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SCHOOL OF FOREST AND ENVIRONMENTAL SCIENCES

Forest productivity of two Quebec boreal forests: climate response and benefits from mixed stands

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1 Resume

Il tema principale di questo elaborato è la produttività forestale con particolare riferimento alla biomassa di carbonio presente nel soprassuolo. Nasce dall'attività di tirocinio del candidato svolta nella piccola cittadina di Amos in Quebec approfittando di parte dei campioni analizzati nel laboratorio dell'Université du Québec en Abitibi-Temiscamingue (UQAT) durante i nove mesi di permanenza. Questo lavoro si inserisce nel contesto del progetto nazionale SmartForest Canada che, coprendo 4400km est-ovest del territorio nazionale, ha l'obiettivo di studiare relazioni intra-/inter- specifiche nei biomi boreale e temperato e come rispondono al cambiamento climatico. Nella parte introduttiva si definisce il significato di produttività forestale e i fattori principali da cui dipende. Vengono, inoltre, discussi i benefici di mixed stand rispetto a popolamenti puri in termini di produttività forestale. Infatti le nostre ipotesi considerano boschi plurispecifici con resistenza e resilienza maggiore rispetto a quelli monospecifici. Le aree di studio sono localizzate nelle città Amos e Authier-Nord nel nord-ovest della regione Abitibi, entrambi quindi appartenenti al bioma boreale e inclusi nel network di SmartForest. L'analisi è avvenuta con approccio dendrocronologico. Le carote sono state estratte nell'estate 2020 ad altezza a petto d'uomo (1,30m) per poi essere sottoposti a sabbatura e incollate su supporti legnosi. Gli alberi campionati appartengono alle tipiche specie presenti nel bioma boreale come abete nero (picea mariana), pino grigio (pinus banksiana) e abete balsamico (balsam fir). Partendo quindi dalla misura della larghezza degli anelli, grazie a specifici software, si sono poi utilizzate equazioni allometriche per calcolare il diametro e quindi risalire alla biomassa totale dell'individuo. La quantità di carbonio è stata considerata equivalente al 50% del peso totale dell'albero riuscendo a calcolare gli incrementi annuali di carbonio nel soprassuolo per metro quadro. I risultati evidenziano effettivamente che la diversità specifica apporta benefici in termini di biomassa e quindi di stoccaggio di carbonio. Infatti, gli incrementi di carbonio annuale totale dello stand (somma degli incrementi delle singole specie) hanno una variabilità minore rispetto a quelli delle singole specie in entrambi i nostri siti. Inoltre, nel sito vicino Amos c'è un riscontro positivo anche nell'analisi con le variabili climatiche. Il pino grigio presentava una response negativa con le temperature massimo entrambi i mesi di settembre di entrambi gli anni considerati (precedente 2019 e corrente 2020). Invece, nel caso in cui ad essere considerati erano gli incrementi totali la response negativa scompare.

2 Introduction

Understanding forest productivity and how it is affected by climate change is a central concern in forestry. Forest productivity is the driver of timber production, carbon sequestration and provision of other ecosystem services. It is strictly related with carbon cycle and all his processes making easy to use this term in a wrong way. We must specify that for forest productivity we mean forest growth and carbon dynamics based on an annual aboveground net primary production (NPP). The NPP is the difference between the net exchange of CO₂ between the ecosystem and the atmosphere (gross ecosystem production, GEP) and the carbon losses by autotrophic respiration (RA) (Li et al., 2020; Pappas et al., 2020). Alternatively, forest productivity may be used as the increment of standing wood volume over a time interval (e.g. annual or decadal) (Li et al., 2020a) or as the increase in economic terms of forest potential products (Crow et al., 2006). In this study we focus on the aboveground carbon biomass increment, as quantified by tree rings and species specific allometric equation. We will not take in count litter inputs as instead they have proposed (Pappas et al., 2020). Wood biomass increments are not only important for production and commerce of timber, but they are an essential carbon pool to mitigate global warming (Lemprière et al., 2013; Luysaert et al., 2008; Moreau et al., 2022; Wirth, 2009), considering that one third of total global fossil fuel emissions are taken up by forests (Pan et al., 2011).

Every tree species has a different growth rate depending on the physical and atmospheric conditions of the growing site (Miyamoto et al., 2010). Pedoclimatic conditions, mean temperature, sun light and nutrients availability have big influence on tridimensional tree growth. For example, mean annual temperature and depth of organic layer can explain almost the 50% of a stand productivity (Paquette & Messier, 2010). Changes in environmental conditions associated with warming, such as the lengthening of the growing season, have been directly linked to changes in forest productivity and composition (Angert et al., 2005; Goetz et al., 2005; Y. Zhang et al., 2013). Trees, especially in early-stage forests, can profit of the current higher CO₂ concentration and longer growing season (Walker et al., 2021). These effects result from the central importance of CO₂ to plant metabolism. As photosynthetic organisms, plants take up atmospheric CO₂, chemically reducing carbon to build the needed carbohydrates for their metabolism. However, doubts remain on the net results of climate change on tree growth. Studies have shown that tree growth rates are stable or decreasing at the population or community level and that no positive direct effect of climate change is visible (Clark et al., 2010; Girardin et al., 2016). Site specific environmental conditions determine the rate of forest productivity through time in the context of climate change, including soil properties linked to nutrient and water availability and species mixture and competition. We can thus define the maximal capacity of biomass supported by a site according to its environment.

