial growth of species within the genus *Fraxinus*. Research suggests that radial growth is positively associated with precipitation variables and negatively associated with temperature variables. However, virtually no information exists about the growth-climate associations of white ash, one of the most common and widespread ash species in North America. Recent publications suggest that tree species with similar biology and ecology may respond similarly to climate variation, which would allow researchers to study climate responses of trees at a “functional group” level. A comparison of growth-climate associations between ash and oak species would represent a test of this hypothesis. However, the time available to study white ash growth-climate associations is limited due to widespread mortality caused by the current EAB outbreak.

## Chapter 2

### WHITE ASH RADIAL GROWTH RESPONSE TO CLIMATE

#### INTRODUCTION

The native range of white ash (*Fraxinus americana* L.) spans from Nova Scotia to northern Florida in the east, and from Minnesota to Texas in the west (Figure 1, Burns and Honkala 1990). A wide variety of soil types can support white ash, most of which are in the orders of Alfisols, Spodosols, and Inceptisols. White ash is particularly sensitive to soil moisture content. Moderately well drained soils in which roots can penetrate to a depth of 40 cm provide for the best growth. While it is rarely found in swamps, white ash is considered an intermediately flood-tolerant species. In the Central States it is most commonly found on slopes along major streams.

Literature regarding dendroecology of the genus *Fraxinus* is non-existent within the United States. Research for ash species in Canada and Europe suggests that members of the genus *Fraxinus* do exhibit correlations between radial growth and precipitation and temperature patterns (Tardiff and Bergeron 1993, 1997; Cherubini et al. 2003 ). Tardiff and Bergeron (1993) studied the principal environmental factors relating to radial growth of black ash (*Fraxinus nigra* Marsh.) in northwestern Quebec, near the northern and western range limits of the species. Samples were collected in 50 quadrats within five stands in different topographic position (sandbar, along river, near bog, upland away from bog or river, and river delta). Redundancy analysis was used to compare the mean standardized chronologies of the 50 quadrats. Response of trees to climate factors was assessed using response function analysis. Four subgroups of

quadrats were formed on the basis of the redundancy analysis: (1) Sandbar and river delta stands, (2) Near bog quadrats, (3) Near-river quadrats, and (4) All quadrats from stands far from river or bog (upland sites). They found that trees in both flood-prone habitats (groups 2 and 3) showed a positive correlation with April and July temperatures of the current year. Group 3 showed no correlation with summer precipitation in the current year. Radial growth of ash trees on upland sites (Group 4) had negative correlation with previous year October temperatures and positive correlation with precipitation during June of the current year. Tardiff and Bergeron concluded that the radial growth of black ash was influenced by weather conditions in the year prior and the year of growth. The results also suggest that the growth-climate associations of black ash are strongly influenced by topographic position. Tardiff and Bergeron (1997) continued to study the effect of climate on radial growth of black ash (*Fraxinus nigra*) in northwestern Quebec. Black ash tree-ring chronologies were developed for an upland site where black ash is not affected by flooding. Samples in this study were processed using standard procedures and Pearson correlation analysis was used to analyze the associations between climate and radial growth. They found that radial growth of black ash on this site was negatively correlated with August temperature of the previous year and positively correlated with August precipitation of the previous year. This suggests that water stress during the previous year causes trees to produce less radial growth the following year. They also found that black ash radial growth was negatively correlated with regional temperature during May of the current year and to Canadian Drought Code during June of the current year. These findings suggests that limited water availability during the early growing season negatively affects the radial growth of black ash on upland sites. While the growth-climate associations for black ash on the upland site were weak,

the results indicate that water availability was a primary influencer of radial growth of black ash on these sites.

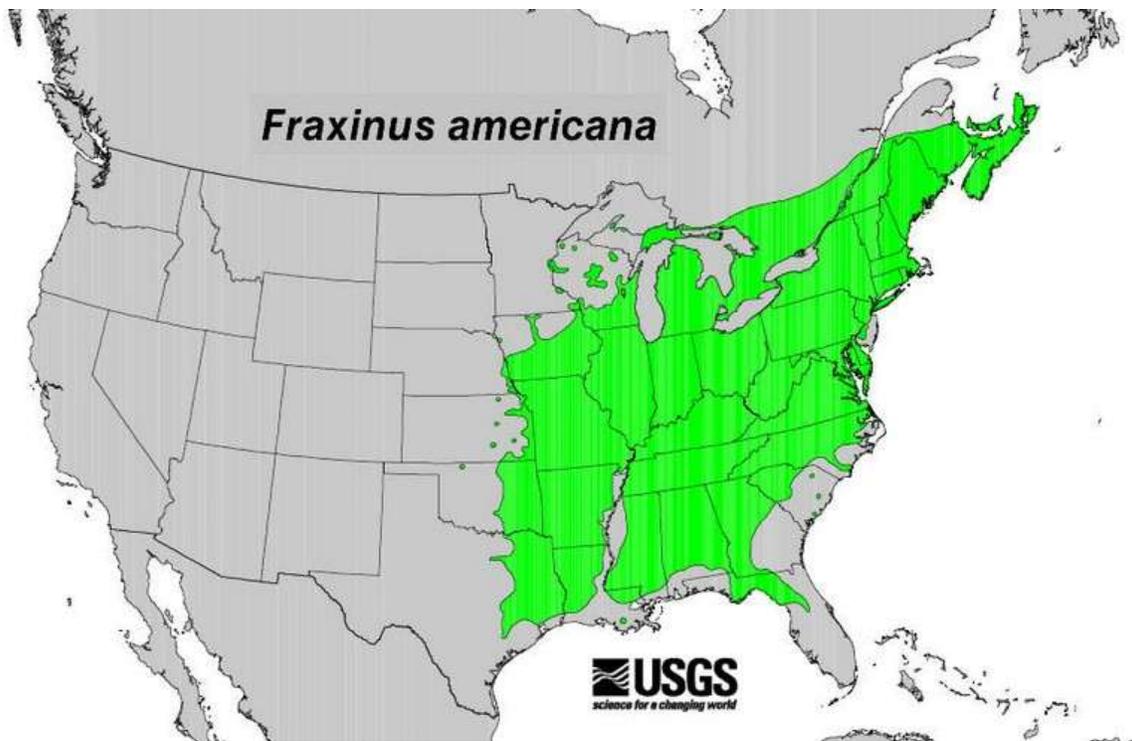
The current emerald ash borer (*Agrilus planipennis* Fairmaire, EAB) outbreak may have the potential to cause complete loss of native ash species in the United States (Bumgardner et al. 2007; Knight et al. 2010). Assuming the EAB continues its invasion at the current pace, a very large proportion of native ash population will be lost. Thus, there is a limited time-frame to acquire information about the growth-climate associations of this species. Once the current EAB outbreak has passed, forest managers may attempt to re-introduce ash to save the species from extinction. However, ongoing climate change means that managers will be introducing ash species under altered climate regimes (IPCC 2007). Detailed information about the climate tolerances of ash species will provide forest managers and researchers with knowledge that might be useful to predict how ash trees planted in future forests might respond to changes in climate. This study is an initial step to understanding the growth-climate relationships of white ash. This type of information may also be used more broadly to improve general predictions of future forest responses to climate change.

The purpose of this study is to identify and describe associations between climate variation (temperature and precipitation) and radial growth of white ash in central and southern Indiana, U.S.A. Specific study objectives were: (1) to describe radial growth-climate associations for white ash, (2) to determine how the production of earlywood and latewood is influenced by climate and (3) to observe any differences in the radial growth response of white ash between well-drained sites and poorly-drained sites.

## METHODS

### STUDY SITES

Sites included in this study were all located in the state of Indiana and chosen to include a range of topographic position and soil drainage. Ginn Woods and Christy Woods were chosen as sites with flat topography, heavy soils, and poor drainage. Wilbur Wright Fish and Wildlife Area and Deam Wilderness area of Hoosier National Forest were chosen for hilly topography and well-drained soils. All sites have similar climate. Indiana is located near the center of the species geographic range (Figure 1).



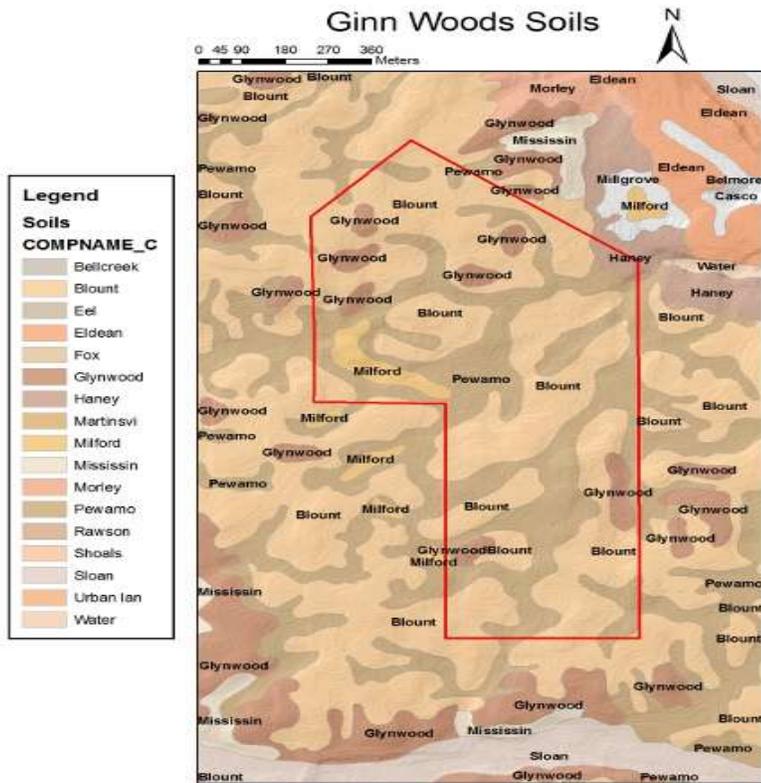
**Figure 1.** Natural range of white ash in North America.

