Isolation of Climate Sensitivities of *Acer saccharum* and *Abies balsamea*

BIOS 569: Practicum in Field Biology

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Abstract

Growth ring-widths are useful indicators of climate sensitivity for individuals or groups of trees that have lived under certain conditions. Different species may respond a unique set of climate variables such as mean, maximum, and minimum temperature, as well as precipitation based on their natural ranges' climate and differences in nutrient requirements. In this study, *Abies balsamea* (balsam fir) and *Acer saccharum* (sugar maple) trees were used as two species with different habitat ranges and life histories in order to determine relationships between ring-width indices and these four climate variables on the University of Notre Dame Environmental Research Center (UNDERC) East property in Land O' Lakes, WI. Departures from the means of annual ring-width growth indices and variation from the mean in annual climate variables were analyzed using a stepwise regression to isolate the most significant relationships. The results suggest that *A. balsamea* trees in the region are relatively insensitive to all four climate parameters. *A. saccharum* was found to be significantly sensitive to all four variables with a lagged response of two years, with the highest sensitivity relationship to total precipitation. Improvements in cross-dating suppressed samples and incorporating modified dendrochronological techniques are needed in order to better understand growth ring responses to climate variables in the region. Better understanding climate sensitivities of tree species will be critical to capturing and predicting range shifts as ecological responses to changing climate.

Introduction

Site quality, made up of parameters such as the physical environment and resource availability, is often the focus of tree growth study when reconstructing processes such as secondary succession (Pecoraro 2013). However, it is important to integrate individual site history in dendrochronological research (Rhemtulla *et al.* 2009). Site history and disturbances include factors such as climate, fires, and human uses and management. Tree growth and climate history relationships provide insight into past trends and potential future growth patterns under the influence of global warming and changing temperature and precipitation patterns (Goldblum and Rigg 2005). As a result of these patterns, tree species' habitat ranges may be forced to change, and important ecological processes and industries may be negatively impacted. This study provides information for future research that may need to consider how individual site histories have influenced stands and species' unique climate sensitivities. The results are relevant at this point in time because tree growth and climate history will become increasingly related as weather patterns change.

Growth ring-widths can tell a story about individual trees' life history, as well as species' climate sensitivities. Graumlich (1993) found that extreme climatic events result in varied tree growth rates using eleven species in the deciduous and mixed hardwood-conifer forest of the upper Great Lakes region. In addition, high annual mean temperatures can increase the water stress on trees resulting in decreased growth for a particular year (Fritts *et al.* 1971). However, Hasenauer *et al.* (1999) found that temperature increase over time lengthens the growing season in the alpine climate of Austria and may improve forest productivity. Similarly, extremely cold temperatures as well as low precipitation levels have a dramatic impact on tree growth from year to year (Corcuera *et al.* 2004; Bouriaud *et al.* 2005). Tree rings can therefore be used to analyze the impacts of temperature and precipitation patterns on annual growth over time. Ring-width is influenced by tree species, location, age, and land management, as well as temperature, precipitation, and sunlight. Thus, a tree-ring chronology indicates climate sensitivities specific to its unique environment, with stronger signals arising from more sensitive trees under limiting conditions (García-Suárez *et al.* 2009).

Following the extensive logging that occurred in the northern hardwood forests of the Great Lakes region from the late 1800s to the early 1900s, trees began to regrow through secondary succession (Albani *et al.* 2006). The UNDERC East forests in the upper Great Lakes area have been largely unmanaged by humans since they were cutover in the 1940's. The land therefore presents a unique environment for tree growth and climate interactions during secondary succession due to the young, unmanaged forests (S. D. Pecoraro, personal communication). There is relatively high precipitation in the UNDERC East region, but interannual temperature is more variable (ISC 2013). It is therefore commonly assumed that temperature bears the strongest relationship to tree growth and is the limiting factor for growth. In other words, temperature is thought to be the climate variable that trees are most sensitive to during growth in the area (Speer 2010). I challenged this assumption by comparing the sensitivities of *A. saccharum* and *A. balsamea* to interannual climatic variation.

A. saccharum and *A. balsamea* were selected because they are both abundant, shade-tolerant tree species found in the region, which can be classified as a deciduous forest biome (Speer 2010, ISC 2013). However, they have different overall ranges and life histories. *A. balsamea* is a conifer native to the northeastern United States and in much of northern, central, and eastern Canada (*Abies* 2013; Figure 1A). *A. saccharum* is a hardwood native throughout the mid and eastern United States, as well as eastern Canada (*Acer* 2013; Figure 1B). Graumlich (1993) found that variation in climate response between species overrules site variation, and temperature and precipitation variables are correlated with growth rates. As a result, I predicted that the two species may react to climate variables based on their potentially different sensitivities and native ranges. Annual temperature extremes (minimums and maximums), annual temperature means, and annual total precipitation were used as the climatic variables.

For each species, it was asked which annual climatic variable(s) is this species' growth most sensitive to when site quality variation has been controlled for. I hypothesized that *A. saccharum* and *A. balsamea* have different climate sensitivities which have impacted tree growth within the last century in the UNDERC East region. It was predicted that *A. saccharum* would be most sensitive to precipitation and temperature, while *A. balsamea* should be limited by temperature alone. This prediction was made because *A. saccharum* is primarily in temperate, moist regions where it is impacted by both yearly rainfall and temperature, which varies across its entire range (Godman *et al.* 2013). The study site is located near the mid to northern region of the *A. saccharum* range. *A. balsamea,* a conifer, can survive in colder and drier conditions than *A. saccharum* and may therefore be impacted to a greater extent by increasing temperature over time due to global warming, especially since the study site is near the southern edge of its range (Frank 2013).