Species mixture can be beneficial to forest productivity at tree and stand levels (Chavardès et al., 2021a; Liu et al., 2018; Paquette & Messier, 2010). Mixed stands provide a better spatial stratification of roots and leaves increasing use of site resources both below and above ground. Different species composition results also different resource needs with potential reduction of negative interactions and competition between trees (Lilles, 2013). The effects of biodiversity on productivity may be less important in temperate forests growing on rich deep soils under more favorable climates than in resource limited boreal stands (Bernal-Escobar et al., 2022). Additionally, mixed boreal stands may be more resilient and resistant to fire and pest disturbances (Paquette & Messier, 2010)(Lilles, 2013). Benefits of species mixture depend on

species composition and complementarity. Two conifer species with very similar requirements, i.e. two shade-intolerant species, will enter fast in competition decreasing productivity of at least one species when they grow together (Chen et al., 2003).

In this work we focus on how forest productivity is affected by climate change in two mixed forests located in the province of Quebec. They belong to the forest monitoring network of SmartForest Canada (Pappas et al., 2022a). It is a nationwide project designed to better assess forest productivity in the context of climate change. At both sites a detailed forest inventory was conducted. Tree diameter was measured, and wood increment cores were sampled from all selected trees following the sampling design proposed by (Babst, Bouriaud, Alexander, et al., 2014; Babst, Bouriaud, Papale, et al., 2014; Pappas et al., 2020). Tree species found were mostly black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* Lamb.), and white spruce (*Picea glauca* (Moench) Voss). Both stands are located within the balsam fir-white birch domain of western Québec. Forest productivity was estimated with a dendroecological approach using measurements of tree ring widths jointly with allometric equations following the methodological procedure proposed by (Babst, Bouriaud, Alexander, et al., 2014; Babst, Bouriaud, Papale, et al., 2014; Pappas et al., 2020). Annual variations of forest productivity are related to climate variables and potential benefits of species mixture are analyzed.

3 Objectives and hypotheses

The objective of this study is to assess how forest productivity varies through time in boreal stands, identifying potential climate forcings and potential positive effects of species mixture. Our working hypotheses are the following:

H1: Climate sensitivity of productivity (negative correlations with climate variables) is more significant for single species than for the sum of the species in boreal mixed stands. This means that species mixture in boreal forests could reduce climate vulnerability.

H2: Total biomass increments of different species in mixed stands is less variable than increments of same species in pure stands. This means that mixture in forest stands could help stabilizing productivity through time.

4 Material and methods

4.1 Smart Forests Canada

SmartForest is a network of high precision forest monitoring plots where detailed inventory is conducted. It's a national project designed to better assess inter-/intra- specific interactions in rapidly changing environmental conditions. The network covers 4400km from Alberta to New Brunswick including very different environmental conditions (Fig. 3.1). In each plot are collected detailed meteorological and soil data with different levels of spatial (from cell to ecosystem) and temporal factors (Pappas et al., 2022b). Multiple sensors provide data in real time such as relative humidity, air temperature, albedo, rainfall, soil moisture, and other ecophysiological parameters. Field surveys and remote sensing tools complete the data recording for the growing season with precise measurements. The latitudinal transect covers two (of the three) biomes occurring in the province: the temperate forest and the boreal forest ones. Our two sites display marked differences in climate, soil, and tree composition. In the first one we mainly find hardwood species dominated by sugar maple (*Acer saccharum L.*) and other secondary species like yellow birch (*Betula alleghaniensis Britt.*) and red oak (*Quercus rubra L.*). Moving up through latitudinal gradient they are slowly replaced by softwood species. In the transition with the boreal biome, we find tree species like balsam fir (*Abies balsamea Mill.*), jack pine (*Pinus banksiana Lamb.*) and some hardwood like white birch (*Betula papyrifera Marsh.*) and trembling aspen (*Populus tremuloides Michx.*), but the most typical vegetation type of the boreal zone is the taiga.