### Christy Woods: Poorly drained site

Christy woods is a 7.3 ha property located on the southwest corner of the Ball State University campus. The topography is relatively flat with a range of 2.5 m in elevation. Due to poor drainage widespread standing water often accumulates in low-lying areas in spring. The entirety of Christy Woods is poorly drained Blount silt loam. Approximately 75% of Christy Woods is covered by mature forest dominated by a mixture of oak, hickory, ash, walnut, and maple. The ash trees are currently under attack from the EAB and are being removed.

### Ginn Woods: Poorly drained site

Ginn Woods is a 65 ha property owned by Ball State University, located in north-central Delaware County, Indiana. It contains the second largest stand of old-growth forest in the state (Ruch et al. 2004). The topography of Ginn Woods is flat, containing many closed depressions which form temporary wetlands. The soils of Ginn Woods are moderately well drained Glynwood silt loam, poorly drained Blount silt loam, poorly drained Pewamo silty clay loam, and very poorly drained Milford mucky silty clay (Figure 2). The mature forest is dominated by maple, beech, basswood, with smaller amounts of oak, elm, ash, and hickory. Ginn Woods provides the opportunity to study ash growth-climate associations in an area with little to no human disturbance on a relatively flat site with poor drainage.



**Figure 2.** Ginn Woods soils map. Red line indicates forest perimeter.

Wilbur Wright Fish and Wildlife Area: Well-drained site

The Wilbur Wright Fish and Wildlife Area contains 433 ha of river valleys and uplands (Figure 3). The upland forest area sampled in this area (Figures 3 & 4) is dominated by Losantville silt loam soils (LeC) and includes white oak, northern red oak, white ash, as well as many other species.



**Figure 3.** Wilbur Wright FWA soils map. Red rectangle indicates sampling area on upland Losantville silt loams (LeC).

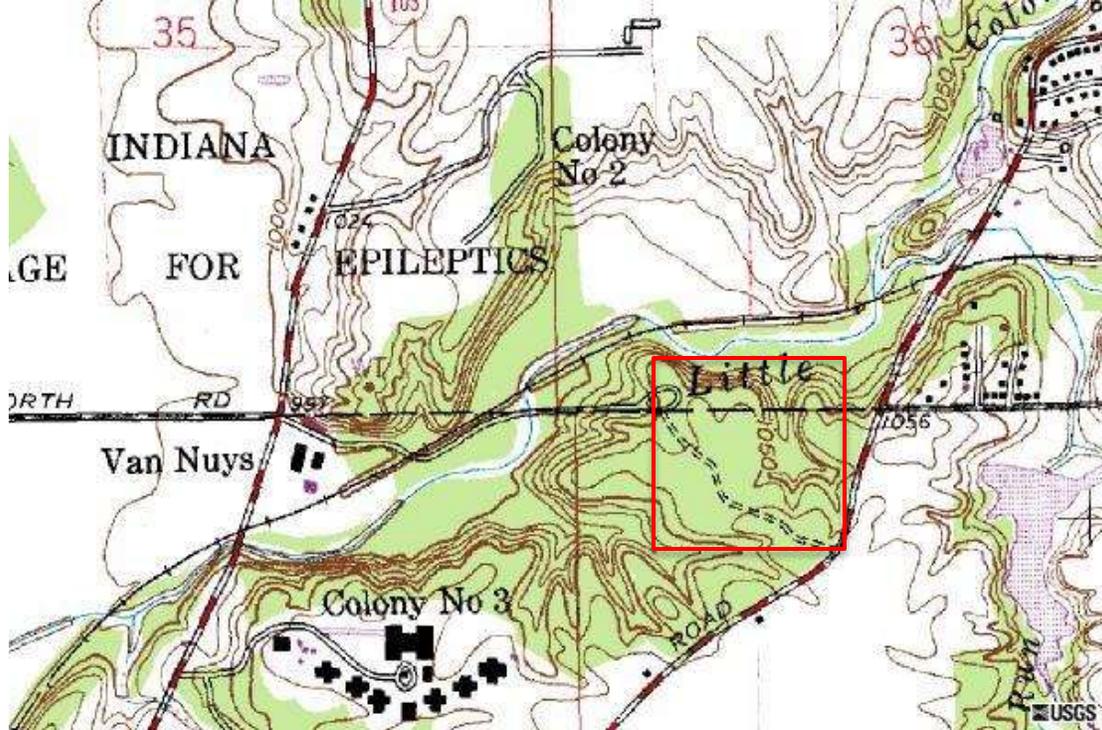
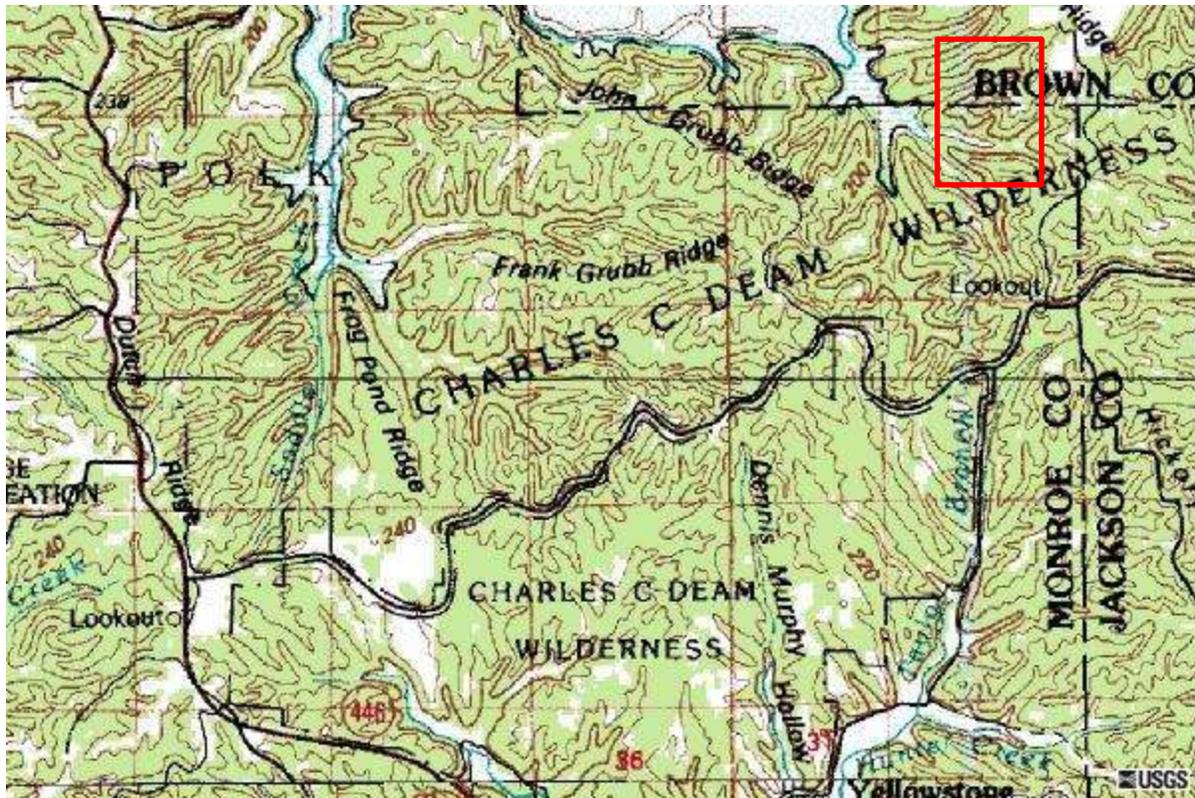


Figure 4. Wilbur Wright FWA topographic map. Red rectangle indicates sampling area.

Hoosier National Forest – Pleasant Run Unit: Well drained site

*Terrill Ridge Area, Charles C. Deam Wilderness Area*

The Charles C. Deam Wilderness area is a 5,260 ha site located within the Hoosier National Forest in south central Indiana. The soils within this area were derived from weathered sandstones and siltstones and are dominated by Berks, Gilpin, and Weikert silt loams (Boerner and LeBlanc 1995). This site contained a diversity of micro-site types depending on aspect and slope position. Site-types included in this study were upper and lower slope positions (Figure 5).



**Figure 5.** Deam Wilderness Area, Hoosier National Forest, Indiana topographic map. Red rectangle indicates slopes where white ash trees were sampled

## SAMPLING

Fifteen trees were sampled at each of the five study sites. Individual trees were selected based on the following criteria: (1) living or recently dead (fine twigs still present), (2) mature trees in the canopy with no obvious signs of physical damage, and (3) no indication of major competitive release or damage within the past 60 years as determined at time of coring. Two increment core samples were taken from each tree at 1.4m above the ground on opposite sides of the stem along an axis perpendicular to the slope. Cores were taken perpendicular to the longest diameter of the stem in trees located on flat topography.

