Comparing the climatic sensitivity of radial growth between Acadian tree species and stand types in New Brunswick

by

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Abstract

In order to understand how the different Acadian tree species and stand types will grow under future increasing temperatures and inform management, I used a dendroecological approach to compare the growth sensitivity of coniferous and broadleaf tree species to historical climate at four different stand types within Acadia Research Forest in New Brunswick, Canada.

At each site, dominant tree species were cored, their ring-widths measured, cross-dated, and correlated with historical climate. We found that higher temperatures and low water availability in summer was associated with lower growth of balsam fir and red maple in a majority of sites, while drought in summer negatively affected the growth of spruce and yellow birch. In winter, high vapor pressure deficit was negatively correlated with the growth of coniferous species, but positively correlated with maple growth. Overall, despite inconsistent climate responses across sites, these results provide compelling evidence of contrasted climate sensitivity among tree species.

Acknowledgements

I would like to express my gratitude to all those who have helped and supported this study. I would like to start by thanking my supervisor Dr. Loïc D'Orangeville, who gave me the opportunity to study and encouraged me throughout my research. He is very kind, sincere and professional, with a great ability to answer patiently and help me solve many problems whenever I encounter them, no matter if they are basic or not. I saw in him a passion for forestry, and this passion was one of the sources that encouraged me to continue my studies. I could not have completed this report without him. Then I would like to thank my committee David A. MacLean and John A. Kershaw for their invaluable comments, guidance on writing in English, and many new ideas for my research, I am very grateful for their dedication.

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Finally, I would like to thank my parents for their long-standing support and tolerance. It was their understanding and encouragement that gave me more motivation to continue my studies and gave me confidence. Without their contribution, I would not be the person I am today.

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growth. The y-axis represents the four sample plots of A, B, C and D. Statistically significant correlation coefficients ($P<0.05$) are represented by black stars. Blue represents positive correlations and red represents negative correlations. 20

List of Symbols, Nomenclature, or Abbreviations

- VPD = Vapor pressure deficit
- PDSI = Palmer Drought Severity Index
- ARF = Acadia Research Forest
- DBH = Diameter at breast height, 1.3 m
- BA = Basal area
- BAI = Basal area increment
- BF = Balsam fir
- RM = Red maple
- SM = Sugar maple
- YB = Yellow birch
- IW = Ironwood

Introduction

Over the past century, annual mean temperatures in eastern Canada have risen by 0.5-1.5°C and total precipitation has increased by 5-35% (Zhang et al. 2000). Global climate models predict global temperatures will increase by another 3 °C by the end of the twenty-first century (IPCC, 2013). Global climate change impacts forest ecosystem dynamics through overall increases in yearly temperature, increases in the frequency and intensity of acute climatic events, and modifications to natural disturbance regimes (Iverson et al. 2008, Allen et al. 2010, Dai 2013). As a result of climate change, increased frequency of extreme weather events like droughts and heatwaves are expected, which impact plants with heat and water stress (Grossiord et al. 2020). These stresses disrupt forest ecosystems processes (Iverson et al. 2008, Allen et al. 2010, Dai 2013). Effects of climate change on forest ecosystems may be dramatic and may alter critical ecosystem goods and services such as wood fiber provision, habitat for biodiversity, and carbon storage (Thompson et al. 2009). Climate change may speed up processes of forest decline and drought stress in water-limited areas, disproportionately affecting vulnerable individuals, species, and populations (McDowell et al. 2008, Anderegg et al. 2016). There is considerable evidence that forests play important roles in critically endangered species, carbon sequestration and storage, water supply, and preservation of human health (Watson et al. 2018). Maintaining sustainable forests and minimizing forest degradation are critical priorities in the ongoing worldwide efforts to prevent the decline of biodiversity and rapid climate change (Watson et al. 2018). In order to better predict how climate change affects forest ecosystems and ultimately to develop and implement adaptive measures, a more in-depth understanding of species-specific vulnerability to

climatic stressors is needed (D'Amato et al. 2013, Allen et al. 2015, Nolet and Kneeshaw 2018).

Since it is challenging to monitor long-term consequences of climate change on natural ecosystems directly, we typically employ indirect methods such as using historical records of processes such as growth rates found in tree rings and linking them to climate records (Blasing and Fritts 1976). Tree rings serve as an ecological indicator to help understand sensitivities of trees to interannual changes in climate (Bollati et al. 2018). The width, density, color, and anatomical structure of annual growth rings vary under different climatic conditions (Blasing and Fritts 1976). Studies of the correlations between climatic effects on radial increments of trees using multivariate statistical methods began in the 1960s (Fritts 1962, 1991, Fritts et al. 1971, Cook and Kairiukstis 1990), a field of ecology referred to as dendrochronology.

Common climatic predictors of growth are monthly mean temperatures and monthly total precipitation rates, given their availability over a large range of locations and time spans on the Earth's surface (Vaganov et al. 2006). In addition, vapor pressure deficit (VPD) has been shown as a significant contributor to recent drought-induced plant mortality independent of other variables linked to climate change (Grossiord et al. 2020). VPD is the difference between the water vapour pressure at saturation and the actual water vapour pressure for a given temperature(Rawson et al, 1977). Plant transpiration is the process of transporting water from roots to aerial plant parts, and transpiration is driven by atmospheric water demand, according to the "big leaf" model, Fick's law, and Darcy's law, ecosystem transpiration depends on the difference in water vapour pressure between the inside and outside of the stomata and stomatal conductance (Dai et al.

2004, McDowell and Allen 2015). VPD is a significant factor in influencing plant transpiration and photosynthesis as well as a key driver of atmospheric water demand for plants (Song et al. 2020). The Palmer Drought Severity Index (PDSI) is another useful climate indicator. The PDSI is the most well-known meteorological drought index used in the United States for drought study and monitoring, and its variation has been used to measure long-term changes in aridity over land in the 20th and 21st centuries (Dai, 2011). Tree-ring based reconstructions of previous droughts in North America and other locations have also frequently used the PDSI (Dai, 2011). Palmer created the PDSI with the intention of measuring the cumulative change in surface water balance (Dai, 2011). It combines past and present moisture demand (potential evapotranspiration, PE) and supply (precipitation, P) into a hydrological accounting system, which includes a 2-layer bucket-type model for calculating soil moisture (Dai, 2011). It is an index that is standardized and typically ranges from -10 (dry) to +10. (wet) (Dai, 2011).