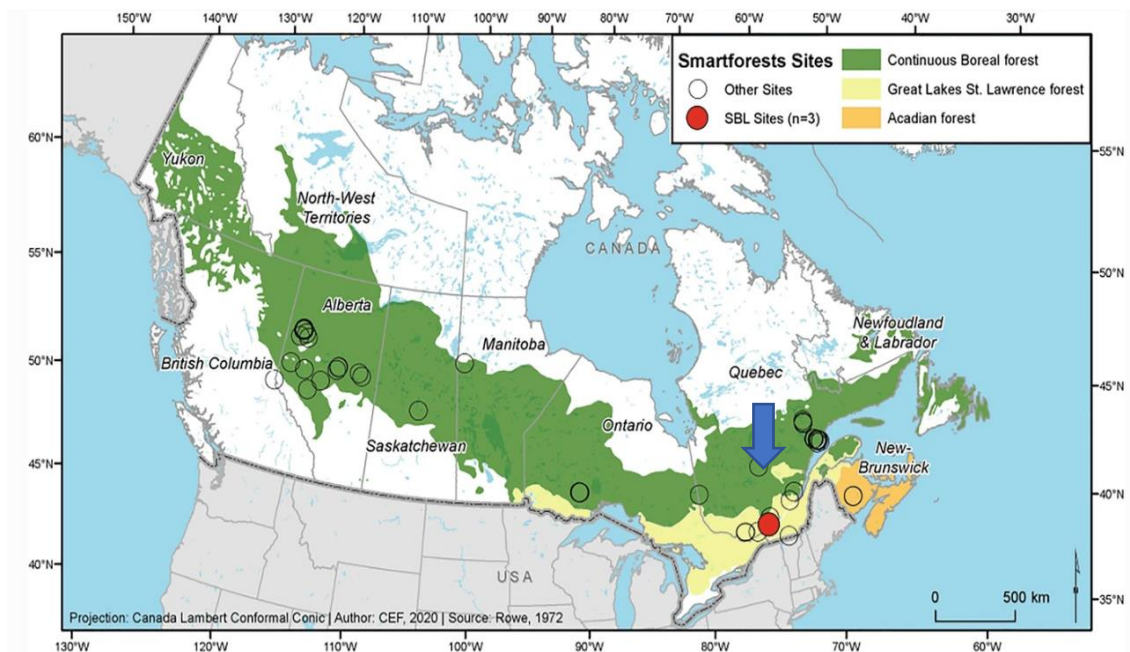


Figure 4-1 A national map of Canada illustrating sites localization of the SmartForest project. In red the Station Biologique des Laurentides (SBL) which has the most comprehensive set of field measurements. The two sites of this work are represented by the circle under the arrow at the Quebec-Ontario border. (Pappas et al., 2022b)

4.2 Study sites

Within the SmartForest project we have carried the analyses at two sites near the city of Amos (PRA) and Authier-Nord (AUN) both in the Quebec region of Abitibi-Témiscamingue (A-T)(Figure 4-2). The Table 4-1 shows sites coordinates and species assemblages. Forest stands in AUN are at a comparable successional stage having established after a stand replacing fire occurred in 1916

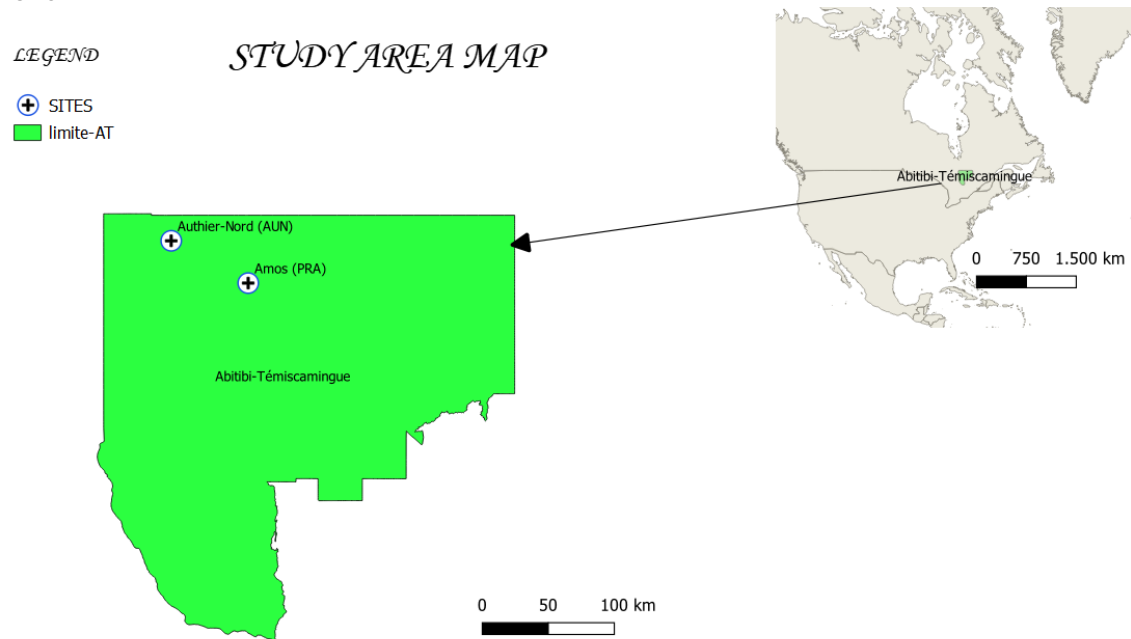


Figure 4-2 Localization of the two study-sites



Figure 4-3 A photo of the site Authier Nord (AUN) with black spruce and jack pine trees.