Materials and Methods

I used a retrospective approach by collecting annual mean temperatures from seven regional stations through the National Oceanic and Atmospheric Administration interactive map tool (NOAA 2013). Data from the following weather stations were averaged: Rest Lake, Minocqua, Rainbow Reservoir Lake, Long Lake Dam, Big St. Germain Dam, St. Germain, and Watersmeet. The closest weather station was Watersmeet at 5.9 miles away from UNDERC East, and the farthest was Long Lake Dam at 30.8 miles away (NOAA 2013). Note that the year 1949 was missing from this data set. Annual mean maximum and minimum temperatures and annual total precipitation were collected from Oregon State's PRISM database (Prism 2013).

I used GIS analyses that binned plots into one of eight possible site quality strata using slope, aspect, and topographic convergence (a proxy for water availability) in a cluster analysis to account for as many confounding site quality factors as possible (Pecoraro 2013). Differences due to light availability and stand dynamics were controlled by the selection of intermediate canopy class trees (Speer 2010). One to two increment cores were taken for each sample tree using standard technique. A t-test was run to determine whether all intermediate trees were similar in size so that ring-width would not be confounded by diameter differences (Figure 2). At least 30 cores are typically required to determine climate sensitivity, so 33 *A. saccharum* cores (1942-2009) and 31 *A. balsamea* cores (1976-2008) were selected (Speer 2010).

Following collection, cores were mounted and sanded with progressively finer sandpaper, up to 1000-grit, per standard dendrochronological techniques (Speer 2010). I cross-dated cores via pinning, skeleton plotting, and measuring ring-widths up to 1μm using the program Tellervo 1.0 (Brewer 2012) with a Velmex measuring platform, or stage micrometer (Velmex, Inc., #TA4030H1-S6). The COFECHA 6.06P program (Holmes 2012) was utilized to check cross-dates and find the overall mean sensitivity and series inter-correlation of all cores to each other as a master chronology. The computer program ARSTAN 44h2 (Cook and Krusic 2013) was employed to de-trend low frequency variation and create indexed growth series for each core with a mean of 1.0 using Friedman's smoothing (Figure 4). This removes samples' age-related growth trends, and allows for analysis of interannual variability in ring widths (Speer 2010). Friedman's smoothing method was used because it did not yield a negative, impossible growth model unlike other splining techniques. García-Suárez *et al.* (2009) found relatively few differences in using different standardization methods in dendroclimatology.

Back-stepping regressions were performed in SYSTAT 13 (Systat Software 2008) and R (R Development Core Team 2008) using annual departures from the mean of indexed growth and climate variables (Fritts and Swetnam 1989). The alpha to remove for *A. saccharum* (1942-2009; n = 68) and for *A. balsamea* (1976-2008; n = 33) was 0.15. I lagged the climate data by 0, 1, 2, and 3 years in order to account for potential delayed growth responses to climate often seen in tree rings (Meko 2013).

Results

The t-test used to determine whether the size of intermediate trees differed between species' found samples to be not significantly different in diameter at breast height (df = 36, p = 0.095; Figure 2). COFECHA analysis of raw measurements found that the series inter-correlation was 0.142, which is the average correlation of all series to the master or average chronology (Grissino-Mayer 2008). The mean sensitivity was 0.303, which quantifies interannual ring-width variability and represents the ease of cross-dating (Grissino-Mayer 2008). A mean sensitivity around 0.2 is typically accepted as sensitive enough for dendroclimatology studies (Speer 2010). COFECHA also found a total of 234 flags, or warnings of potential problems, out of 2714 total sample years that did not match the other series in the chronology as dated and reduced overall series inter-correlation (Grissino-Mayer 2008).

A stepwise regression found no significant relationship between *A. balsamea* ring-width indices and any climate variables between 1976 and 2008 (Figure 5). *A. saccharum* indices were significantly correlated with mean temperature (p = 0.015; Figure 6A), mean maximum temperature ($p = 0.012$; Figure 6B), mean minimum temperature ($p = 0.046$; Figure 6C), and total precipitation departures from the mean ($p < 0.001$; Figure 6D), all with two-year lags between 1942 and 2009 ($R^2 = 0.213$). A Shapiro-Wilk test found the *A. saccharum* indices to be normally distributed with a p value of 0.777.

Discussion

It was predicted that *A. saccharum* would be most sensitive to precipitation and temperature, while *A. balsamea* would be most sensitive to temperature alone. The results did support the first hypothesis in that *A. saccharum* was significantly sensitive to all four climate variables, including extreme temperatures. However, contrary to our second hypothesis, it was found that *A. balsamea* growth ring indices were not significantly related to any of the climate variables. This indicates that *A. balsamea* is relatively insensitive to climate overall, although sensitivity approached significance for annual mean maximum temperature ($p = 0.212$; Figure 5A) and total precipitation with a three-year lag ($p = 0.149$; Figure 5B). It is possible that *A. balsamea* has evolved a decreased sensitivity to extreme conditions such as freezing temperature or unpredictable rainfall as a result of its natural range (Figure 1A), or that it is more sensitive to interannual weather patterns that were not examined. *A. saccharum* is found in more temperate regions where climate is naturally more variable, and certain annual conditions are likely required for optimal growth such as predictable seasonal shifts (Figure 1B) (ISC 2013). The results suggest that *A. saccharum* trees in this region are highly sensitive, and could be negatively impacted by climate change in the future.

Dendroclimatologists typically use the growing months between April and September to correlate past climate and tree growth response (García-Suárez *et al.* 2009). This study used annual mean or total values for climate variables, rather than a monthly range. Perhaps restricting climate data to the months of high tree growth would have resulted in greater correlations. In addition, indices were used for tree ring measurements to remove any age-related growth trends. Though interannual variation in climate variables was used for analysis, using indices for these data as well to remove the long term trends might improve correlations and graphical trends. When reconstructing precipitation history, dendroclimatologists tend to core trees that are known to be suppressed such as those found in extremely dry climates. The cores used in this study came from a region high in moisture and quality conditions for tree growth. Hence, it may be more difficult to pick up distinct climate sensitivity responses.