Canada's maritime provinces (Nova Scotia, New Brunswick, and Prince Edward Island) stretching down to the Northeastern United States (Maine, Vermont, New Hampshire, and New York) make up the Acadian Forest Region, which is characterized by a high degree of physiographic and biological diversity due to its location at the confluence of the Gulf Stream's warm, moist influence from the south and the Labrador Current's coldness (Loo and Ives, 2003). The region also features a gradual transition from boreal to mostly deciduous forest (Loo and Ives, 2003). Natural forest types in the Acadian Forest Region include a variety of coniferous, deciduous, and mixed intermediate types, as well as rich tolerant hardwoods that are similar to the deciduous forests to the south and spruce-fir forests that are similar to the boreal forests to the north (Loo and Ives,

2003). The Acadian Forest Region is known to be characterised by the red spruce ((*Picea rubens* Sarg.), yellow birch (*Betula alleghaniensis* Britton), sugar maple (*Acer saccharum* Marsh.), and balsam fir (*Abies balsamea* (L.) Mill., Loo and Ives, 2003).

Among these species, the most research is on the sugar maple, red maple and red spruce. These species play an important role in forests. Sugar maple has a long lifespan, grows slowly, and tolerates shade. The yearly agricultural contribution of maple syrup is 494 million Canadian dollars (Agriculture and Agri-food Canada, 2017). And the red maple (*Acer rubrum* L.) is one of the most common broadleaf trees in eastern North America, which is also used to delineate the boundary between the boreal and temperate biomes in eastern Canada (Walters and Yawney 1990). The red spruce in the eastern United States (US) experienced needle damage, crown deterioration, growth decreases, and increased mortality around the middle of the 1980s (Johnson et al., 1988, McLaughlin et al., 1987, Scott et al. 1984). Red spruce decline was one of the most extensively researched cases of forest degeneration in the US in the next decades (Eagar and Adams, 1992). Coincidentally, according to different dendroclimatic research, the growth of red maple, red spruce and sugar maple exhibited the same climatic correlation. High summer temperatures are negatively correlated with the growth of red maple (Kosiba et al., 2017a, Zhang et al. 2013), sugar maple (Bishop et al. 2015, Copenheaver et al. 2020, Goldblum and Rigg, 2005, Moreau et al. 2020, Payette et al. 1996) and red spruce (Girardin et al. 2008, Johnson et al. 1988; Kosiba et al. 2017b, 2018, Yetter et al. 2021), but high precipitation in the previous summer or fall is positively correlated with the growth of these three species. Unfortunately, there are no peer-reviewed tree-ring studies on climate-growth coupling in the Acadian Forest of Canada, especially for balsam fir,

yellow birch, and ironwood (*Parrotia persica* C.A. Meyer). Our study area is the Acadian Research Forest, which is in Canada's New Brunswick. Our main research species are red maple, spruce, sugar maple, balsam fir and yellow birch. We can partially cover the lack of information regarding the relationship between common tree species and the climate in eastern Canada.

The objective of this research is to compare tree growth to historical climate of key Acadian tree species in coniferous and broadleaf stands using a dendroecology approach, in order to better anticipate the species response to future warming. Our driving hypothesis is high summer temperature and low water availability will have negative impacts on spruce (*Picea* spp.), red maple, and sugar maple.

Methods

Study area and stand characteristics

This study took place at Acadia Research Forest (ARF) in the lowlands of New Brunswick, Canada (Figure 1). The climate in the ARF is intermediate between a maritime and a continental climate (Swift et al. 2006) with a monthly average high temperature of 18.4°C and a monthly average low temperature of -9.7°C (Swift et al. 2006). Average annual snowfall and precipitation are high, at 267 cm and 1144 mm, respectively. The soils at ARF are primarily acidic and nutrient-poor, dominated by gleysolic soils, or podzolic soils in the drier parts (Crampton 1971). The subsoils are composed of red-brown compact clays, and the surface tills are made up of clay or sandy loam textures.

The ARF is a typical disturbed Acadian Forest composed of a diverse combination of coniferous and hardwood species, dominated by spruce, balsam fir, red maple, and white birch (*Betula papyrifera* Marsh., Swift et al. 2006), as well as yellow birch, sugar maple, and white ash (*Fraxinus americana* L.), on more productive sites. Red spruce, a characteristic tree species of the Acadian Forest Region, also occurs frequently in the research forest, where it often hybridizes with black spruce (*Picea mariana* (Mill.) B.S.P., Manley 1972).



Figure 1. Locations of the four study plots, within the ARF (black line). Red, green, blue, and purple represent the plot A, plot B, plot C and plot D.

Four plots were established in 2018 within a 4-km radius to represent the diversity of Acadian Forest types, from low-productivity, conifer-dominated stands to rich upland hardwood-dominated. In hardwood stands, the content of rocks and clay is much lower than in softwood stands, but the content of sand is higher than in softwood stands.

An inventory of all trees with DBH ≥ 9cm was conducted in 2019 to describe and compare the four study plots. Plot A had the highest stem density (1660 trees· ha^{-1}) and the smallest average DBH (13.9cm). It was dominated by small-diameter balsam fir (66% of BA), along with red maple and red-black spruce hybrids. Compared to other plots, plot A displays the lowest productivity, as evidenced by its perched water table and prolonged spring flooding.

Small-diameter balsam fir was also abundant in plot B (mean DBH=14.1cm), but represents only 33% of the total basal area, while larger red maple and red-black spruce hybrids, referred to herein as spruce (average DBH=23-27cm) make up most of the remaining stand BA. Relative to plot A, plot B displays a lower density (1454 trees· ha^{-1}), larger trees (average DBH=18cm), and includes the presence of small yellow birch trees (average DBH=15cm) and a few remaining, large white birch (mean DBH=33cm).

Plot C displays a much lower density of 923 trees· ha^{-1} than plot A and B, and supports a higher hardwood component, with the presence of a few sugar maple and striped maple trees in addition to the species found in plot B. Contrary to plot B, balsam fir makes up less than 17% of the stand BA, which is dominated by red maple (47% of total BA), followed by large-diameter yellow birch (mean DBH=33cm) and white birch trees (mean DBH=47cm).

Of all study plots, plot D displays the lowest density (550 trees· ha^{-1}) and the highest hardwood component. Similarly to plot C, red maple makes up 48% of the basal area and displays an average DBH of 27cm. However, plot D is also characterized by the presence of large white ash trees (19% of total BA), along with large yellow birch (17% of total BA), as well as the presence of an important smaller cohort of ironwood and sugar maple trees.

The analysis of mineral soil samples collected at each plot indicates similar fertility and texture. All plots display 48-60% sand, along with 30-39% silt, which are characteristic of loams and sandy loams. Soils are acidic, with pH ranging from 3.6 (plot B) to 4.2 (plot D), with low C:N ratios between 11 (plot D) and 16 (plot B).