Table 4-1 A resume of site geographical characteristics and species assemblages (specify the size of the plots). For this work we will use the Quebec standard French abbreviation for species (acronym in brackets).

	Authier-Nord (AUN)	Near Amos (PRA)
Location		
Plot area	415 m ²	616 m ²
Latitude	49.157	48.573
Longitude	-78.799	-78.115
Elevation (m)	300	300
Specie composition [sampled - crossdated]		
Jack Pine (PIG)	26-25	46-44
Black spruce (EPN)	74-68	1-0
White spruce (EPB)	0-0	26-25
Trembling aspen (PET)	1-0	0-0
Balsam fir (SAB)	0-0	1-0

AUN and PRA both belong to the boreal biome where the climate is characterized by cool short summers, cold long winters, large annual ranges in temperature, and quite high amounts of precipitation concentrated in summer. We calculated mean annual precipitation of 700-800 mm from Climate.NA (a standalone application that downscales climate data from PRISM Climate Group) using time series from 1901 to 2021. Climate is highly continental, except in coastal areas, which explains the large seasonal and daily temperature excursions. The mean annual temperature of 0-1 °C with a short growing season of about 140-160 days making temperature the first limiting factor. Day length, and photoperiod, are long during summer because of the high latitudes of this zone. The site are in the continuous boreal forest sub-zone and regarding the vegetation they are classified in the balsam fir-white birch domain. This extends over the Clay Belt region of Quebec and Ontario, a major physiographic region resulting from the deposits left by the proglacial Barlow and Ojibway lakes at the time of their maximum expanse, in the Wisconsinian glacial stage. The balsam fir-white birch forest type occupies the southern portion of the boreal zone for the 8% of the total Quebec land surface. The forest landscape is dominated by balsam fir and white spruce stands mixed with white birch on mesic sites. The yellow birch and red maple grow only in the southern portion of the domain. In riparian environments species like speckled alder (*Alnus incana* (L.) Moench) and willows (*Salix* spp.) are common. On less favorable sites, black spruce, jack pine and larch often grow alongside white birch or trembling aspen. In fact, sandy soils of the eskers are mainly colonized by black spruce and jack pine forests. The eskers are ridges made of sands and gravels, deposited by glacial meltwater flowing through tunnels within and underneath glaciers. With the retreat of the glaciers started 10000 years ago all these sediments remained on place forming long land tongues. Another peculiarity is that our study sites are located on one of the oldest bedrocks ever explored on earth history. The formation of Canadian Shield that came across a large part of Quebec is dated about 3 billion years. During the millennium it was widely shaped by precipitation, wind and ice that formed the current flat landscape. It is made of hard acid rocks and oligotrophic soils. A cold and wet climate associated with acid rocks represent perfect condition for the genesis of podzols that are frequently found in Quebec under conifer stands (Sanborn et al., n.d.). The O horizon due to cold temperatures and very low rate of decomposition could have a maximum thickness of 5 cm. Then we found the typical grey eluvial horizon E poor in elements. It is usually above the B horizon where we find more colored layers rich in iron and aluminum.

4.3 Tree cores collection

In 2020 increment cores (one for each tree) were collected with a Pressler borer at breast high (1,30m approximatively) in one plot for each site with a radius of 11.5 m for AUN and 14 m for PRA. Plot size was chosen according to tree density in order to have sufficient trees at each site. In the laboratory of the Canadian Research Chair of dendroecology and dendroclimatology (UQAT) all cores were mounted on wooden supports and thoroughly polished with progressively finer sandpaper. We have selected all trees with a DBH ≥ 9 cm. In AUN a total of 101 trees were sampled: 74 were black spruce (EPN), 26 jack pine (PIG) and 1 trembling aspen. We could complete the tree ring cross-dating of most cores (Table 3-1). In PRA we extracted 1 core from 73 trees: 24 white spruces (EPB), 46 jack pines, 2 balsam fir and 1 black spruce. Finally, we proceeded with the analyses only of the most representative species: black spruce and jack pine in Authier-Nord, white spruce and jack pine for the site near Amos.