I determined climate-growth trends using mean species responses from all samples, including ones from different plots, rather than individually analyzing each sample. This could be confounding and may have reduced the strength of sensitivity signals. Carrer (2011) hypothesized that replication and standardization to remove age-related growth trends may not fully remove stand dynamics and other disturbances. It would therefore be helpful to individually select and analyze cores to better understand climate sensitivities and responses such as growth releases. Kerhoulas and Kane (2012) found that growth rings showed an increased sensitivity to climate when cores were taken from higher positions on trees, possibly due to increased gravitational force and water stress at these heights. Additionally, cores could be analyzed based on their stand of origin, as one recent study done at UNDERC East found that stand diversity may impact productivity and therefore biomass (N. Poinsatte, unpublished data). Therefore, more individual selectivity based on canopy class, core height, and stand diversity may result in higher ring-width and climate sensitivity relationships.

Using the graphing tools in Tellervo allowed for shifting of paired core measurements to more visually accurate cross-dates. Graphs of indices and climate sensitivities showed similar patterns such that shifting sections appeared to create highly matched peaks. This indicates that errors likely occurred during cross-dating and correctly inserting or deleting certain years in the cores might have made more peaks line up with climate data over time (Figure 3). Cross-dating ability would have also increased if a regional master chronology existed for both species. One master chronology was found and had been compiled from Eastern hemlock trees at Loon Lake, WI (Cook 2013). However, the chronology was made up of the years 1570-1983, which was not particularly helpful for this study due to a lack of overlap in the critically suppressed years of *A. saccharum*. Cross-dating dominant *A. saccharum* trees in the region might result in a master chronology that could be used in the future to more accurately date suppressed cores from lower canopy classes. Dominant trees tend to grow more consistently because they have better access to sunlight in recent years of growth, resulting in clearer rings near the bark and fewer missing rings. Sampling only co-dominant or dominant trees is preferable but these trees do not typically exist on the UNDERC East property for *A. balsamea* (S. D. Pecoraro, personal communication).

A. saccharum cores were difficult to cross-date due to the high level of suppression in the past two decades. When attempting to match years between cores, it was often debated if there were missing rings, and whether extremely thin rings were actually false or pseudo rings. Such anomalies would result in tree age underestimates and overestimations, respectively. Acer species have diffuse-porous wood, whose growth rings have an abundance of small vessels that complicate measurements (Coder 1999). Lorimer *et al.* (1999) found that intermediate trees had a maximum of 5-7 missing rings and 2.6 anomalies per tree on average. I utilized the best tools available to cross-date *A. saccharum* cores including pinning, skeleton plotting, pairing cores, and matching graphs on the program Tellervo. Nonetheless, it is likely that some cross-dating errors persisted. I was more confident in intermediate *A. balsamea* cores, which tend to present fewer difficulties during cross-dating.

Possible causes of *A. saccharum* suppression include stand quality and drought. For example, competition between trees for light, space, and nutrients can affect growth and subsequently growth ring-width. The Western Upper Peninsula experienced a significant drought from 2006 to 2008 and continued to be affected by dry conditions in 2011 (Hovel 2013). This has had a major influence on declining tree health and food reserves, and forests will likely not be able to recover quickly. Additionally, recent maple dieback has increased from about 2% in 2010 to 16.5% in 2011 in the Western Upper Peninsula (Hovel 2013). Healthy sugar maple stands should have less than 10% dieback (Hovel 2013). It is not known why maples have been dying at this rate, although observation and research continues. Dry conditions and maple decline may explain why tree rings following the year 2000 are generally suppressed and difficult to read, with a high frequency of anomalies.

The results of this study suggest that *A. saccharum* trees in this region are highly sensitive to multiple climate variables, which may put it at risk for further decline. However, some of the significant factors may have been arbitrary correlations as indicated by the low R^2 value of 0.213. The correlations between *A. saccharum* ring-width indices and climate may have just been due to chance because these trees have high interannual variation in growth (S. D. Pecoraro, personal communication). Although cross-dating *A. saccharum* is known to be labor intensive, it is important to continue monitoring sugar maple growth and condition. As a result of warming trends, *A. saccharum* area may be reduced to 56% of its area in 2005 by the year 2100 using the Canadian Climate Center model of climate change (Iverson *et al.* 2005). In combination with maple dieback, this could have a negative impact on forest ecology as well as on maple industries such as building, furniture, and maple food products (Arbor Maple 2013). Groups such as the Ojibwe Native Americans may lose a great deal of their livelihood if *A. saccharum* trees experience drastic habitat shifts, as they use these trees for maple sugar harvesting. While *A. balsamea* was found to be insensitive to the annual climate variables tested, it is possible that this species' ring-widths would have a stronger correlation to intra-annual climate such as temperature and precipitation variation during the growing season (Bouriaud *et al.* 2005). *A. balsamea* could also be at risk of decline or ecological stress due to climate change, which may impact industries that utilize this tree such as lumber, landscaping, and holiday decoration (Arbor Fir 2013). Isolating climate sensitivities of trees will be a key method for forest management and species conservation in the future. Understanding how species will react to changes in climate may help us to foresee and mitigate negative ecological responses.