## MEASUREMENTS

Cores were air dried, mounted, sanded, and visually crossdated using marker rings (narrow growth rings formed by many trees in a region, often associated with regional drought). Annual ring width was measured to 0.01mm precision using a Velmex measuring table. These measurements included separate earlywood and latewood measurements. The computer program COFECHA (Holmes 1983) was used to verify visual crossdating and identify large measurement errors. COFECHA works by first creating an average master chronology for all cores from a site. Data for each core is split into smaller 20 yr segments and statistically correlated against the master chronology. Correlations below a specified level were cause for increased scrutiny to identify potential errors in initial visual crossdating and for large measurement errors.

## CHRONOLOGY DEVELOPMENT

The ARSTAN program (Cook 1985) was used to calculate a mean tree-ring chronology for each site in a multistep process. First a cubic smoothing spline was applied to each of the two individual cores taken from each tree. ARSTAN takes the ring width and divides it by the model fit created by the cubic smoothing spline which results in an index value with the average of 1.0. This step removes much of the variance associated with tree aging and stand dynamics. ARSTAN then models temporal autocorrelation between successive annual ring indices and removes this to produce a chronology of statistically independent ring indices that reflect yearly variation in growth. A robust bi-weight mean function was used to calculate a master chronology of mean ring width index values by year to produce the residual ring index chronology for each site and site-type. This chronology was used in the analysis of growth-climate associations.

ARSTAN was used to perform a common period analysis of tree-ring chronology statistics that are used to assess relative influence of climate on radial growth. Ring-width chronologies were shortened to a common time period shared across enough trees within a study sites to reach an expressed population signal (EPS) of at least 0.85. This  $EPS \geq 0.85$  criterion is widely used in dendroclimatology literature to determine the minimum sample size to compute a mean chronology that has adequate precision for analyzing growth-climate associations. ARSTAN produces a set of EPS values as a function of the number of cores in the sample. The mean chronology is shortened to the longest period of years that are common across increment cores with different numbers of annual rings while still maintaining an EPS of at least 0.85. This ensures the dominant signal in the chronology is a coherent stand-level signal, rather than the individual tree-level signal. Based on this criterion, the time interval used for all common period analyses was 1943 to 2008.

## CLIMATE DATA

Climate data were obtained from existing databases. Mean monthly temperature, total monthly precipitation, and monthly Palmer Drought Severity Index data for state climate divisions were obtained from the National Climate Data Center (NCDC 1994). Data for state climate division 8 (south central Indiana) were used for the sites in the Hoosier National Forest and for state climate division 6 (east central Indiana) were used for Chrisy Woods, Ginn Woods, and Wilbur Wright FWA sites. Mean monthly maximum temperature data was obtained from the United States Historical Climatology Network (Easterling et al. 1999). Since this data was

recorded from individual weather stations it was averaged across the multiple stations that were in the same state climate divisions as the study sites.

## DATA ANALYSIS

Simple Pearson's product-moment correlation analyses was performed between the ARSTAN residual chronologies computed for each of the study sites and monthly climate variables for the period beginning with June of the year prior to ring formation through October of the year when the ring was produced. Monthly climate variables included mean temperature, mean maximum temperature, precipitation, and Palmer Drought Severity Index. Correlation analyses were also performed using seasonal and annual averages of the same climate variables. Seasons were defined as prior year summer (June-August), prior year autumn (September-November), prior year winter (December-February), spring (March-April prior to annual ring formation), and early growing season (May-July when most of the annual ring is formed).

Growth-climate correlations were compared across site types (poorly-drained versus well-drained). Where consistent differences were found the Fisher z-transformation and a two-sample t-test were used to determine the significance of the differences (Zar 1996).

ARSTAN chronology common period statistics (mean sensitivity, percent variance in the first principal component, expressed population signal, and between tree correlation) were compared among tree ring width variables and across different site types. Mean sensitivity is a measure of year-to-year variation in a chronology. Percent variance is the percentage of variation that is due to the common signal among trees in the sample. Expressed population signal (EPS) is an expression of the strength of the common signal in the stand. Between-tree

correlation ( $\bar{r}$ ) is used to evaluate the signal-to-noise ratio throughout the chronology. Larger values for all of these statistics indicate a stronger climate signal in the chronology.