4.4 Dendrochronological analysis

4.4.1 Tree-ring measurements

All the samples were named and scanned using a resolution of 1200 dpi. Then we proceeded measuring tree ring widths with the software CooRecorder. This program is used for registering coordinates collected from images. For each selected point we will have X and Y coordinate in millimeter, with a precision until 0.001 millimeter, saved in a file “.pos”. The application has several useful functions that make analyses more precise and faster. It allows us: accounting for core cracks like a gap, estimating pith and its distance to the last ring, calculating the total radius. Thanks to CDendro we were able to date ring and save the decadal format file .rwl, the same used for storing file in the International Tree Ring Data Bank (ITRDB). In these files tree ring width are showed for each year in units of 0.01 millimeter.

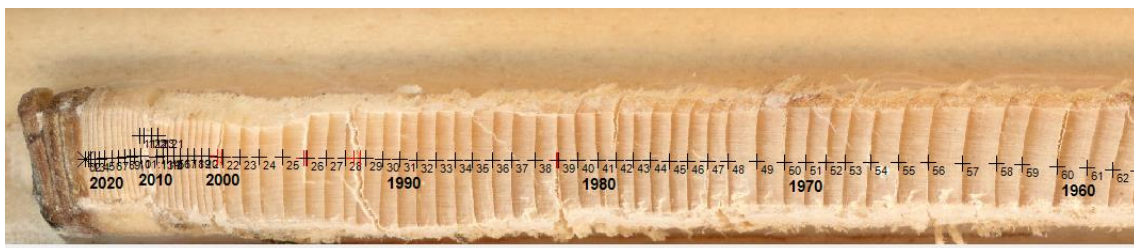


Figure 4-4 A part of a scanned black spruce core after the measurements with CooRecorder. The crosses are the ring boundaries semi-automatically detected. In bold the corresponding decades.

4.4.2 Crossdating

With the software PAST5 and his statistical tests we then started the series cross-dating for the different species at the two sites. With COFECHA we assessed the quality of crossdating and measurements accuracy of tree-ring series. In crossdating high-frequency trends are more significant than low-frequency (or longer term) ones that could be associated with non-environmental factors (e.g. age trend). The software use of segmented time series correlation helps to avoid the longer-term variance due to competition or age effect on growth rates. COFECHA can also detect higher correlation and outlier ring measurements putting a “flag” on them speeding up the correction measurements error. For detrending we have chosen the

default spline rigidity of 32 years with 50% cutoff response. The program allows to select the segment length to be tested, as well as the amount of overlap in succeeding segments. We opted for the 50-year segments with 25 year overlapping period. We kept on the autoregressive modeling that removes low-frequency persistence that may remain after applying the spline using residuals. Before the analysis each series was transformed into logarithms to better weigh proportional differences. For the correlation of each series with the master series we used the quantitative Pearson coefficient and a critical level of .3281 with 99% confidence level.

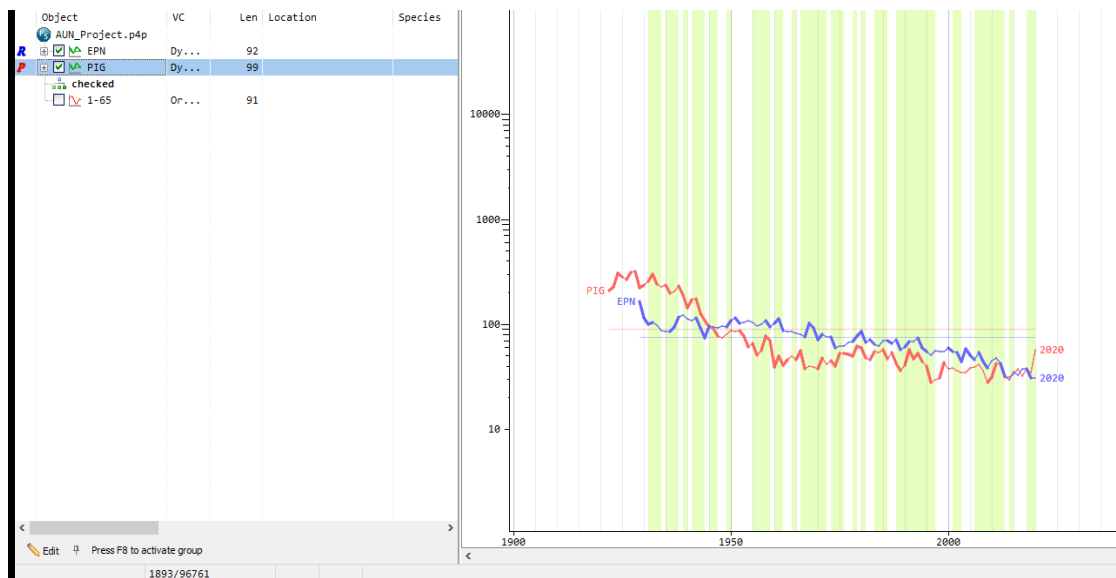


Figure 4-5 The chronologies of the two species in AUN (in blue black spruce, and in red jack pine) used as reference for the crossdating in PAST5. Each one is the result of the mean of all the dated samples added one by one during crossdating.