Tree-ring collection and preparation

In each plot, growth increment cores were collected on at least 20 trees with DBH ≥ 9cm of the dominant tree species, and their DBH measured, for a total of 279 trees. Balsam fir was sampled in plots A, B and C; red maple was sampled in all four plots; spruce was sampled in plots A, B and C; yellow birch was sampled in plots C and D; sugar maple and ironwood were sampled in plot D only. The average DBHs of trees cored gradually increase from plot A to D, at 16cm, 21cm, 22cm and 26cm in plots A, B, C and D, respectively. For each tree, we collected two cores at breast height, from the south and north sides, perpendicular to the ground. Only undamaged cores with intact bark and absence of rotting were retained for analyses. Cores were glued to wooden mounts, air-dried, gradually sanded and their bark thickness measured. But there are some recent tree rings missing because all cores were not collected in the same year, and some cores were collected in 2018, some were collected in 2022.

Tree cores were scanned using a Laxco™ SeBaCam Digital Microscope Camera under 5.1mp. Individual images were merged automatically to cover entire cross sections using SeBaView software ver. x64 (LAXCO, U.S.). Annual ring boundaries were then measured at a 0.01mm accuracy from digital images scanned in CooRecorder 9.5 (CYBIS Elektonik and Data AB, Saltsjöbaden, Sweden), and cross-dated using CDendro 9.5 (CYBIS Elektonik and Data AB, Saltsjöbaden, Sweden). Cross-dating was based on the comparison of individual growth curves to the mean growth curve per species and plot. Threshold individual correlations under 0.2 were used to identify poorly dated individual series, which were then carefully inspected to eliminate false annual growth estimates caused by partially missing ring boundaries. Cross-dated ring width series were

then averaged annually per tree. After measuring the thickness of the bark and removing it from the DBH measurements, the cross-dated ring width series were converted to annual basal area increment (BAI) using the recorded DBH of each tree. BAI is more representative of the increase in tree biomass than diameter increment (Pedersen, 1998) and corrects for difference in tree size. BAI was calculated using the tree DBH and raw ring widths (Equation 1), which was carried out with the bai.out function in the dplR package in R (R: The R Project for Statistical Computing, 2023):

$$BAI_t = \pi\left(R_t^{\,2} - R_{t-1}^{\,2}\right)$$

where R_t and $R_{t-1}$are the tree radius at year *t* and *t*-1. To remove the low-frequency BAI trends related to age and other biological effects and isolate climatic signals, each individual tree-ring series was standardized using a spline function with a 50% frequency response (Cook and Peters 1981). For each plot and species, individual residual BAI series were averaged into an annual chronology using a bi-weighted robust mean that reduces the influence of outliers (Cook and Peters, 1981), excluding years with a sample size lower than three trees. Also, we calculated descriptive statistics for the detrended chronologies, including mean inter-series correlation and the expressed population signal (EPS) to evaluate the robustness of each chronology. These analyses were performed using the "dplR" (CRAN - Package DplR, 2022) package in R(R: The R Project for Statistical Computing, 2023).

Climate

Historical different monthly climate for 1960-2020 was downloaded for the four study plots from TerraClimate, a dataset of the monthly climate and climatic water balance at high spatial resolution (1/24°, 4 km) for all terrestrial surfaces worldwide from 1958 to 2020 (Abatzoglou et al. 2018). Monthly climate variables included average daily maximum temperature (℃), total precipitation (mm), VPD (Kilopascals) and PDSI (PDSI).

Analysis of climate-growth coupling

To relate growth to monthly climate among species and sites, we computed correlations between the chronologies and monthly climatic variables using bootstrapped correlation functions using the Treeclim package (Zang and Biondi, 2015) using R software (R: The R Project for Statistical Computing, 2023). Dendrochronological relationships with climate variables are frequently calculated using response and correlation functions (Blasing et al. 1984). The pronounced intercorrelation of the climatic variables used as predictors, also known as multicollinearity, is a general issue with these methods (Cropper, 1984), this situation possibly leading to over- or under-fitted models (Blasing and Fritts, 1976). Guiot (1991) suggested bootstrapping as a method for gaining more accurate results for response functions, and Biondi (1997) gave the concept of using bootstrapped correlation and response functions to several time intervals to evaluate the stationarity of such responses. This method, as described in detail by Biondi (2000), gave mathematics a way to define and examine what is now known as the "divergence problem." For each climate variable, we included monthly values from June of the year

preceding growth-ring formation to August of the year of actual ring formation in order to reflect the relationship better and maximally between climate and tree growth. Significance of correlations was assessed at $p < 0.05$ through a 1000 bootstrap replicate approach.

Results

Statistics of growth and chronologies

On average, trees were youngest in plot A, with an average age of 36 years and no trees older than 50 years, while trees in plot D were the oldest, with an average age of 83 years and a 187-year-old yellow birch (Table 1). Trees in plots B and C were intermediate in age, with ages ranging between 25 to 161 years.

Looking at raw BAI trends over time, we report an increasing BAI trend for balsam fir in plots A, B and C up to the early 2000s, followed by a decreasing trend (Supplementary Figures 1, 2, 3, 4). The BAI of red maple in all four sample plots gradually leveled off after the trees matured. However, no clear trend was observed in other species.

For annual chronologies, we report significant declines in Balsam fir and spruce growth between 1980 to 1990 (Figure 2, 3). Prior to 2000, the growth of red maples growing in plot A, B and D had one or two declines, but not those growing in plot C (Figure 4). The yellow birch growing in plot C was stable, which was almost the same as the red maple and spruce growing in plot C (Figure 5). However, the yellow birch growing in plot D showed some fluctuations between 1950 and 1960 (Figure 5). Same as red maples and yellow birches growing in plot D, sugar maple and ironwood growing in plot D also showed large fluctuations between 1950 and 1960 (Figure 6).

Cross-dating was successfully performed on all species and sites, with high average inter-series correlations ranging between 0.36 and 0.61 (Table 1).