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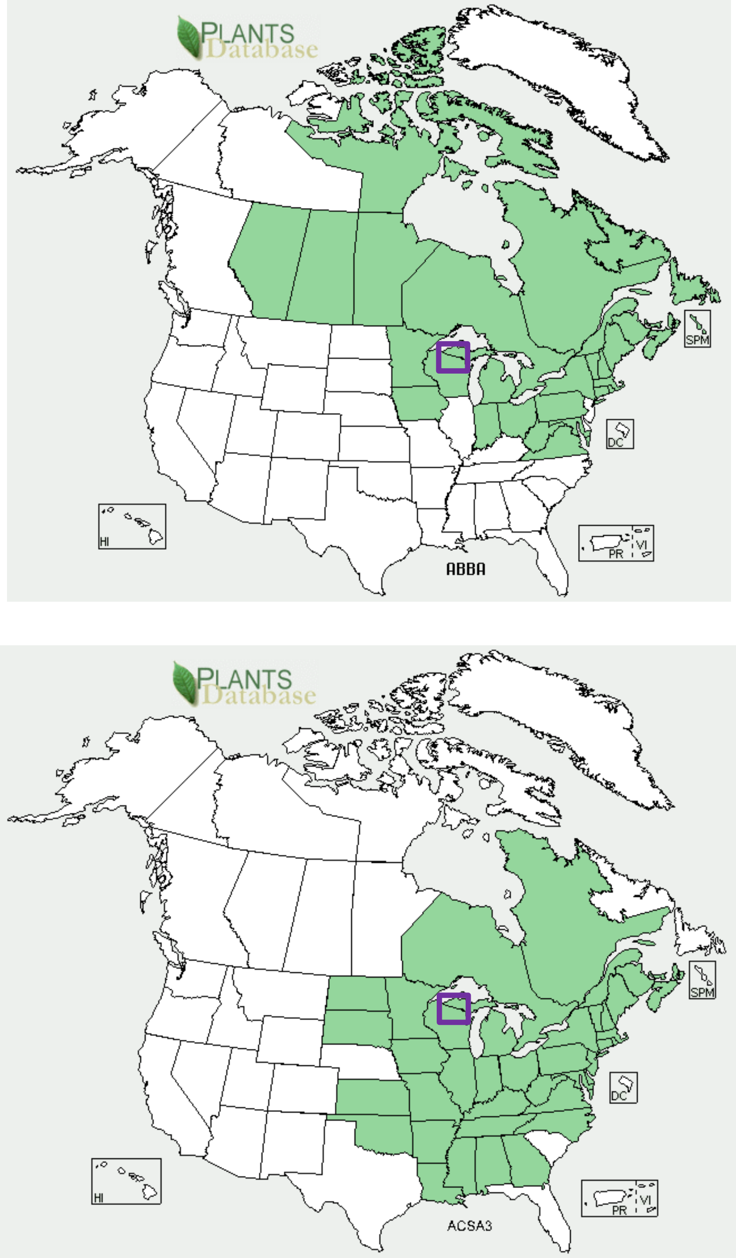
Figures



(A)

(B)

Figure 1. Native ranges of *A. balsamea* and *A. saccharum*. The study site was at UNDERC East in Land O' Lakes, WI. It is located in the upper Great Lakes region near the center of the purple box on each map. **(A)** *A. balsamea* is found natively in the northeastern United States and in much of northern, central, and eastern Canada (NRCS *Abies* 2013). UNDERC East is near the southern edge of this range. **(B)** *A. saccharum* is found primarily in the mid and eastern United States. It is also found in eastern Canada (NRCS *Acer* 2013). UNDERC East is near the mid to northern area of this range.

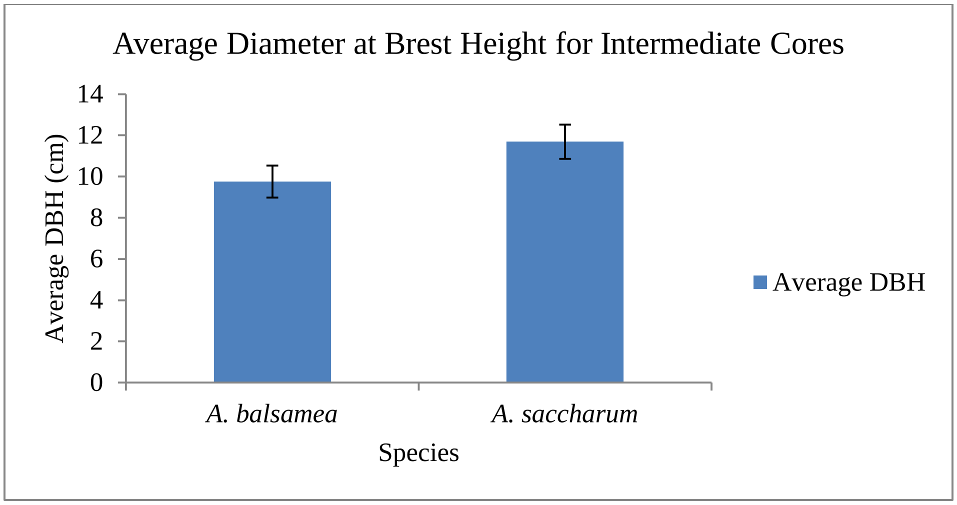


Figure 2. Average diameters at breast height not different between two study species. A t-test was run in in SYSTAT 13 (Systat Software, Inc. 2008) in order to determine if species differed in mean diameters at breast height in intermediate canopy class trees. The test found that the means for *A. balsamea* (n = 20, SE = 0.770) and *A. saccharum* (n = 18, SE = 0.825) were not significantly different (df = 36, p = 0.095). It can therefore be assumed that size was not a confounding factor in trees' climate sensitivity responses.