4.4.3 Statistical analysis.

The open-source software RStudio allow us a better manipulation and visualization of our data with his 4 screens interface. We exploited the *tidyverse* (Wickham et al., 2019) packages with *ggplot2* (Wickham, 2016) functions to build our graphics and resume ours results. The “dendrochronology program library in R” (dplR) (Bunn, 2008) was necessary to read our file formats and perform tree-ring analyses. Finally, *treeclim* (Zang & Biondi, 2015) provide us specific functions to assess climate correlation with tree-ring width.

For each species with the function *interseries.cor* of dplR we have calculated correlation serially between each tree-ring series and a master chronology built from all the other series in the *rw1* object, named TRW (Tree Ring Width). From the same package with *seg.plot* and *spag.plot* we could see timespan of each series and have a first idea of tree ring width. We applied also *detrend* which divides values of each series (TRW) by the correspondent ones of the growth trend curve to produce dimensionless Ring Width Index (RWI). We opted for the method *spline* where the frequency response is 0.50 at a wavelength of $0.67 * \text{“series length in years”}$. More precisely it is a smoothing spline that has a more natural fit to tree ring data because it operates effectively as a centrally weighted moving average on the data. At this point we are ready to build a mean chronology with *chron* averaging our TRW using a Tukey’s biweight robust mean excluding outliers with a standard deviation roughly +/- 6.

4.4.3.1 DBH function

CooRecorder allows to estimate the distance to the pith. We were consequently able to estimate the total radius for all our samples even if the pith was missing. We applied a cumulative sum to TRW adding distance to pith where necessary (Equation 4-1). Multiplying for 2 and dividing for 10 we were able to estimate DBH chronologies for each tree in cm.

$$DBH (cm) = \left(\sum_{i=x}^n TRW_i + distpith \right) \times 2 \div 10$$

Equation 4-1 Equation used to estimate diameter at breast height (DBH) in centimeter for each tree. TRW= tree ring width in millimeter, 1= first measured ring , n= last measured ring, distpith= distance to pith

4.4.3.1.1 DBH model equation for unmeasured trees

For unmeasured or undated cores (rotten, non-visible rings, broken core; see table 3-1) only DBH at the time of the sampling was available. We used a linear mixed model to estimates DBH back in time. This want could be afforded founding at first correlation between original DBH of the samples correctly measured and DBH_less1 (DBH of previous year) where the chronologies were displaced of one year back. After having founded the right function, we applied it to the DBH at the collected time and we were able to rebuild DBH chronologies, including problematic cores for the total time span (Equation 4-2). The function *lmer* (Bates et al., 2015) applies a linear mixed model to estimates maximum likelihood between DBH_less1 and DBH values. The function *isSingular* evaluates whether a fitted mixed model is (almost / near) singular and if the parameters are on the boundary of the feasible parameter space: variances of one or more linear combinations of effects are (close to) zero.

Equation 4-2 Linear mixed-effects model to estimate past DBH of unmeasured or undated cores

$$DBH_less1_k = \beta_{0_{year_k}} + \beta_{1_{year_k}} DBH_k + error$$

Where DBH_less1_k is the DBH of the previous year for the tree k estimated from the fixed effect DBH_k (the DBH at one year). Year is a random effect on the intercept and on the slope of fixed effect DBH.

4.4.3.2 Allometric equation for biomass estimation

Estimating the DBH for each series and for each year we could also assess the variation of aboveground biomass through time. Allometric equations provide biomass values from tree measurements like DBH. Lambert et al (2005,2008) produced a national system of equations for the aboveground compartments of tree biomass with an estimated accuracy. This effort responds to the concern in accounting for the uncertainty in balancing the national carbon budget. They determined total biomass dividing trees in compartments like bark, branches, foliages and wood. We considered the equation based only on dbh because we did not have the tree height.

Equation 4-3 Equations to estimate the total aboveground tree biomass. The parameters a and b for the studied species are noted in **Error! Not a valid bookmark self-reference.**

$$BARK = a1 \times DBH^{b1}$$

$$BRANCHES = a2 \times DBH^{b2}$$

$$FOLIAGES = a3 \times DBH^{b3}$$

$$WOOD = a4 \times DBH^{b4}$$

$$ABOVEGROUND\ BIOMASS = BARK + BRANCHES + FOLIAGES + WOOD$$

Table 4-2 Model parameters from Lambert et al. (2005) to complete the dbh-based allometric equations estimation
EPN=black spruce, PIG=jack pine, EPB=white spruce.