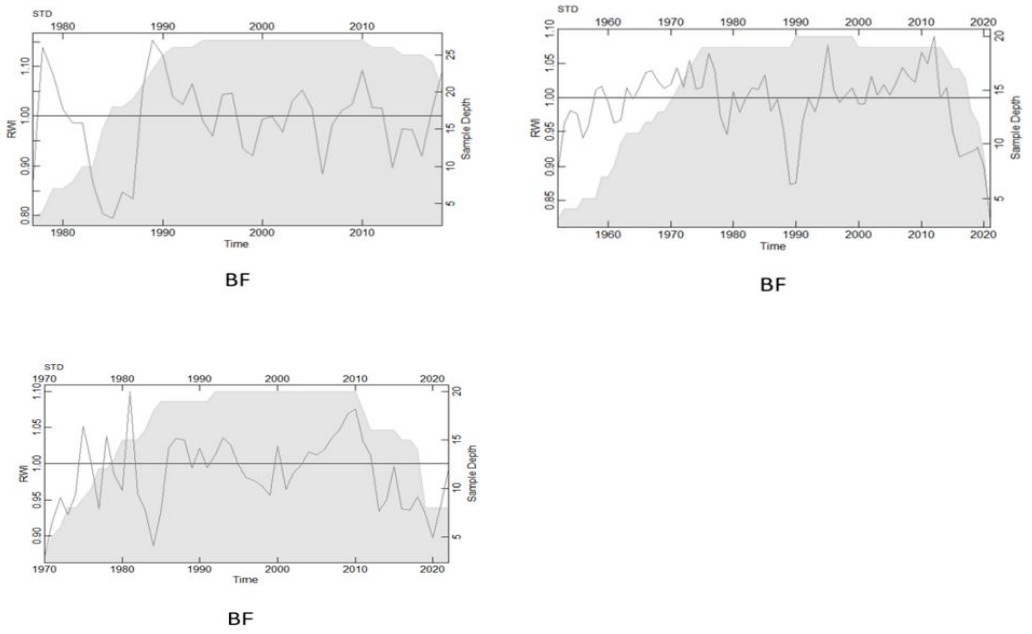


Figure 2. Chronologies for balsam fir (BF) in plot A (top left), plot B (top right) and plot C (bottom). The grey area indicated sample depth (the number of series available in that year).

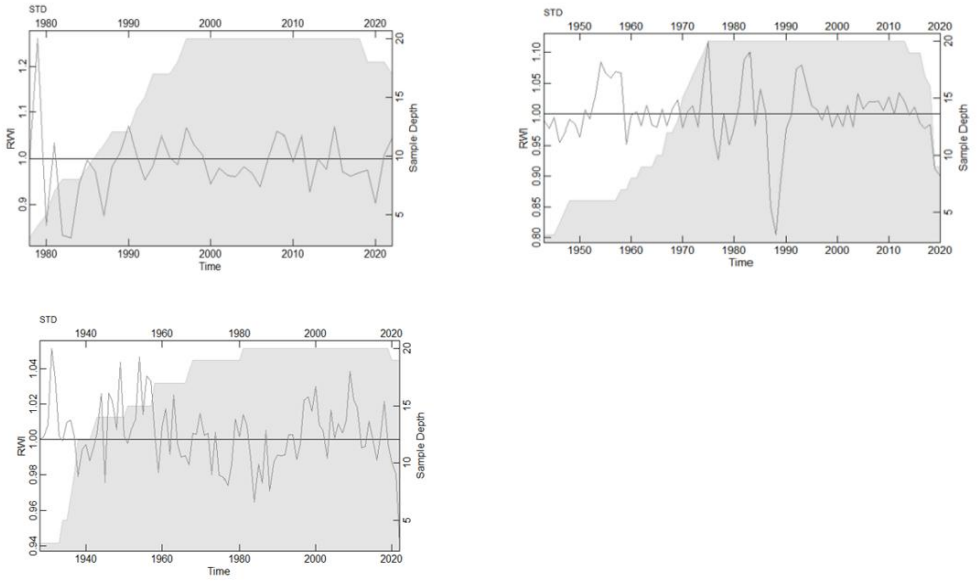


Figure 3. Chronologies for spruce in plot A (top left), plot B (top right) and plot C (bottom). The grey area indicated sample depth (the number of series available in that year).

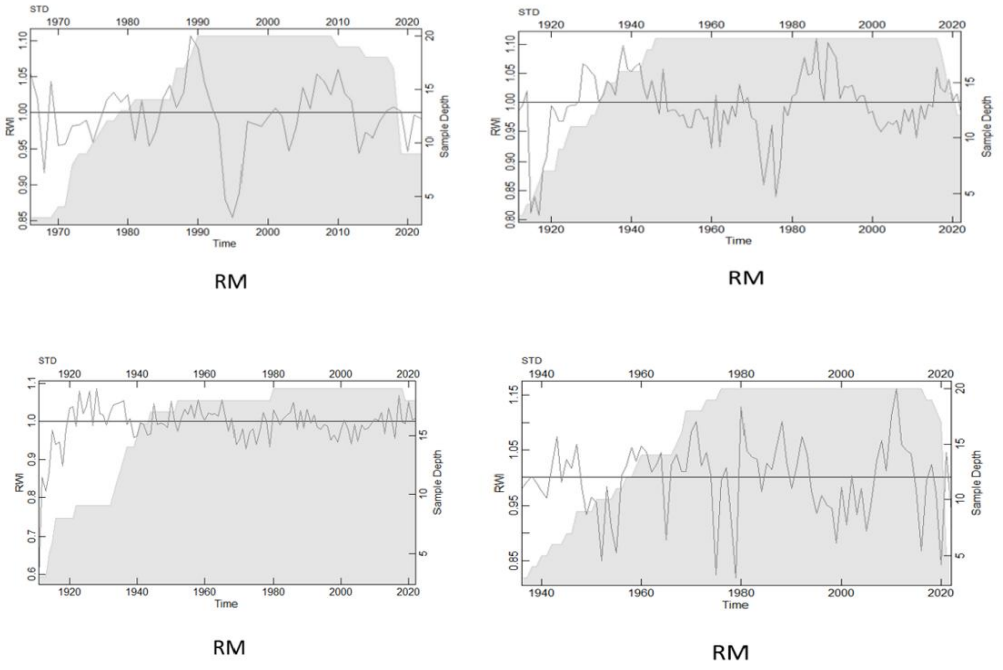


Figure 4. Chronologies for red maple (RM) in plot A (top left), plot B (top right), plot C (bottom left) and plot D (bottom right). The grey area indicated sample depth (the number of series available in that year).