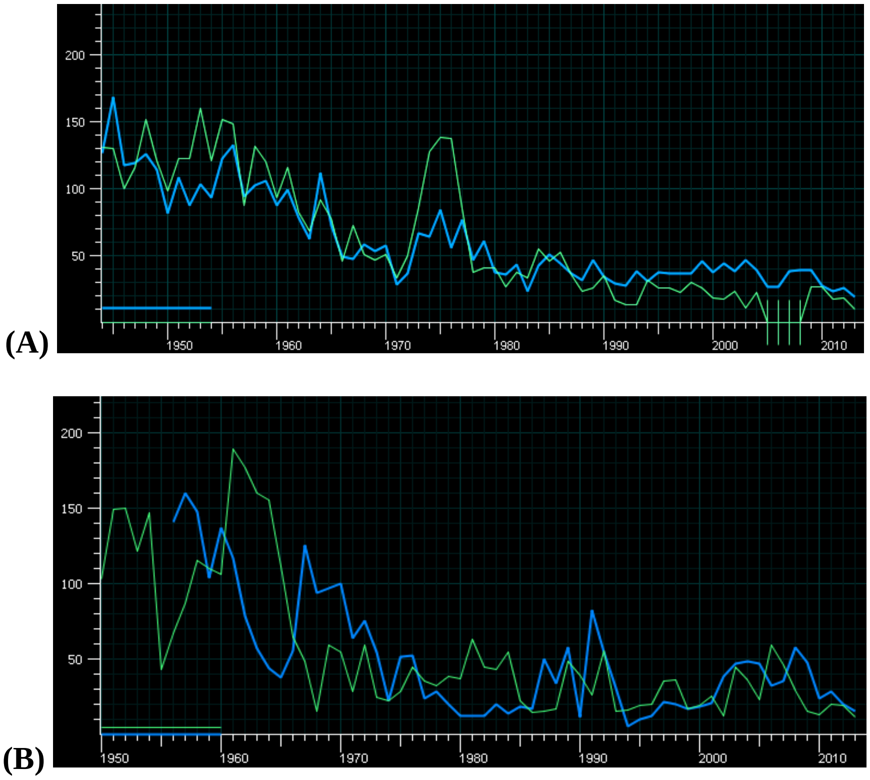


Figure 3. Tellervo graphing tools allowed for matching of peaks between core pairs. The computer program Tellervo 1.0 (Brewer 2012) was used to graph raw ring-widths to predict if

cores' dates had been underestimated or overestimated. The approximate locations of misdates could be visualized by moving individual lines left and right. However, inserting a year typically requires deleting another elsewhere. **(A)** In the first example of cores 726A and 726B from an *A. saccharum* tree, three years are missing near 2005 on one core and the two lines generally match peaks. This indicates that the cores were likely dated correctly, with the right number of missing year included. **(B)** The second pair of cores are 718A and 718B, also from *A. saccharum* trees. Shifting the green line about five years ahead or the blue line five years back produced more matched peaks. This indicates that years may have been missed and/or added when counting and measuring rings. It presents a source of error in cross-dating.

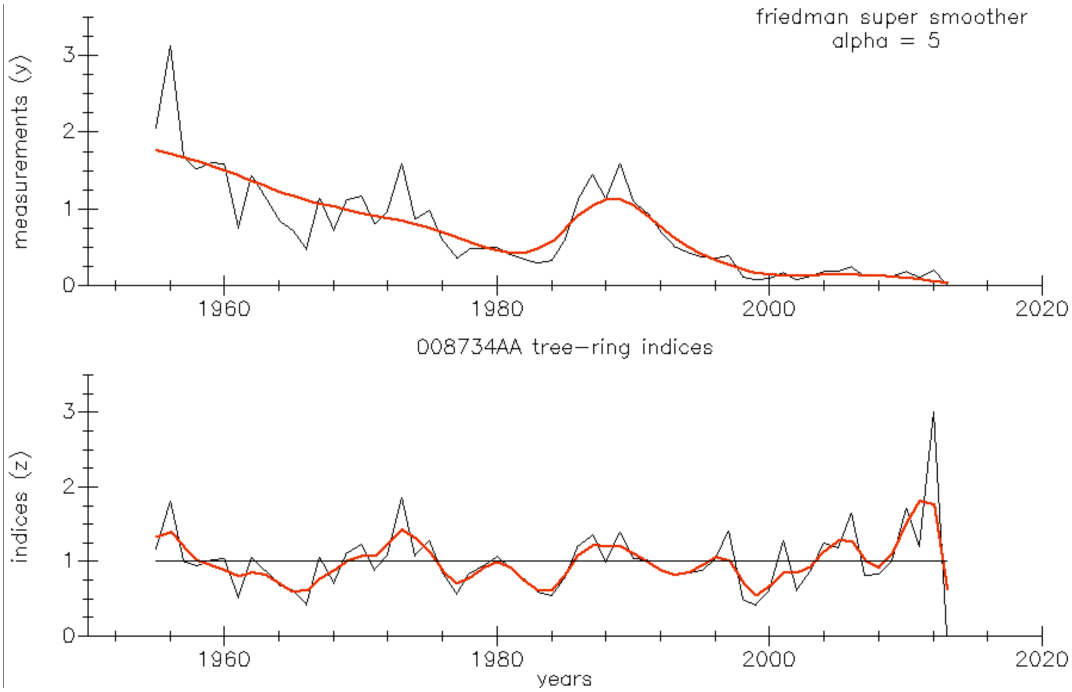


Figure 4. Friedman's smoothing produced growth ring measurement indices for statistical analysis. Core 734A is shown as an example of the Friedman's smoothing technique in ARSTAN 44h2 (Cook and Krusic 2013) that was done for each sample. De-trending was necessary in order to remove much of the age-related growth trend and maintain low frequency variation. It also created indexed growth series for each core with a mean of 1.0. These indices were then used for stepwise regression analysis.