	EPN	PIG	EPB
a1	0,0148	0,0184	0,0114
b1	2,2494	2,0703	2,3057
a2	0.0291	0,0079	0,0302
b2	2.0751	2,4155	2,0927
a3	0.1631	0,0389	0,1515
b3	1,4222	1,729	1,5012
a4	0,0494	0,0804	0,0334
b4	2,5025	2,4041	2,598

coefficients a and b were computed from collected data from “ENergy for the FORest” (ENFOR) research project. ENFOR was conducted by the Canadian Forest Service between '80 and '95 in all provinces and territories. During the years it was widely used to build allometric equations at national scale.

Given our interest on the carbon assessment, the results must be divided in half because it has been estimated that the carbon amount in a tree could be approximated as the 50% of the total biomass. After estimation of the aboveground annual carbon biomass for individual trees we focused on the increments through time. With the function **apply** we used a lagged difference with lag=1 and difference=1 across all our matrix. The result is a new matrix where increments are reported according to the year (row) and sample (column). With a row cumulative sum of all the increments which provided the annual increments of the whole stands.

4.4.3.3 Climate responses and variability of the annual C increments

We downloaded temperature and precipitation from Climate.NA, a standalone software application that extracts and downscales gridded (4 x 4 km) monthly climate data for the reference normal period (1961-1990) from PRISM and WorldClim to scale-free point locations. It also calculates more than 200 monthly, seasonal, and annual climate variables. The downscaling is achieved through a combination of bilinear interpolation and dynamic local elevational adjustment. ClimateNA also uses the scale-free data as a baseline to downscale historical and future climate variables for individual years and periods between 1901 and 2100. A time-series function is available to generate climate variables for multiple locations and multiple years.

In RStudio the package *treeclim* was essential for this study, especially for the function *dcc*. This function calculates response and correlation functions from tree-ring chronologies and monthly climatic data. We have chosen to compute the response functions. The term ‘function’ indicates a sequence of coefficients computed between the tree-ring chronology and the monthly climatic variables, which are ordered in time from the previous-year growing season to the current-year. In the case of ‘response’ the coefficients are multivariate estimates from a principal component regression model. Then, 1000 bootstrap samples are taken from the original distributions of climate and tree-ring data to obtain more accurate results. The stationary bootstrap mimics the stationary properties of the original time series in the resampled time series by resampling within blocks. Within each block, the number of observations is random and has a geometric distribution. We applied this analysis to annual carbon biomass increment, both species individually and the stand as a whole, at the same time with monthly precipitation and maximum monthly temperature from June of the previous year (2019) and September of the current year (2020). Only for white spruce we accounted for the last twenty years whereas for all the others (jack pine, black spruce and both total stand) we considered the period from 1980 to calculate our climate response. In addition, we used a bootstrap technique to test differences between coefficients of variation of yearly carbon biomass increments computed for single species and total stands. The results allowed answering our second working hypothesis

5 Results

5.1 ANALYSES OF TREE RINGS

The minimum and maximum length of species specific chronologies are respectively 40-98 and 21-98 for AUN and PRA respectively (Figure 5-1). We can also see that the jack pine is the oldest in both stands especially in PRA where all the individuals of white spruce are younger than 50 years. Some samples have length of 30-40 years most likely not because the tree age is relatively short, but for some technical limitations in the analysis (e.g. rotten core, miss rings...). From the first site it seems that there were 2 different periods of establishment for the two species. Almost all jack pine individuals look older than the oldest black spruce. Indeed, in Authier Nord occurred a fire in the 1916 favoring the settlement of the two species, giving us the proof of the same settlement period but different growth rate. In the 2020 the coring was made at breast high (130 cm) for all the trees, species independently, therefore it is normal to miss some initial rings in black spruce. In the site Near Amos, PRA (second plot in Figure 5-1), the matter is different. Here the white spruce (red line) really has a different period of settlement. Some disturbance, like a partial cutting, occurred in the 1970 providing a better habitat.

Table 5-1 Resume of site and tree rings statistics.

SITE	SPECIES	n.cores	AVERAGE TRW (mm year-1)	n.tot	Rbar.tot	eps	snr	Int.cor
AUN	EPN	68	0.36 ± 0.13	2257	0.243	0.956	21.865	0.560
	PIG	25	0.29 ± 0.13	299	0.460	0.955	21.265	0.555
PRA	EPB	20	1.45 ± 0.41	71	0.267	0.826	4.747	0.543
	PIG	44	0.56 ± 0.31	946	0.387	0.965	27.752	0.604

n.cores= cores number, *AVERAGE TRW*= average tree-ring width, *n.tot*=total number of correlations calculated as $n.wt + n.bt$. *Rbar.tot*=the mean of all the correlations between different cores, *eps*= the expresse population signal using the average number of trees as $n * rbar.tot / ((n-1) * rbar.tot + 1)$, *snr*=the signal to noise ratio calculated using the average number of trees as $n * rbar.tot / (1 - rbar.tot)$, *int.cor*= mean correlation between each series and master chronology