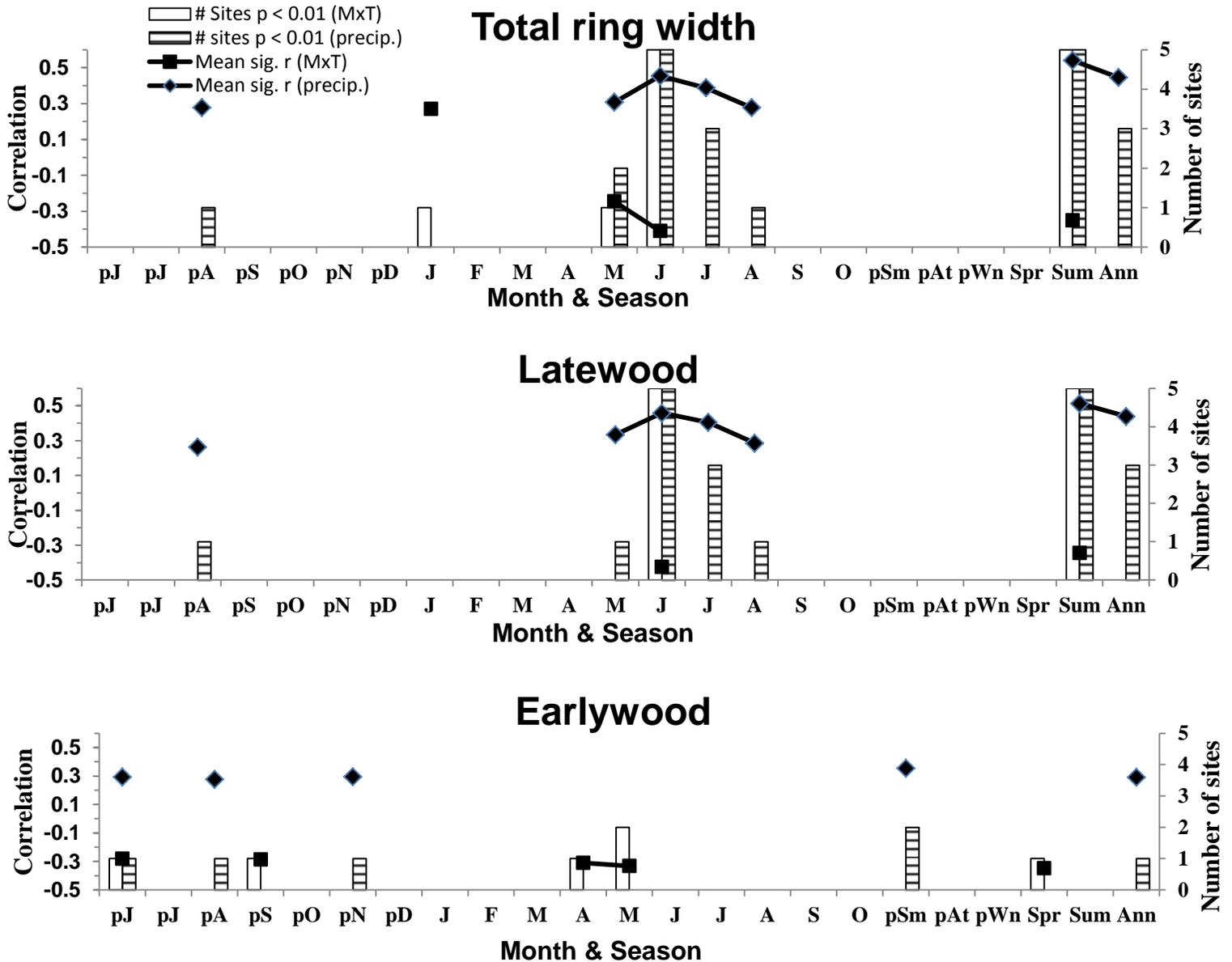
## **RESULTS**

### **CORRELATIONS WITH CLIMATE VARIABLES**

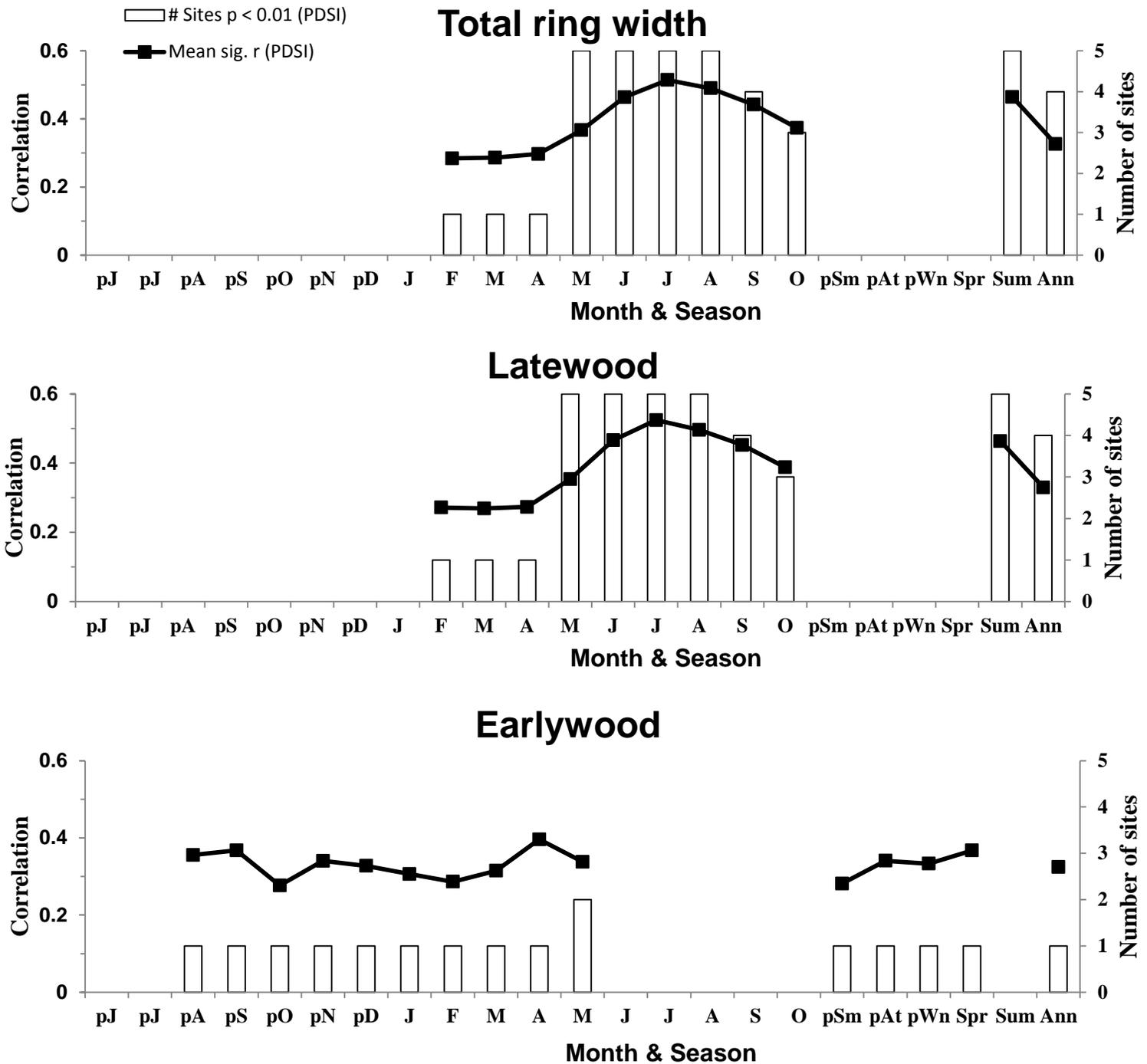
Correlation analysis was performed in two steps: first correlations between radial growth and climate variables at each site were analyzed, then significant correlations were averaged among sites to determine which climate variables were consistently significantly correlated with radial growth across study sites (Figures 6 & 7). Climate variables for June of the year the annual ring was formed were most consistently significantly correlated with ash radial growth. Positive correlations were found between ash total ring width and June precipitation and June PDSI at all sites. Negative correlation was found between ash total ring width and June mean temperature and June mean maximum temperature at all sites. Significant positive correlations were found between ash total ring width and PDSI and precipitation in the months of May and July at several sites. Growth-climate correlations were virtually identical for latewood width and total ring width. Ash earlywood was significantly correlated with some monthly climate variables prior to the growing season however the specific months were not consistent across any sites. Correlations between ash radial growth and mean monthly temperature variables are not presented because the monthly and seasonal patterns of correlations were the same as for mean monthly maximum temperature, but the correlations were weaker.

Consistent correlations were also found between ash radial growth and seasonal climate variables. Total ring width and latewood were significantly positively correlated with

precipitation and negatively correlated with maximum temperature during the current year early growing season (Sum) at all sites (Figure 6). Earlywood was correlated with prior growing season precipitation and PDSI, but not consistently across sites. There were no significant correlations between earlywood width and any current growing season variables after May.



**Figure 6.** Correlations between white ash total ring width, latewood, and earlywood and monthly, seasonal, and annual maximum temperature (MxT) and precipitation (precip.). Months on the X-axis range from June of year prior to ring formation (pJ) to October of year when ring was formed (O). Seasons range from summer of prior year (pSm) to summer of current year (Sum). Lines with symbols indicate the mean of significant correlations ( $p < 0.01$ ). Histogram bars indicate number of sites (out of 5) where a significant correlation was observed.



**Figure 7.** Correlations between white ash total ring width, latewood, and earlywood and monthly, seasonal, and annual Palmer drought severity index (PDSI). Months on the X-axis range from June of year prior to ring formation (pJ) to October of year when ring was formed (O). Seasons range from summer of prior year (pSm) to summer of current year (Sum). Lines with symbols indicate the mean of significant correlations ( $p < 0.01$ ). Histogram bars indicate number of sites (out of 5) where a significant correlation was observed.

## GROWTH-CLIMATE ASSOCIATIONS ON SITES WITH DIFFERENT DRAINAGE

Comparisons of radial growth-climate correlations between well-drained sites and poorly-drained sites did not indicate any consistent differences attributable to site drainage (Tables 1 & 2). Significant correlations between June climate variables and both total ring width and latewood were similar across all sites (Table 1). Correlations between earlywood and seasonal climate variables were inconsistent across sites with different drainage (Table 1). Earlywood was positively correlated with precipitation and PDSI prior to the current growing season at two of three well-drained sites, but correlations with these variables were weak or non-significant for poorly-drained sites. None of the between-site differences were statistically significant.

Climate variables	Well-drained sites			Poorly-drained sites	
	Wilbur Wright	DW – Upper Slopes	DW – Lower Slopes	Christy Woods	Ginn Woods
<b><u>Total Ring Width</u></b>					
June MxT	-0.47**	-0.41**	-0.38**	-0.33**	-0.45**
June P	0.37**	0.42**	0.43**	0.53**	0.49**
June PDSI	0.46**	0.36**	0.43**	0.56**	0.50**
Sum MxT	-0.41**	-0.35**	-0.36**	-0.28**	-0.35**
Sum P	0.51**	0.40**	0.35**	0.67**	0.59**
Sum PDSI	0.49**	0.33**	0.41**	0.57**	0.52**
<b><u>Latewood</u></b>					
June MxT	-0.50**	-0.41**	-0.38**	-0.36**	-0.47**
June P	0.43**	0.42**	0.44**	0.55**	0.51**
June PDSI	0.50**	0.34**	0.42**	0.57**	0.50**
Sum MxT	-0.40**	-0.34**	-0.34**	-0.30**	-0.34**
Sum P	0.54**	0.38**	0.37**	0.68**	0.60**
Sum PDSI	0.51**	0.30**	0.40**	0.59**	0.52**
<b><u>Early Wood</u></b>					
pSm MxT	0.09	-0.23*	0.13	-0.07	0.11
pAt MxT	-0.04	-0.02	-0.13	0.07	0.06
pWn MxT	0.11	0.12	0.21*	0.18	0.10
Spr MxT	-0.04	-0.35**	-0.10	-0.12	-0.20
pSm P	0.29**	0.42**	-0.08	0.24*	-0.01
pAt P	0.15	0.18	-0.01	-0.06	-0.08
pWn P	-0.01	0.04	0.08	-0.06	-0.20
Spr P	0.09	0.24*	0.16	0.25*	0.14
pSm PDSI	0.19*	0.28**	0.04	0.22*	-0.03
pAt PDSI	0.24*	0.34**	-0.02	0.09	-0.14
pWn PDSI	0.20*	0.33**	0.03	0.05	-0.15
Spr PDSI	0.18	0.37**	0.14	0.05	0.01

**Table 1.** Correlations between white ash total ring width, latewood, and earlywood, and monthly and seasonal climate variables ranging from summer of year prior to annual ring formation (pSm) to summer of year of ring formation (Sum) for sites with different drainage. Asterisks after correlation coefficient indicate level of significance (\*,  $p < 0.05$ ; \*\* $p < 0.01$ ).

ARSTAN common period statistics showed similar results for total ring width and latewood, but a much lower common signal for earlywood across all sites (Table 2). Mean

sensitivity, mean between tree correlation, percent variance in the first principal component, and expressed population signal values were consistently higher in ash latewood than earlywood. Chronology statistic values for ash latewood were higher or nearly identical to total ring width values across all sites. Mean sensitivity, mean between tree correlation, percent variance, and expressed population signal values were consistently higher among well-drained sites (Table 2). However, these differences were often small and no statistical tests of significance exist for comparing these statistics.