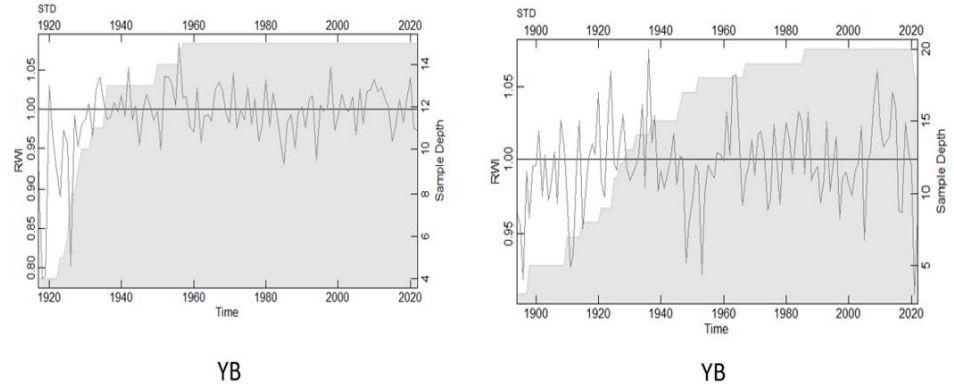


Figure 5. Chronologies for yellow birch (YB) in plot C (left) and plot D (right). The grey area indicated sample depth (the number of series available in that year).

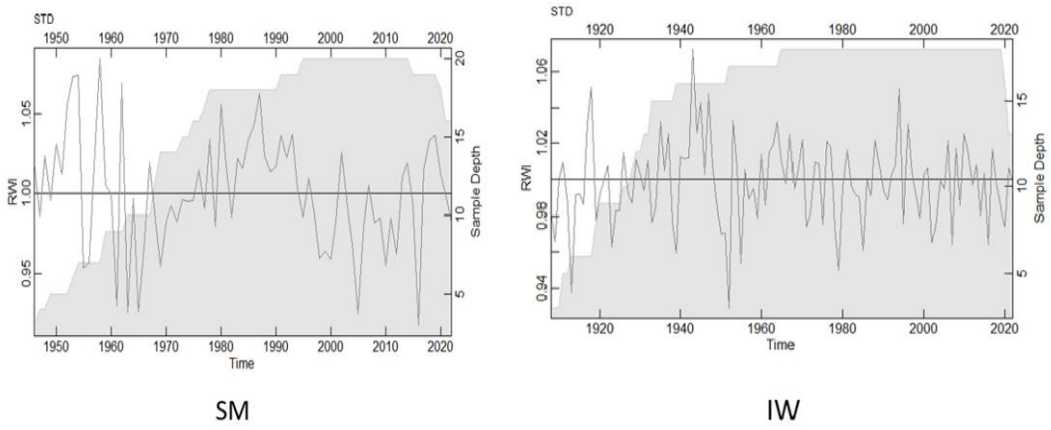


Figure 6. Chronologies for sugar maple (SM) in plot D (left) and ironwood (IW) in plot D (right). The grey area indicated sample depth (the number of series available in that year).

Table 1. Average inter-series correlation and age range for each chronology.

	Plot A			**Plot B**			**Plot C**				**Plot D**			
Species	BF	RM	RS	BF	RM	RS	BF	RM	RS	YB	SM	RM	YB	IW
Age [min]	44	24	22	29	77	45	25	39	42	59	28	44	29	45
Age [max]	44	33	48	87	161	84	59	142	106	125	107	106	187	117
Correlations	0.61	0.45	0.40	0.58	0.36	0.65	0.5	0.39	0.37	0.36	0.37	0.58	0.40	0.47

Notice: BF, RM, RS, YB, SM, IW means balsam fir, red maple, spruce, yellow birch, sugar maple, ironwood. Correlations means Average inter-series correlation.

Summer climate-growth coupling

Bootstrapped correlation functions indicate that higher maximum temperature and lower precipitation in summer were significantly correlated to reductions in growth for balsam fir and red maple (Figure 7). For balsam fir, the negative correlation of growth with maximum temperature was observed with prior-year July and August at two sites (plots B and C), as well as a negative correlation with VPD in prior-year July (plot C). For red maple, negative correlations of growth with summer temperature were observed with prior-year and current-year June at three sites (plots A, B and D), along with a negative correlation of growth with VPD in prior-year June and August at two sites (plots A and C; Figure 7). The positive correlation of growth with precipitation was observed in prior-year July for balsam fir (plot B), and in prior-year August and current August for red maple (plots A and C; Figure 7). In apparent contradiction with these responses, both species displayed higher growth during summer drought anomalies. We report negative correlations of red maple growth with current-year July and August PDSI in plot B, (PDSI increases with available moisture), and a negative correlation between balsam fir growth and PDSI in prior-year June in plot C (Figure 7).

The negative correlations reported for balsam fir and red maple at multiple sites under higher temperatures and lower precipitation in summer was less consistent for other species including spruce, yellow birch, sugar maple and ironwood. Both spruce and yellow birch displayed significant negative effects of July and August drought on their growth, as supported by the positive correlations between growth and the PDSI index. The significant correlations of spruce growth with PDSI were observed in August (plot A) and in prior-year July (plot B), while that of yellow birch growth was observed during

current-year July and August in plot D, indicating water limited growth during these months (Figure 7). We also observed positive correlation between spruce, yellow birch growth and precipitation observed in August in plot A and June in plot D. Meanwhile, there is a negative correlation between the growth of yellow birch and maximum temperature in August in plot D. But this was not observed from spruce, In contrast, we observed a positive correlation between spruce and VPD in plot A in August, but a negative correlation with VPD in June. In addition, there are no obvious correlations were observed in ironwood and sugar maple (Figure 7).

Winter climate-growth coupling

We report a high number of significant correlations between winter climate (December, January, and February) and tree growth. Balsam fir growth was negatively correlated with VPD in prior-year December, January, or February (plots B and C), while spruce growth also displayed negative correlations, this time with prior-year December, January, or February VPD in plots A, B, and C (Figure 7). We also observed a negative correlation between the growth of balsam fir and the precipitation in February in plot C. For both conifer species, only winter VPD was related to growth, as winter temperature, precipitation or PDSI had no obviously significant correlations.

Contrary to conifers, both red and sugar maples displayed increased growth following high winter VPD. Red maple growth was positively correlated with VPD in February (plot C), while sugar maple growth was positively correlated with VPD in prior-year December, January, and February (plot D). In addition to VPD the growth of both species was negatively correlated with prior-year winter precipitation (plots B and D for red

maple; plot D for sugar maple; Figure 7). We also observed a positive correlation between the growth of red maple and the maximum temperature in January in plot A.

Contrary to previous species, yellow birch growth displayed a positive correlation with winter precipitation in November and PDSI in November along with a negative correlation with December temperature (plot D; Figure 7). We also observed negative correlations between the growth of ironwood and VPD (December) in ironwood from plot D (Figure 7).