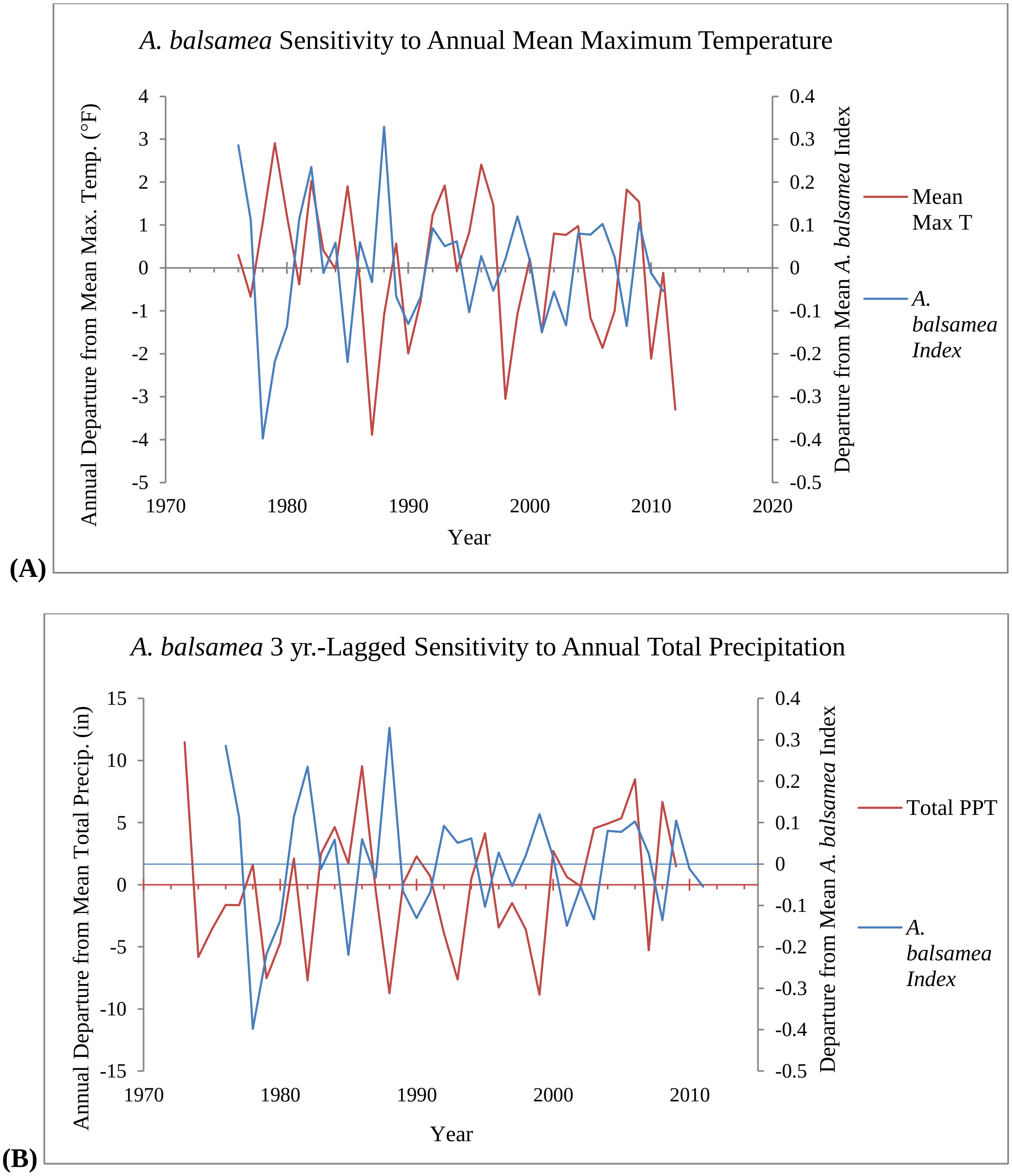
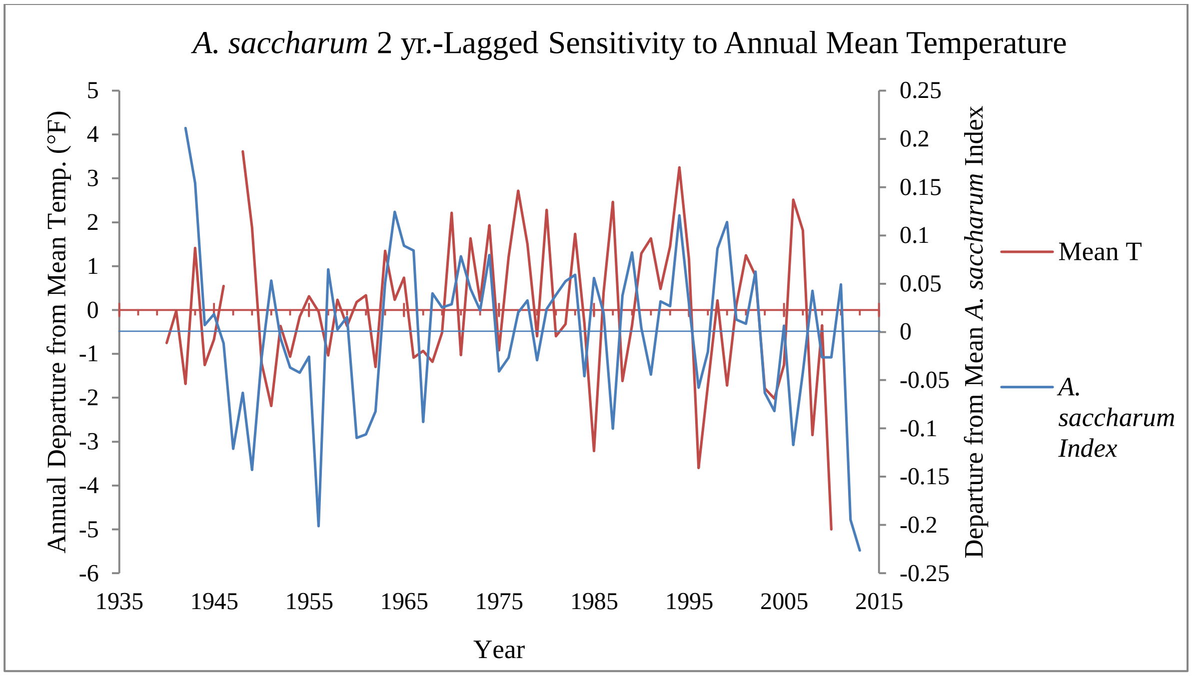
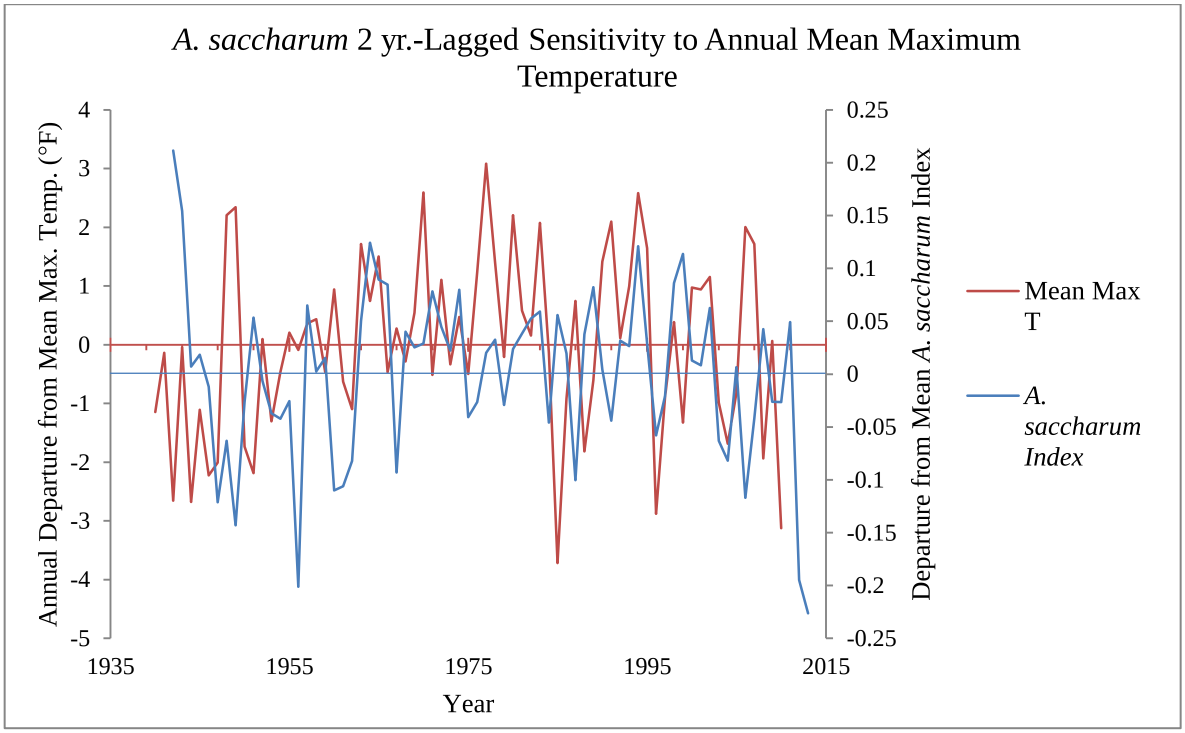