<b>Chronology Statistic</b>	<b>Well-drained sites</b>		<b>Poorly-drained sites</b>		
	<b>Wilbur Wright</b>	<b>DW – Upper Slopes</b>	<b>DW – Lower Slopes</b>	<b>Christy Woods</b>	<b>Ginn Woods</b>
<b><u>Total Ring Width</u></b>					
Mean Sensitivity	0.250	0.276	0.274	0.250	0.233
$r_{\text{between}}$	0.416	0.405	0.406	0.371	0.231
% Variance	0.446	0.458	0.455	0.423	0.307
EPS	0.953	0.949	0.948	0.941	0.853
<b><u>Latewood</u></b>					
Mean Sensitivity	0.414	0.389	0.426	0.397	0.364
$r_{\text{between}}$	0.452	0.439	0.437	0.376	0.324
% Variance	0.483	0.477	0.486	0.423	0.390
EPS	0.959	0.952	0.954	0.942	0.900
<b><u>Earlywood</u></b>					
Mean Sensitivity	0.178	0.153	0.160	0.159	0.165
$r_{\text{between}}$	0.192	0.156	0.168	0.069	0.081
% Variance	0.239	0.207	0.223	0.123	0.156
EPS	0.870	0.821	0.842	0.676	0.630

**Table 2.** Summary of common period chronology statistics generated by ARSTAN for total ring width, latewood, and earlywood.

## DISCUSSION

This analysis suggests that the radial growth of white ash is most strongly influenced by temperature and water availability during the current growing season, specifically in the month of June. While significant correlations between radial growth and climate variables for months other than June (most often May and/or July), were found at some sites, June correlations were strongest and most consistent across all sites. Significant correlations in May or July across several sites are likely the reason for significant correlations with the seasonal climate variables for early growing season (Sum) at all sites. These results are consistent with other studies of the radial growth response for members of the genus *Fraxinus* (Tradif et al. 1993, 1997).

Earlywood growth is weakly influenced by climate during the months and seasons prior to the current growing season, but there were no correlations with current growing season climate variables. These observations are further supported by the ARSTAN chronology statistics that indicate a much lower common signal that might be related to climate responses in the earlywood compared to latewood and total ring width. This suggests that the variation in annual ring width due to climate influence is almost exclusively due to variation in the latewood.

The results did not consistently support the hypothesis that white ash radial growth responds to climate differently on well-drained sites versus poorly drained sites. A possible explanation is the higher sensitivity to drought of trees on wetland sites to drought due to a reduced ability of the roots to penetrate soil (Phipps et al. 1979; Good and Patrick 1987). Shallow root systems can result in trees losing access to water during droughts when the surface water is depleted. For example, Phipps et al. (1979) reported a direct correlation between precipitation and radial growth of selected trees in swamps. Relative to mesic sites, both wetland

and dry sites tend to produce chronologies with increased ring-to-ring variation and stronger correlations with climate variables (Fritts 1976; Phipps et al. 1979).

The results of this study identify and describe the specific climate variables that influence the radial growth of white ash. These results are consistent with studies of other temperate ring-porous species (Tradif et al. 1993, 1997; LeBlanc and Terrell 2009 and 2011) and suggest that the radial growth-climate response of white ash is similar to other temperate zone hardwood species with ring-porous wood anatomy.

## Chapter 3

# COMPARISONS OF GROWTH-CLIMATE ASSOCIATIONS BETWEEN WHITE ASH (*FRAXINUS AMERICANA* L.) AND WHITE OAK (*QUERCUS ALBA* L.)

## INTRODUCTION

Analyses that relate historical variation in width of tree annual growth rings to past variation in climate variables provide a direct means to improve simulation models that are used to predict tree and forest responses to potential climate change (Cook et al. 2001; LeBlanc and Foster 1993; Graumlich 1993; LeBlanc and Terrell 2009, 2011). Recent publications suggest that similar tree species may respond similarly to climate variation, which would allow researchers to study climate responses of trees at a “functional group” level. Cook et. al (2001) demonstrated that radial growth of tree species within phylogenetic groups respond to climate in similar ways. The chronologies developed for this study were analyzed using rotated principal components analysis (RCPA). This analysis revealed three distinct phylogenetic signals; *Pinus* species, oak species in the black oak subgenus, and species in the white oak subgenus combined with *Fagus* species. Precipitation and maximum temperature data were used to model the dendroclimate signals in the chronologies and the resulting correlations were subjected to RCPA. The phylogenetic groups that emerged from the climate correlations RCPA were the same as the RCPA results from the chronologies. The results suggest that there is a genetic mechanism that determines how phylogenetic groups of trees respond to climate. These results further suggest that functional groupings of tree species can be used in vegetation/climate models to realistically predict how forests will respond to future climate change.

Research conducted by Cherubini et al. (2003) suggests that radial growth of members of the genera *Fraxinus* and *Quercus* may respond similarly to climate variation. The study analyzed annual growth rings of *Arbutus unedo* L., *Fraxinus ornus* L., *Quercus cerris* L., *Q. ilex* L., and *Q. pubescens* Willd. growing in Tuscany, Italy. *Fraxinus ornus*, *Q. pubescens* and *Q. cerris* are deciduous species with ring-porous wood that undergo a winter dormancy phase. The authors found that mean ring-width chronology patterns for both species are similar to precipitation patterns during dry periods. In addition the authors found the highest between species correlation of mean chronologies of the five species analyzed was between *F. ornus* and *Q. pubescens* (0.88) and correlations between these two species and the other winter deciduous oak species (*Q. cerris*) were greater than or equal to 0.8. Between species correlations were much lower (0.46 to 0.66) when evergreen hardwood species or diffuse-porous species were compared to deciduous ring-porous oak and ash species. This study supports the hypothesis that species with similar biology and ecology may respond similarly to variation in climate.

LeBlanc and Terrell (2009) described mechanistic growth-climate relationships for white oak (*Quercus alba* L.). This study indicated soil water balance during the early growing season has the greatest influence on white oak radial growth throughout its range. The results were consistent with other dendroecological studies of white oak in eastern North America (Graumlich 1993; Tardif et al. 2006). LeBlanc and Terrell (2011) studied the growth-climate associations for northern red oak (*Quercus rubra* L.) across eastern North America and compared these to the same associations in white oak. The high degree of similarity in growth-climate relationships between white oak and northern red oak suggest that other species with similar biology/ecology (temperate zone, hardwood, ring-porous species) may respond similarly to climate variation.

They proposed that studying climate variation responses by functional groups rather than for individual species could simplify forest simulation models.

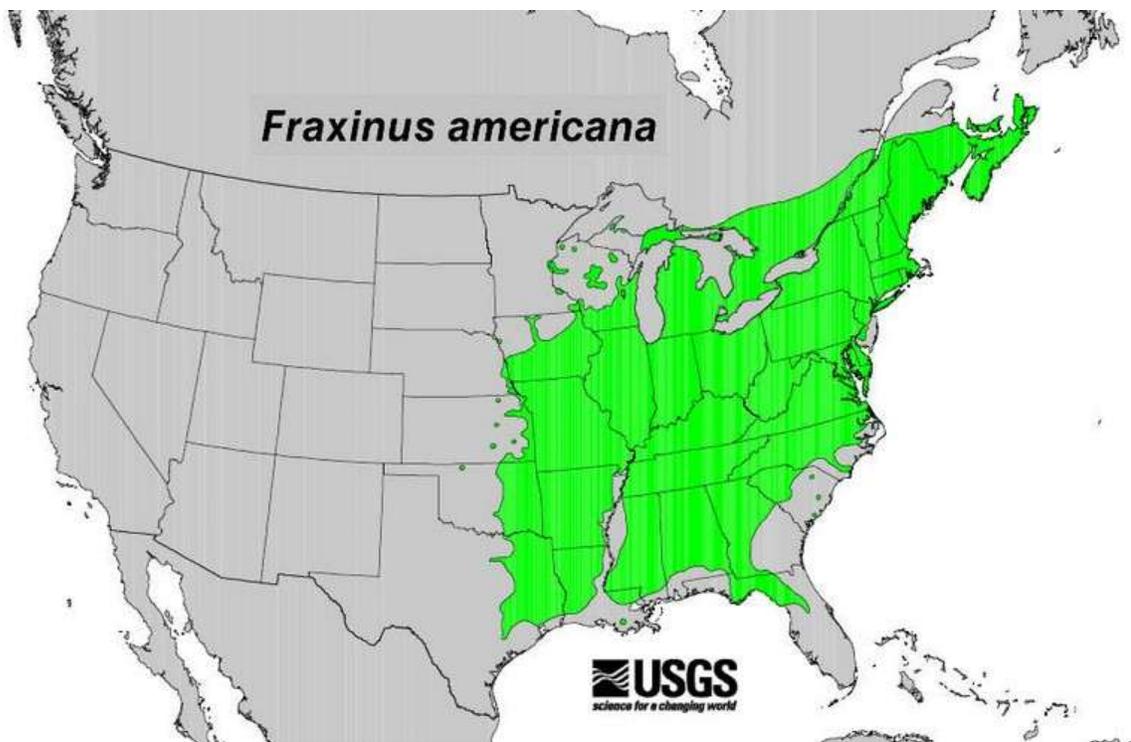
This study tested the hypothesis proposed by LeBlanc and Terrell (2009 and 2011), that temperate zone deciduous tree species with preformed apical growth patterns and ring-porous wood anatomy should have similar growth responses to climate. White ash has biological and ecological characteristics similar to white oak (temperate zone, winter deciduous, hardwood, ring-porous), and they might be expected to have similar growth responses to climate. Demonstrating that similar species can be placed into “functional groups” based on these biological and ecological characteristics could provide a basis to simplify forest simulation models used to predict effects of future climate change.