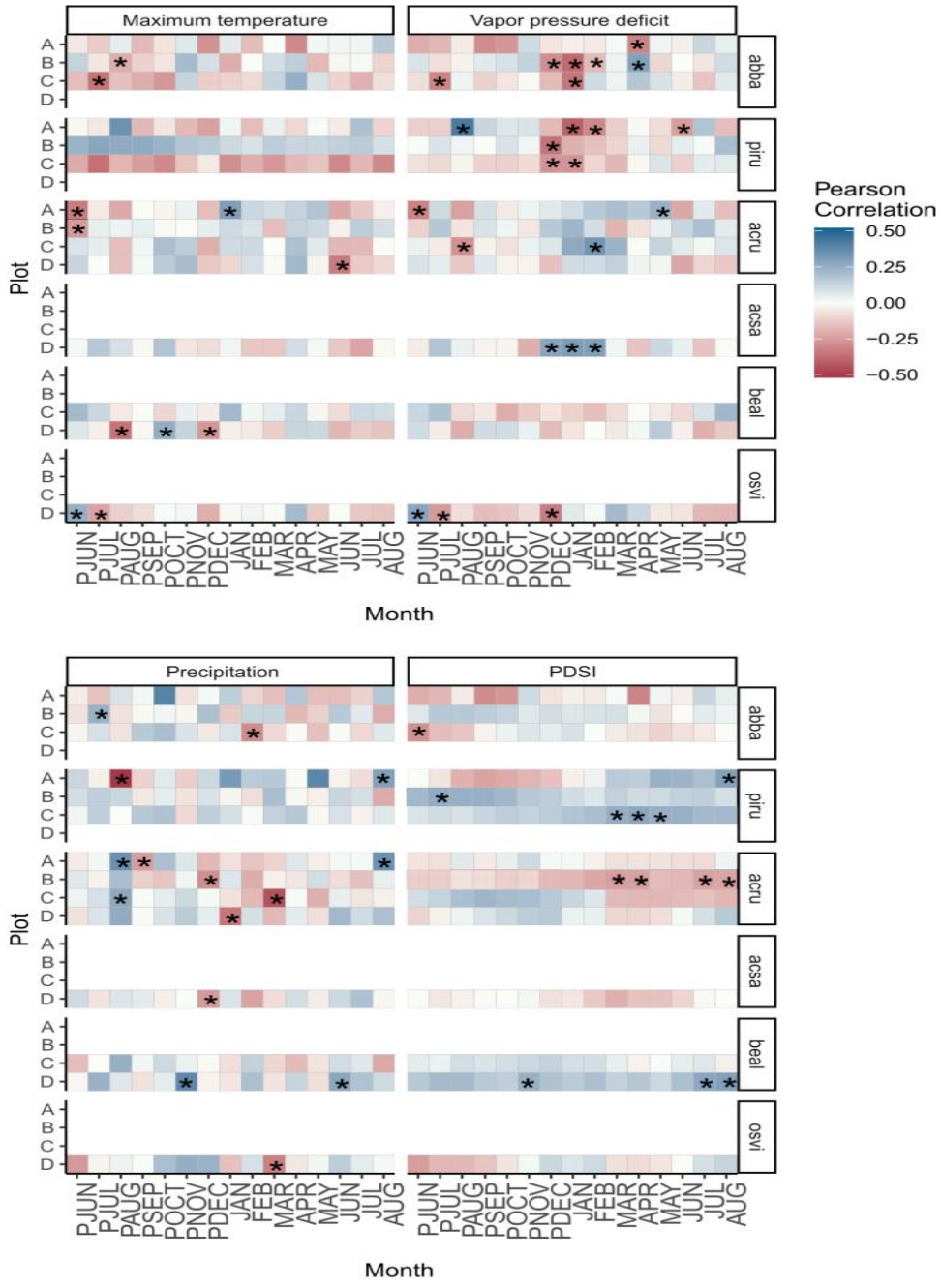


Figure 7. Bootstrapped response function coefficients computed between balsam fir (abba), spruce (piru), red maple (acru), sugar maple (acsa), yellow birch (beal) and ironwood (osvi) chronologies and the monthly climatic variables over the 1961–2020 period. The letter P before each month on the x-axis indicates the months of the year prior to growth (year-1), while no letter P before each month indicates months of years of growth. The y-axis represents the four sample plots of A, B, C and D. Statistically significant correlation coefficients ($P<0.05$) are represented by black stars. Blue represents positive correlations and red represents negative correlations.

Discussion

Taylor et al. (2017). used the forest ecosystem simulation model PICUS (Lexer and Hönninger. 2001, Seidl et al. 2011), which simulates individual tree establishment, growth, and mortality on 100 m^2 gaps or "patches" of forest area They found that the Acadian Forest Region in Canada will start to "deborealize" under the rapid warming of the twenty-first century when important tree species fail to renew and survive. Balsam fir was reported to be likely to grow in response to increasing temperatures, but additional warming reverses this trend and declines sharply (D'orangeville et al. 2018). Also, balsam fir seedlings are not adapted to warming and drought (Vaughn et al. 2021). This is consistent with our study of balsam fir. We report that balsam fir displayed a higher sensitivity to warming and drying compared to other species, as supported by their repeated significant growth declines under high temperature and low precipitation in summer. Zhang et al. (2015) found that the increasing temperature in summer is not suitable for the growth of red maple This is also supported by the negative correlation between summer and temperature of red maple in our study. However, in a recent report, red maple seedlings have been observed to exhibit higher absolute growth and survival rates with a warming climate (Vaughn et al. 2021). We also found contradictory effects of drought on red maple and balsam fir. Both balsam fir and red maple were positively correlated with precipitation in summer, but negatively correlated with PDSI. This may be due to the fact that while temperature and precipitation are important factors in determining whether the area is experiencing drought, they do not provide a complete picture. The PDSI considers both temperature and precipitation, as well as other factors such as soil moisture, evapotranspiration, and the storage and release of water in the soil

and provides a more comprehensive picture of drought conditions (Connor and Palmer. 1965). It is a standardized index that compares current moisture conditions to average conditions for a given location and time of year, allowing for comparisons across different regions and time periods (Connor and Palmer. 1965).

We also found that summer drought can adversely affect the growth of spruce and yellow birch. According to a study by Dr. Philip B. White et al. (2014) in a red spruce forest, southern Appalachian Mountains, USA, they used the same dendrochronological techniques as we did for tree-ring studies on climate-growth coupling and found that the temperature sensitivity of red spruce shifted significantly after the 1930s, with a positive growth response to warm temperatures shifting to a negative response, and a positive correlation between red spruce growth and precipitation was observed in summer. This is similar to our findings. Contradictory to this, in the study by Dr. Steenberg et al. (2013) who used the landscape disturbance model LANDIS-II to simulate two climates and two harvest scenarios in Acadian forests watershed, they concluded that in the case of red spruce and yellow birch, the loss in the case of increasing temperature and climate change is low and these two species have abundant resistance.