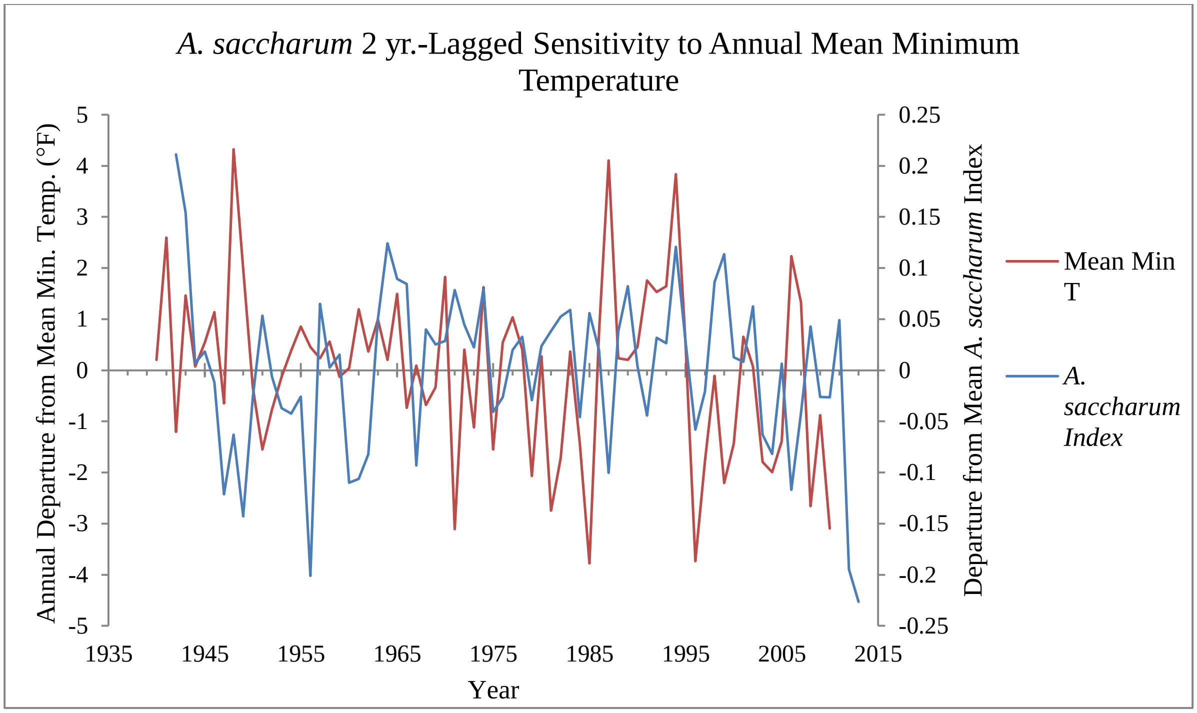
Figure 5. *A. balsamea* insensitivity to annual mean temperature, mean maximum temperature, mean minimum temperature, and total precipitation. Using back-stepping regression analysis in SYSTAT 13 (Systat Software, Inc. 2008), *A. balsamea* ring-width was found to be relatively insensitive to each of the four climate between 1976 and 2008 (n = 33). The two most correlated relationships were **(A)** between annual ring indices and mean maximum temperature (p = 0.212) and **(B)** between annual ring indices with a three year lag and total precipitation (p = 0.149).