## **METHODS**

This study used white oak tree-ring width data collected by LeBlanc and Terrell (2009) and white ash tree-ring width data for trees sampled at the same sites. The sampling protocols, measurement, and data quality protocols used to create white ash tree-ring chronologies for this study were the same as those used by LeBlanc and Terrell.

## STUDY SITES

Ginn Woods and Christy Woods sites were chosen as sites with poor drainage, while Wilbur Wright Fish and Wildlife Area and Deam Wilderness area of Hoosier National forest were chosen as well-drained sites. All sites are within the state of Indiana, and all have similar climate. Indiana is located approximately in the center of the white ash geographic range (Figure 1; Burns and Honkala 1990).



**Figure 1.** Natural range of white ash in North America.

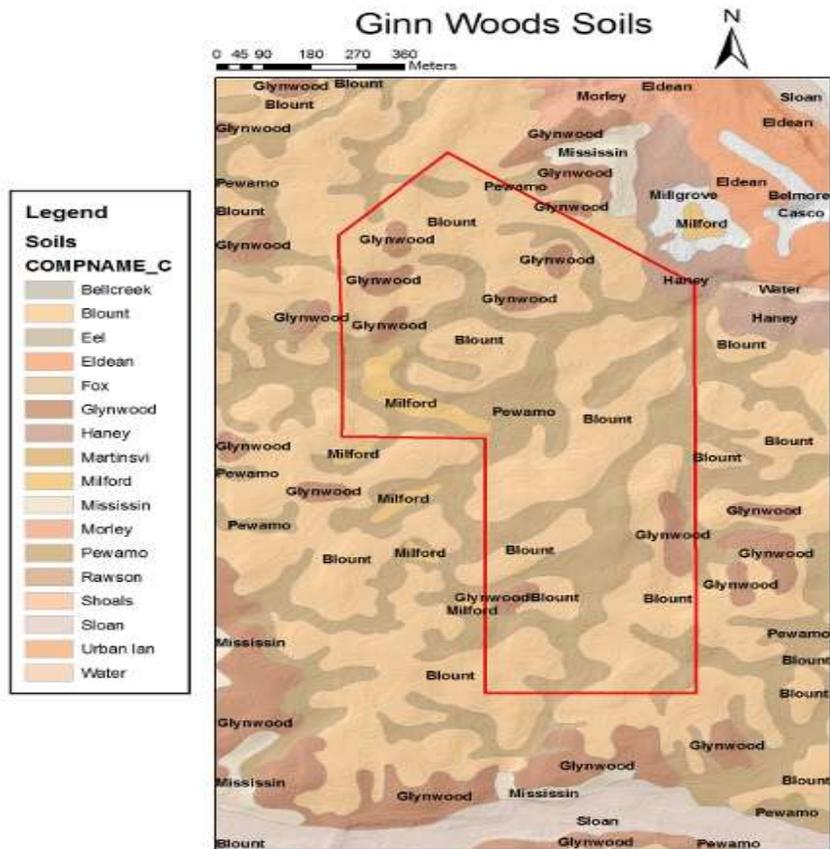
### Christy Woods: Poorly drained site

Christy woods is a 7.3 ha property located on the southwest corner of the Ball State University campus. The topography is relatively flat with a range of 2.5 m in elevation. Due to poor drainage widespread standing water often accumulates in low-lying areas in spring. The entirety of Christy Woods is poorly drained Blount silt loam. Approximately 75% of Christy

Woods is covered by mature forest dominated by a mixture of oak, hickory, ash, walnut, and maple. The white ash trees are currently under attack from the EAB and are being removed.

#### Ginn Woods: Poorly drained site

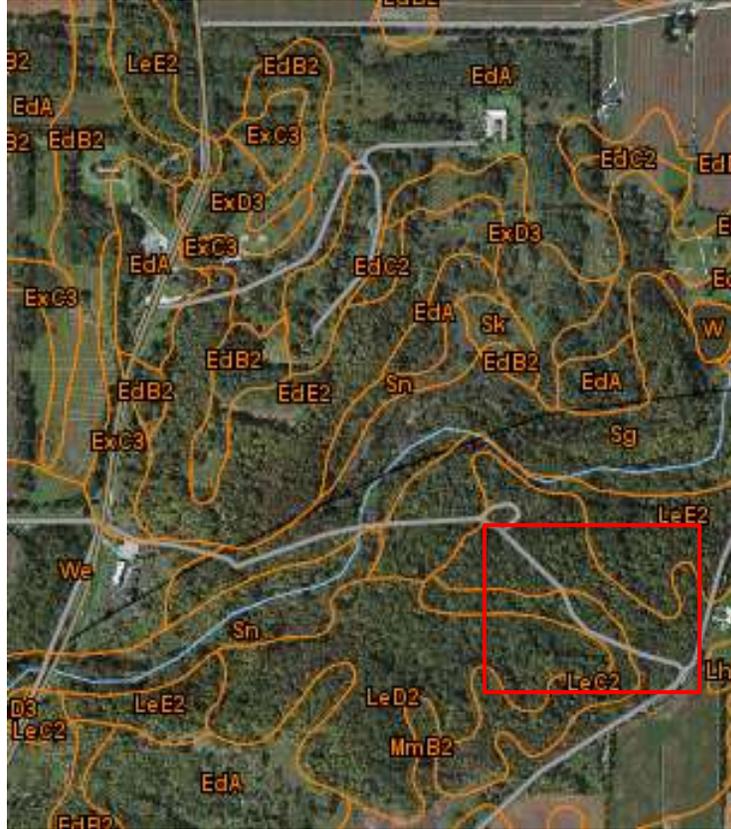
Ginn Woods is a 65 ha property owned by Ball State University, located in north-central Delaware County, Indiana. It contains the second largest stand of old-growth forest in the state (Ruch et al. 2004). The topography of Ginn Woods is flat, containing many closed depressions which form temporary wetlands. The soils of Ginn Woods are moderately well drained Glynwood silt loam, poorly drained Blount silt loam, poorly drained Pewamo silty clay loam, and very poorly drained Milford mucky silty clay (Figure 2). The mature forest is dominated by maple, beech, basswood, with smaller amounts of oak, elm, ash, and hickory. Ginn Woods provides the opportunity to study ash growth-climate associations in an area with little to no human disturbance on a relatively flat site with poor drainage.



**Figure 2.** Ginn Woods soils map. Red outline indicates forest perimeter.

Wilbur Wright Fish and Wildlife Area: Well-drained site

The Wilbur Wright Fish and Wildlife Area contains 433 ha of river valleys and uplands (Figure 3). The upland forest area sampled in this area (Figures 3 & 4) is dominated by Losantville silt loam soils (LeC) and includes white oak, northern red oak, white ash, as well as many other species.



**Figure 3.** Wilbur Wright Fish and Wildlife Area soils map indicating Losantville silt loams (LeC). The red rectangle indicates sampling area.