Our winter results indicate that the growth of balsam fir and spruce is reduced under increasing VPD, while both maple species display the opposite response, although this response is not very strong, which only appeared in one plot. In most previous studies, spruce (Johnson et al. 1988, Kosiba et al. 2017, 2018, Yetter et al. 2021) and balsam fir (Goldblum and Rigg, 2005) did show adaptability to low temperatures in winter, while the higher sensitivity of sugar maple growth to low winter temperatures has been previously reported (Moreau et al. 2020, Payette et al. 1996). However, in the study by

Goldblum and Rigg (2005), it was found that sugar maples also seemed to exhibit adaptation to low temperatures in winter. Although VPD and temperature are two different concepts in environmental science, they are related. The temperature refers to the degree of heat present in the environment, which affects plant growth and development, as well as the rate of photosynthesis and transpiration (Larcher, 2003). VPD, on the other hand, is a measure of the difference between the amount of moisture in the air and the maximum amount of moisture that the air can hold at a particular temperature, the high VPD means the air is relatively dry, transpiration rates will increase, and it also affects plant water use and can influence plant growth and yield as same as temperature (Larcher, 2003).

During the winter months of November or December, we observed that the growth of yellow birch is negatively correlated with maximum temperature and positively correlated with precipitation. Previous studies have shown that yellow birch is a frost-tolerant tree species that at -33 °C, the damage to the branches of yellow birch was only 2% and the root system remained viable (Calme et al. 1994). Also in this study, sugar maple seems to show partial adaptation to low temperatures (Calme et al. 1994).

Overall, the results of our analysis do not fully support our hypothesis, we did observe that high temperatures and low precipitation negatively affect the growth of red maple in most plots during summer, while lower water availability also negatively affects spruce, as evidenced by the positive correlation between spruce and PDSI. However, there is no clear evidence that high temperatures and low precipitation in summer affects the growth of sugar maple, as no significant correlation was observed.

Conclusion

Our study suggests that under future global warming trends, higher summer temperatures and low water availability may inhibit the growth of balsam fir, red maple, and yellow birch. Also, while high summer VPD negatively affected yellow birch and spruce, it did not have any significant effect on sugar maple and ironwood growth. In wintertime, higher VPD and warmer temperatures could have a negative impact on the growth of both conifer species. To the contrary, two maple species show good growth following such warm winters, but this situation was only apparent in one out of four plots for red maple, and one plot of sugar maple (only plot D had sugar maple). Therefore, More evidence is needed to confirm this trend.

Such results were possible with the dendroecological approach used. The strength of this approach is that it allows for the discovery of a strong and comprehensive climatic signal in the study area by analyzing a small sample of strongly correlated tree-ring series. In recent decades, this strategy has become increasingly popular, and it has proven to be quite helpful in improving our understanding of the relationship between tree growth and climate. However, one significant disadvantage is that the use of small subgroups of dominant trees restricts our ability to infer the effects of severe climatic events on growth dynamics.

Our results provide evidence that high summer temperatures and low water availability are currently negatively affecting the growth of several Acadian tree species, among them boreal species like balsam fir but also red maple and yellow birch. Also, we find that warm winters are associated with growth reductions in boreal species, while maple species display increasing growth under the same conditions. However, we also observe

limited consistency in climate-growth couplings, where a majority of significant correlations were not observed at all sites for a given species. This weak climate signal suggests that stand and site conditions remain strong constraints on growth.

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SUPPLEMENTARY FIGURE

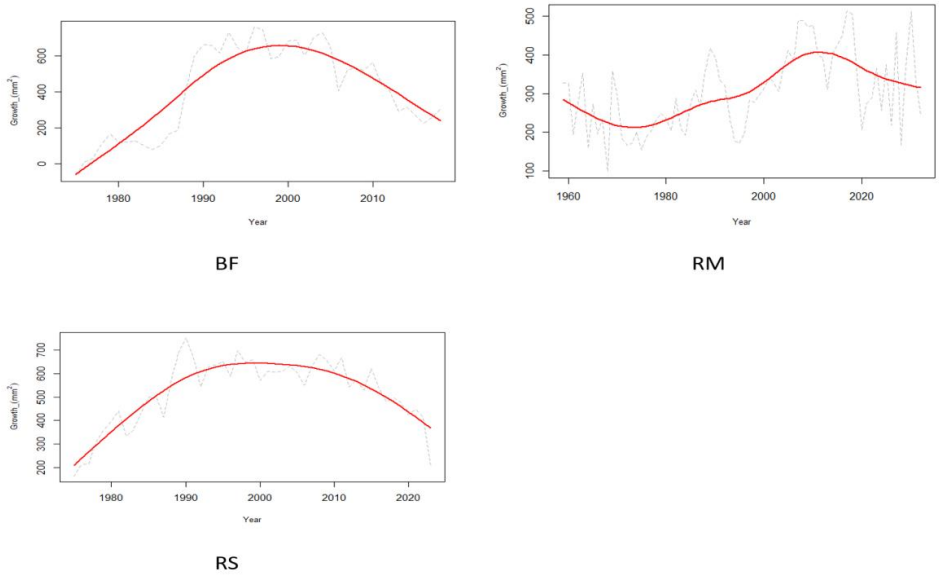


Figure 1: Basal area increment of balsam fir (BF), red maple (RM) and red spruce (RS) in plot A. The grey line represents the raw BAI data and shows the actual values of BAI over time. The red line represents a smoothed version of the BAI data, calculated using a Fourier-based cubic smoothing spline, to highlight the overall trend in BAI over time.