A. saccharum 2 yr.-Lagged Sensitivity to Annual Mean Temperature
Annual Departure from Mean Temp. (°F)
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
Departure from Mean *A. saccharum* Index
1935
1945
1955
1965
1975
1985
1995
2005
2015
Year
Mean T
A. saccharum Index

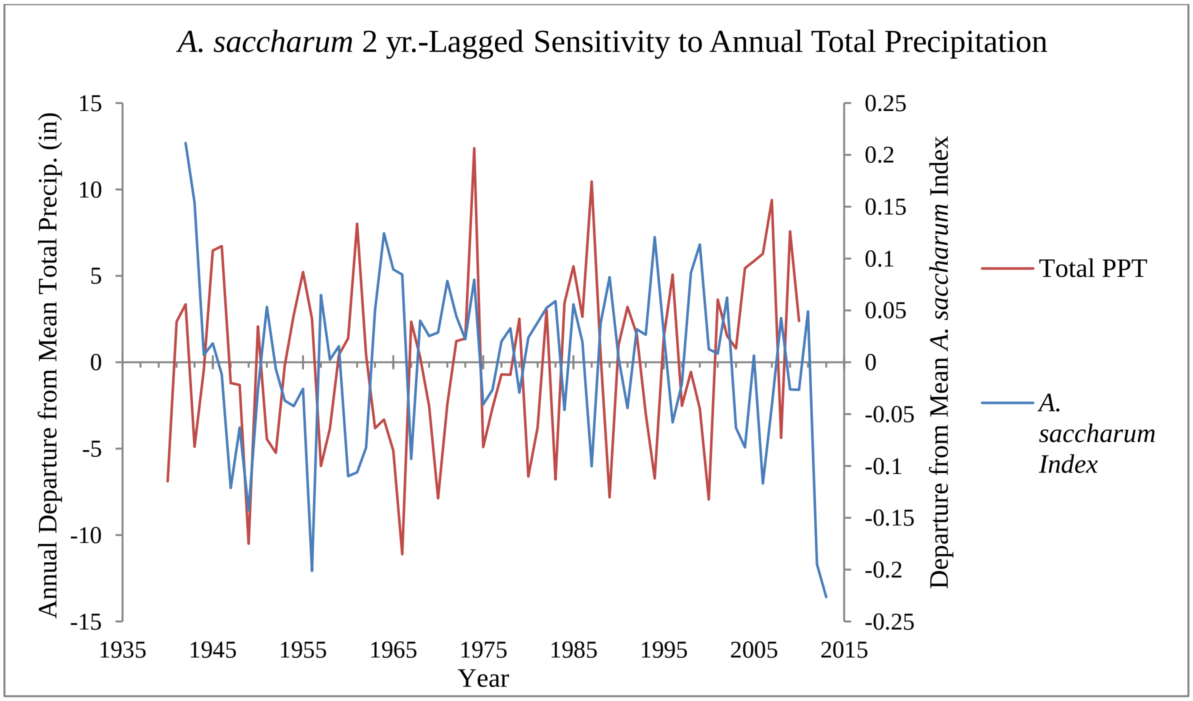
(A)


A. saccharum 2 yr.-Lagged Sensitivity to Annual Mean Maximum Temperature
Annual Departure from Mean Max. Temp. (°F)
4
3
2
1
0
-1
-2
-3
-4
-5
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
Departure from Mean *A. saccharum* Index
1935
1955
1975
1995
2015
Year
Mean Max T
A. saccharum Index

(B)



(C)



(D)

Figure 6. *A. saccharum* 2 yr.-lagged sensitivity to all four annual climate variables. Following a back-stepping regression analysis in SYSTAT 13 (Systat Software, Inc. 2008), *A. saccharum* ring-width was found to be significantly correlated, or sensitive, to each of the four climate variables. Between the years 1942 and 2009 (n = 68) the best relationship was found to have a two year lagged response from ring-widths for each climate variable. **(A)** There was a significant relationship between annual ring indices and mean temperature (p = 0.015). Note that

the year 1949 was missing from the NOAA climate data and was not used to generate a departure from the mean. **(B)** The relationship between annual ring indices and mean maximum temperature was significant with a p value of 0.012. **(C)** A significant relationship was also found between annual ring indices and mean minimum temperature (p = 0.046). **(D)** Finally, the relationship between annual ring indices and total precipitation with a two year lag was the most significant with a p value of less than 0.001.