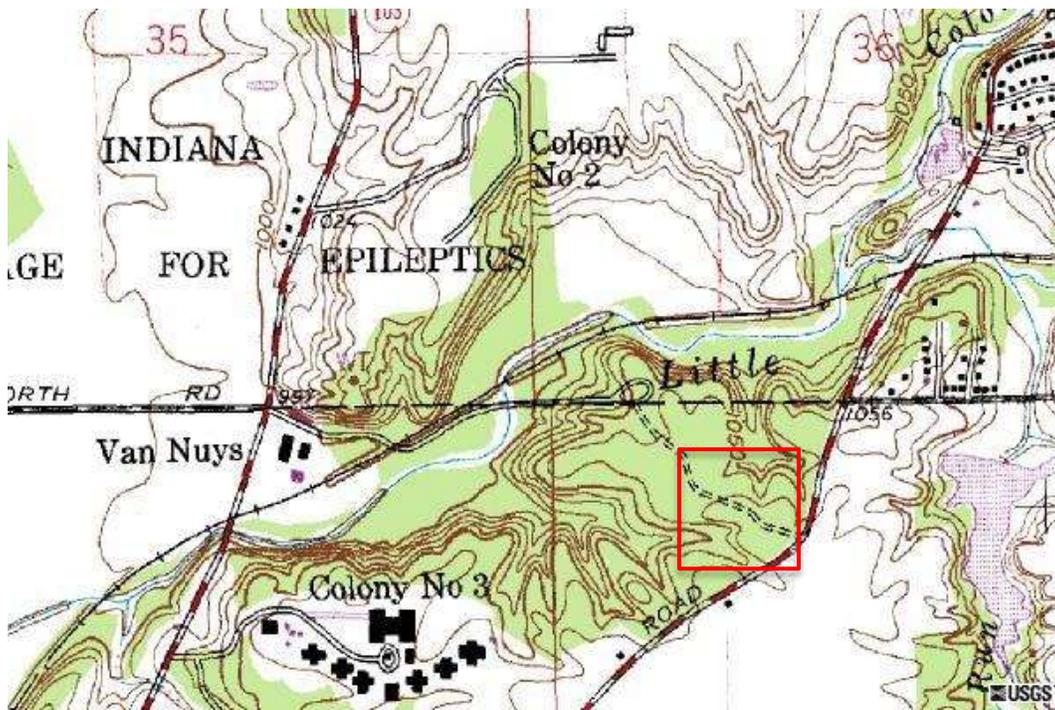
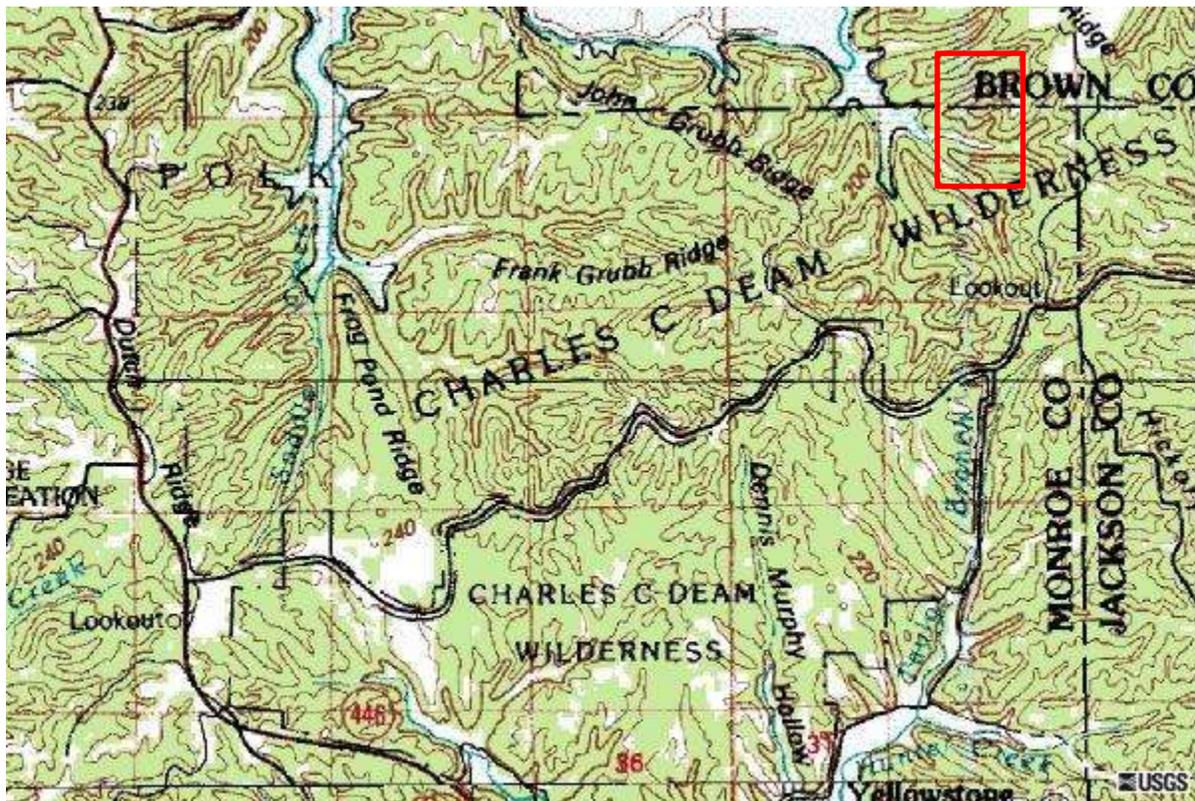


Figure 4. Wilbur Wright Fish and Wildlife Area topographic map. Red Rectangle indicates sampling area.

Hoosier National Forest – Pleasant Run Unit: Well drained site

The Charles C. Deam Wilderness area is a 5,260 ha site located within the Hoosier National Forest. The soils within this area were derived from weathered sandstones and siltstones and are dominated by Berks, Gilpin, and Weikert silt loams (Boerner and LeBlanc 1995). This site contained a diversity of micro-site types depending on aspect and slope position. Site-types included in this study were upper and lower slope positions (Figure 5).



**Figure 5.** Deam Wilderness Area, Hoosier National Forest, Indiana topographic map. Red rectangle indicates slopes where white ash trees were sampled.

## SAMPLING

Fifteen trees were sampled at each of the five study sites. Individual trees were selected based on the following criteria: (1) living or recently dead (within last year), (2) mature trees in the canopy with no obvious signs of physical damage, (3) no indication of major competitive release or damage within the past 60 years at time of coring. Two increment core samples were taken from each tree at 1.4 m above ground on opposite sides of the stem along an axis perpendicular to the slope. Cores were taken perpendicular to the longest diameter of the stem in trees located on flat topography.

## MEASUREMENTS

Cores were air dried, mounted, sanded, and visually crossdated using marker rings (narrow growth rings formed by many trees in a region, often associated with regional drought). Annual ring widths were measured to 0.01mm precision using a Velmex measuring table. These measurements included separate earlywood and latewood measurements. The computer program COFECHA (Holmes 1983) was used to verify visual crossdating and identify large measurement errors. COFECHA works by first creating an average master chronology for cores from a site. Data for each core to be analyzed is split into smaller 20 yr segments and statistically correlated against the master chronology. Correlations below a specified level were cause for increased scrutiny to identify potential errors in initial visual crossdating and for large measurement errors.

## CHRONOLOGY DEVELOPMENT

The ARSTAN program (Cook 1985) was used to calculate a mean tree-ring chronology for each site in a multistep process. First a cubic smoothing spline was applied to each of the two individual cores taken from each tree. ARSTAN takes the ring width and divides it by the model fit created by the cubic smoothing spline which results in an index value with the average of 1.0. This step removes much of the variance associated with tree aging and stand dynamics. ARSTAN then models temporal autocorrelation between successive annual ring indices and removes this to produce a chronology of statistically independent ring indices that reflect yearly variation in growth. A robust bi-weight mean function was used to calculate a master chronology of mean ring width index values by year to produce the residual ring index chronology for each site and site-type. This chronology was used in the analysis of growth-climate associations.

ARSTAN was used to perform a common period analysis of tree-ring chronology statistics that are used to assess relative influence of climate on radial growth. Ring-width chronologies were shortened to a common time period shared across enough trees within a study sites to reach an expressed population signal (EPS) of at least 0.85. This  $EPS \geq 0.85$  criterion is widely used in dendroclimatology literature to determine the minimum sample size to compute a mean chronology that has adequate precision for analyzing growth-climate associations. ARSTAN produces a set of EPS values as a function of the number of cores in the sample. The mean chronology is shortened to the longest period of years that are common across increment cores with different numbers of annual rings while still maintaining an EPS of at least 0.85. This

ensures the dominant signal in the chronology is a coherent stand-level signal, rather than the individual tree-level signal. Based on this criterion the time interval used for all common period analyses was 1943 to 1992.

All sampling methods and chronology development methods were the same for both white ash and white oak data.

## CLIMATE DATA

Climate data were obtained from existing databases. Mean monthly temperature, total monthly precipitation, and monthly Palmer Drought Severity Index data for state climate divisions were obtained from the National Climate Data Center (NCDC 1994). Data for state climate division 8 (south central Indiana) were used for the sites in the Hoosier National Forest and for state climate division 6 (east central Indiana) were used for Christy Woods, Ginn Woods, and Wilber Wright FWA sites. Mean monthly maximum temperature data was obtained from the United States Historical Climatology Network (Easterling et. al 1999). Since this data was recorded from individual weather stations it was averaged from multiple stations that were in the same state climate divisions as the study sites.

## DATA ANALYSIS

Simple Pearson's product-moment correlation analyses was performed between the ARSTAN residual chronologies computed for each of the study sites and monthly climate

variables for the period beginning with June of the year prior to ring formation through October of the year when the ring was produced. Monthly climate variables included mean temperature, mean maximum temperature, precipitation, and Palmer Drought Severity Index. Correlation analyses were also performed using seasonal and annual averages of the same climate variables. Seasons were defined as prior year summer (June-August), prior year autumn (September-November), prior year winter (December-February), spring (March-April prior to annual ring formation), and early growing season (May-July when most of the annual ring is formed).

ARSTAN chronology common period statistics (mean sensitivity, percent variance in the first principal component, expressed population signal, and between tree correlation) were compared between white ash and white oak and between well-drained and poorly-drained site types. Mean sensitivity is a measure of year-to-year variation in a chronology. Percent variance in the first principal component is the percentage of variation that is due to the common signal among trees in the sample. Expressed population signal (EPS) is an expression of the strength of the common signal in the stand. Between-tree correlation ( $\bar{r}$ ) is a measure of the common signal strength and is used to evaluate the signal-to-noise ratio throughout the chronology. Larger values for all of these statistics indicates a stronger climate signal in the chronology.

## **RESULTS**

### **CORRELATIONS WITH CLIMATE VARIABLES**

Correlation analysis was performed in two steps: first correlations between radial growth and climate variables at each site were analyzed, then significant correlations for each species were averaged among sites to determine which climate variables were consistently significantly correlated with radial growth across study sites (Figure 6). This summarization was done separately for each of the two tree species.

Maximum temperature in the month of June was negatively correlated with white ash and white oak radial growth at all sites. Significant negative correlations were observed between maximum temperature and white oak radial growth at multiple sites in the months of July and August, but not for white ash. Negative correlations between early growing season (Sum) maximum temperature and radial growth for both species were observed at three of four sites.