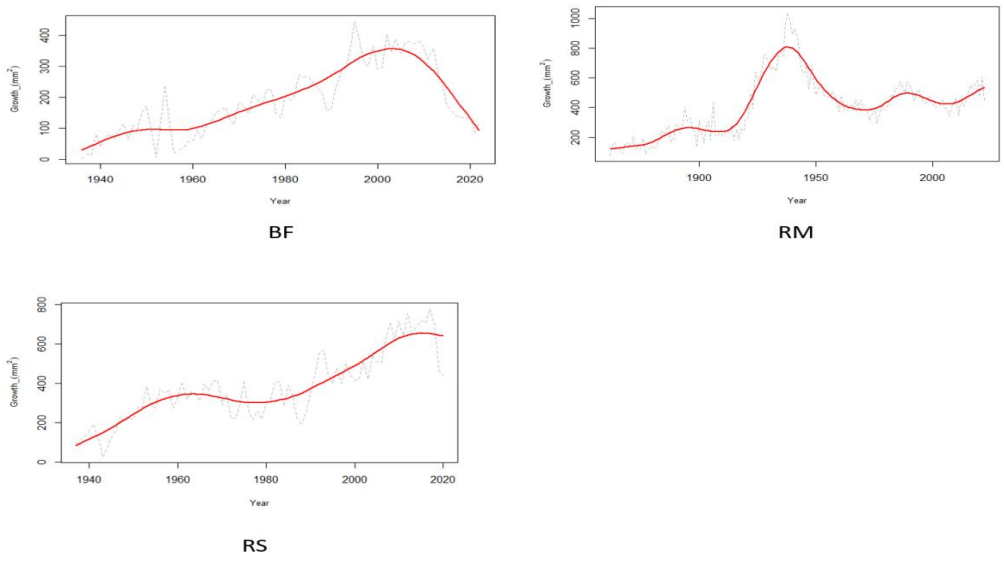


Figure 2: Basal area increment of balsam fir (BF), red maple (RM) and red spruce (RS) in plot B. The grey line represents the raw BAI data and shows the actual values of BAI over time. The red line represents a smoothed version of the BAI data, calculated using a Fourier-based cubic smoothing spline, to highlight the overall trend in BAI over time.

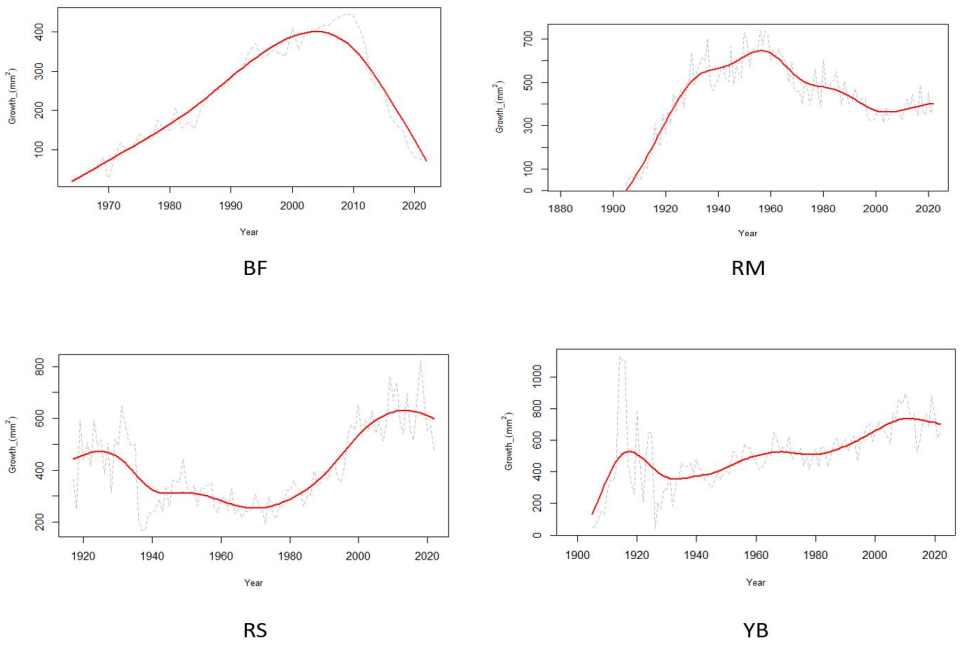


Figure 3: Basal area increment of balsam fir (BF), red maple (RM), red spruce (RS) and yellow birch (YB) in plot C. The grey line represents the raw BAI data and shows the actual values of BAI over time. The red line represents a smoothed version of the BAI data, calculated using a Fourier-based cubic smoothing spline, to highlight the overall trend in BAI over time.

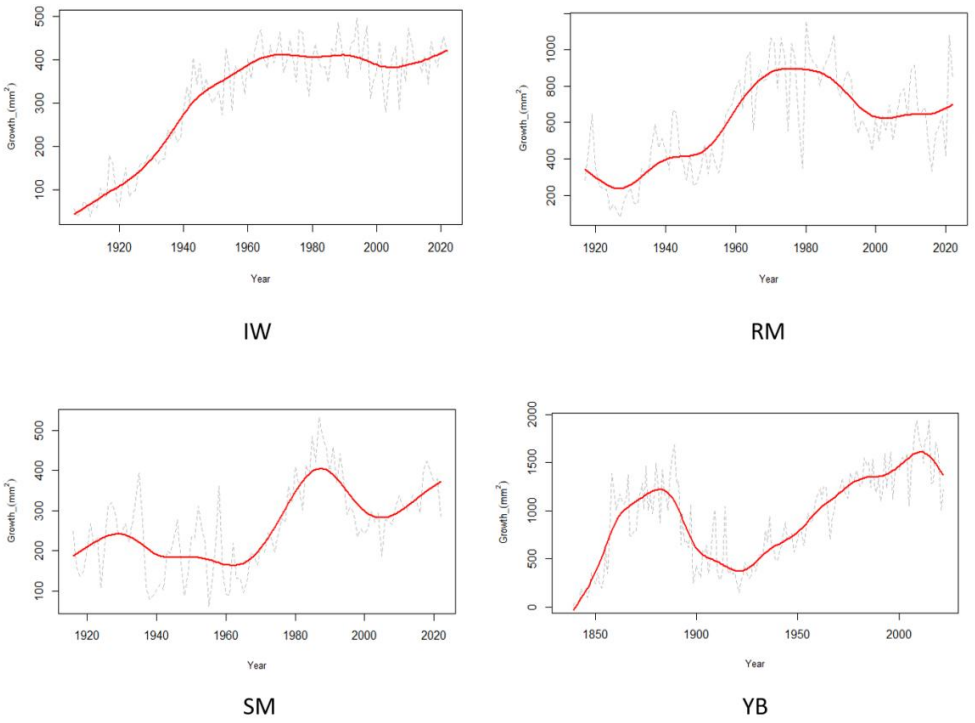


Figure 4: Basal area increment of ironwood (IW), red maple (RM), sugar maple (SM) and yellow birch (YB) in plot D. The grey line represents the raw BAI data and shows the actual values of BAI over time. The red line represents a smoothed version of the BAI data, calculated using a Fourier-based cubic smoothing spline, to highlight the overall trend in BAI over time.

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