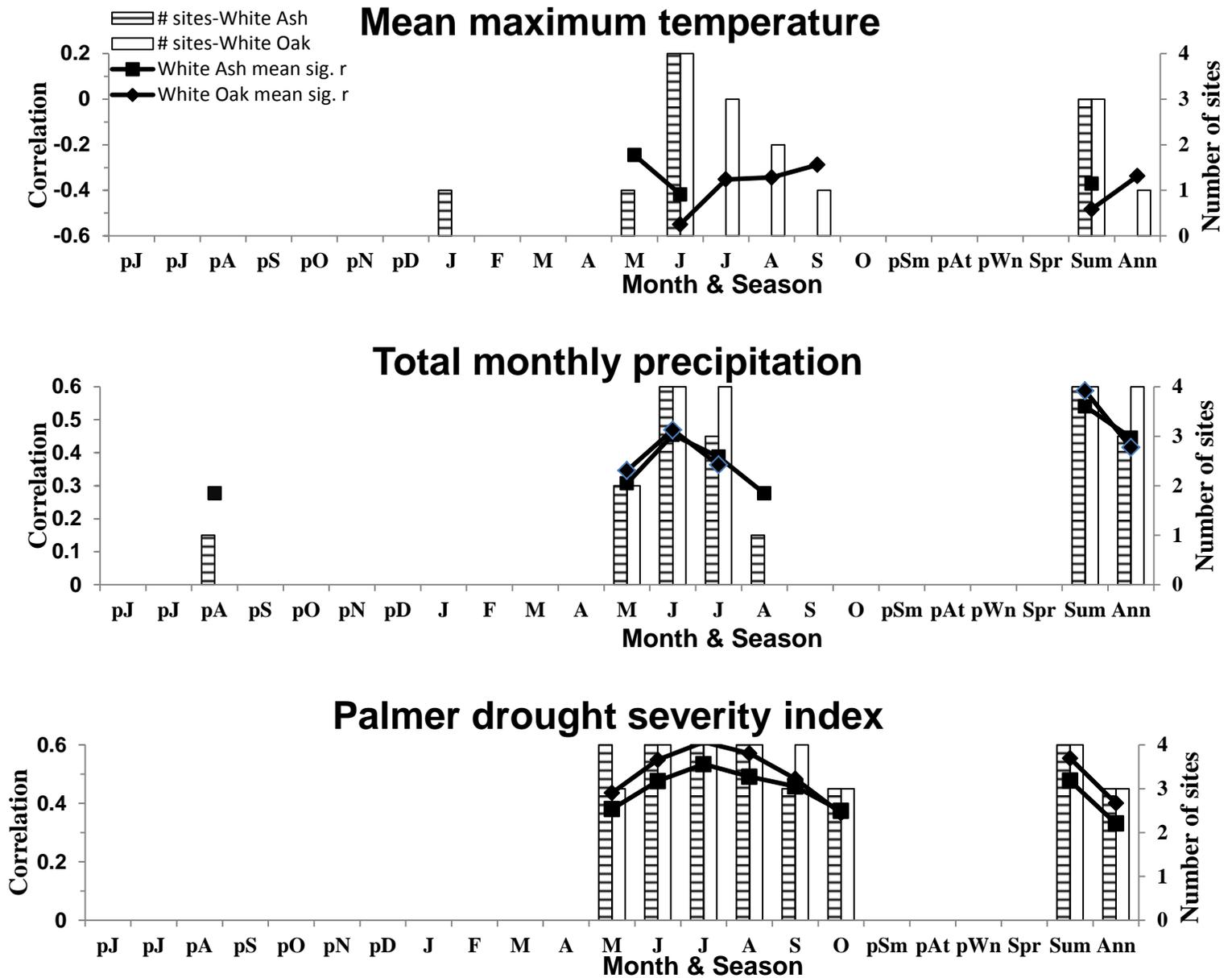
Monthly precipitation was positively correlated with radial growth of both species at all sites in the month of June (Figure 6). Positive correlations were also observed between precipitation and white oak radial growth at all sites in the month of July and at three of four sites for white ash. Radial growth of both species was correlated with May precipitation at multiple sites. Early growing season and annual precipitation were strongly correlated with

radial growth of both species. Mean significant  $r$  values were nearly identical between the two species in months when significant correlations were observed at multiple sites.

Palmer drought severity index (PDSI) was consistently positively correlated with radial growth of both species across sites for the months of June, July and August (Figure 6). PDSI is calculated using a running sum of precipitation additions, which can cause autocorrelation among successive monthly values and may explain the strong positive correlations observed for both species in the months of July, August, and September (Leblanc and Terrell 2009). Radial growth of both species was also correlated with early growing season and annual PDSI.

White ash and white oak responded similarly to climate variables during the early growing season and particularly the month of June. No consistent differences in growth-climate correlations were observed between the two species during any other month or season (Table 1). Also no consistent differences were observed in growth-climate correlations of either species growing on well-drained versus poorly drained sites.

**Figure 6.** Analysis of correlations between white oak and white ash total ring width residual chronologies and climate variables for the period beginning in June of the year prior to annual ring formation (pJ) through October of the year when the ring was formed (O). Seasons range from summer of the prior year (pSm) to summer of the current year (Sum). Histogram bars represent number of sites (out of 4) where significant correlations ( $p < 0.01$ ) were observed. Lines and symbols indicate the mean significant correlation.



Climate variables	Well-drained sites		Poorly-drained sites	
	Wilbur Wright FWA	Deam Wilderness Area	Christy Woods	Ginn Woods
<b>Monthly</b>				
<b>June P</b>				
White Ash	0.37	0.42	0.53	0.49
White Oak	0.47	0.40	0.50	0.50
<b>June PDSI</b>				
White Ash	0.46	0.36	0.56	0.50
White Oak	0.57	0.38	0.63	0.55
<b>June MxT</b>				
White Ash	-0.47	-0.41	-0.33	-0.45
White Oak	-0.61	-0.55	-0.45	-0.52
<b>Seasonal</b>				
<b>Summer P</b>				
White Ash	0.51	0.40	0.67	0.59
White Oak	0.63	0.53	0.66	0.55
<b>Summer PDSI</b>				
White Ash	0.49	0.33	0.57	0.52
White Oak	0.58	0.36	0.64	0.57
<b>Summer MxT</b>				
White Ash	-0.41	-0.35	-0.28*	-0.35
White Oak	-0.53	-0.46	-0.31*	-0.39

**Table 1.** Summary of June and summer growth-climate correlations for white ash and white oak separated by site. All correlations are significant ( $p < 0.01$ ) with the exception of asterisked values (\*) which are significant at the  $p < .05$  level.

## CHRONOLOGY STATISTICS

White oak and white ash chronologies showed similar common signals likely related to climate influences in the common period chronology statistics (Table 2). Common period for analysis was from 1943 to 1992. No consistent differences were found between white ash and white oak mean sensitivity. Between-tree correlation, percent variance in the first principle component, and expressed population signal were all consistently higher in white oak than white ash. However, These differences were often small and no statistical tests exists for comparing these statistics. No consistent differences were observed between well-drained sites and poorly-drained sites.

<b>Chronology Statistic</b>	<b>Well-drained sites</b>		<b>Poorly-drained sites</b>	
	<b>Wilbur Wright FWA</b>	<b>Deam Wilderness Area</b>	<b>Christy Woods</b>	<b>Ginn Woods</b>
<b><u>Mean Sensitivity</u></b>				
White Ash	0.250	0.276	0.250	0.233
White Oak	0.222	0.245	0.239	0.267
<b><u><math>r_{\text{between}}</math></u></b>				
White Ash	0.416	0.405	0.371	0.231
White Oak	0.419	0.447	0.475	0.343
<b><u>% variance</u></b>				
White Ash	0.446	0.458	0.423	0.307
White Oak	0.467	0.480	0.512	0.410
<b><u>EPS</u></b>				
White Ash	0.953	0.948	0.941	0.853
White Oak	0.954	0.962	0.957	0.899

**Table 2.** Summary of ARSTAN chronology common period statistics for white ash and white oak separated by site.

## DISCUSSION

Growth-climate correlations observed at these sites were nearly identical between white ash and white oak. The findings for white oak were similar to other studies of its growth-climate relationships (Cherubini et al. 2003; Cook et. al 2001); and the high degree of similarity between white ash radial growth and white oak radial growth suggests that these species respond similarly to variation in climate.

White oak and white ash radial growth was most strongly influenced by climate during the months of the early growing season (May-July). Radial growth for both species was most strongly and consistently correlated with climate variables during the month of June. Strong positive correlations with precipitation and PDSI and strong negative correlations with maximum temperature indicate that soil water balance during the early growing season is a primary influence on the radial growth of both white ash and white oak.

Oak ecophysiological studies have demonstrated that oak trees undergo a shift in carbon allocation from radial growth to carbohydrate storage during the late growing season (McLaughlin et al. 1980; Barboux and Breda 2002; Zweifel et al. 2006; LeBlanc and Terrell 2009 and 2011). Similarly high correlations between radial growth and climate variables during the early growing season, and low and inconsistent correlations during the late growing season for both species suggest that white ash undergoes a similar shift in carbon allocation from current growth to storage during the late growing season.

The results of this study support the hypothesis that white ash and white oak respond similarly to climate. Similar analyses for other temperate zone, hardwood, ring-porous species would provide stronger evidence for defining a functional group that includes other species with

similar biology and ecology. Furthermore, the results of this study support the conclusion of Cook et al. (2001) that functional groups of tree species with similar responses to climate exist, and they may have the potential to simplify forest simulation models. Additional studies comparing growth-climate associations for similar species are needed to expand on the potential for using functional groups to simplify forest simulation models.

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