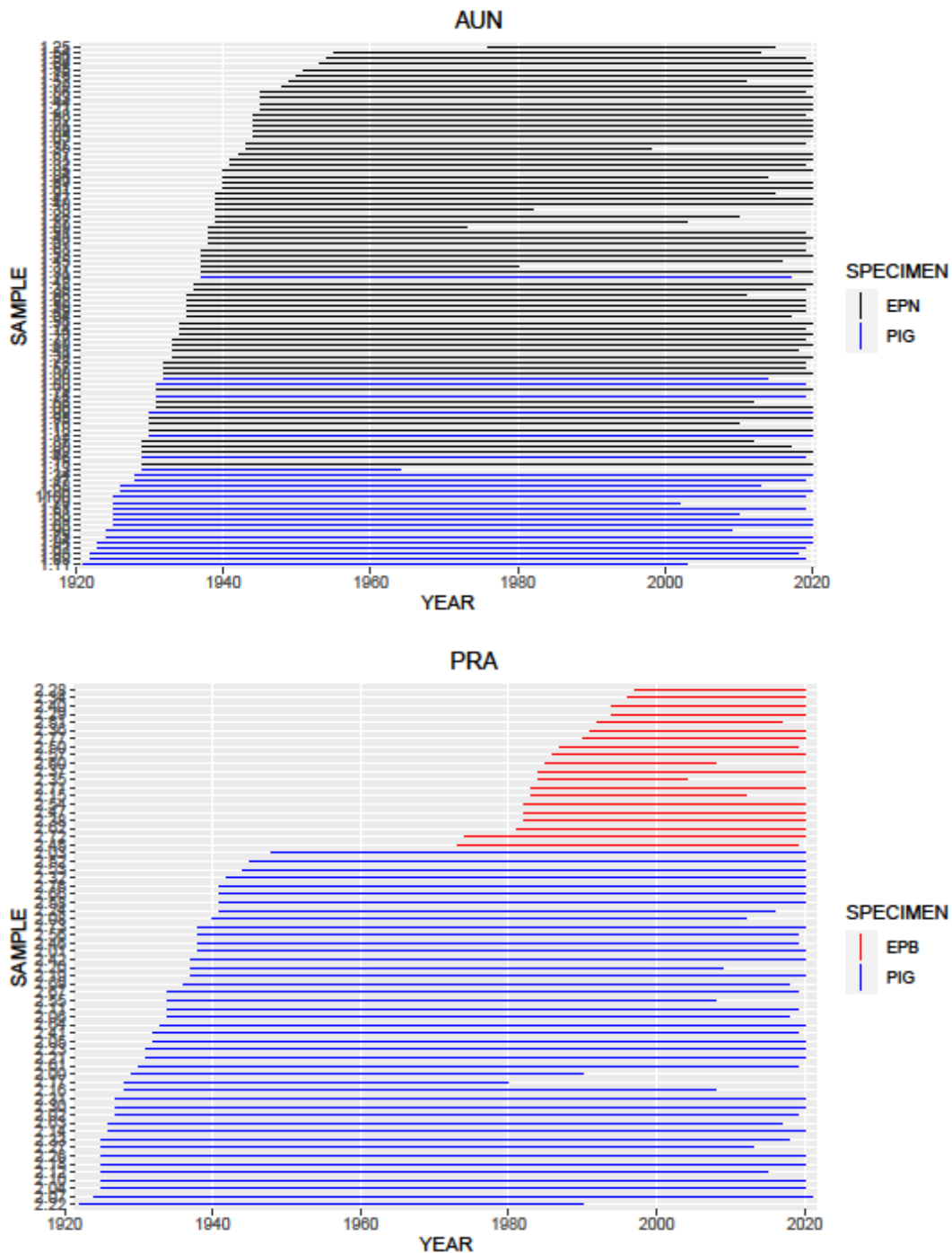


Figure 5-1 Time spans of measured tree-rings per tree. On the Y-axis, trees are identified with their ID.

5.2 DIAMETER ESTIMATION

The diameter curve follow a standard development. For the first 30-40 years it has a bigger growth rate, typical of the vegetative phase. After, the curves slowly appear flatter for both species in AUN (). The maximum reached DBH is about 20 centimeters for all the populations. Only for jack pine in PRA we often estimated trees with 25 centimeters circumferences, even one of 30 centimeters (Figure 5-3). The minimum estimated DBH is about 5 centimeters for

white spruce in PRA. We have to highlights also the progression relatively to jack pine in AUN. This specie present a 10 cm diameter increments in the first twenty years . We can clearly mark it thanks to the curves inclination much bigger than the other populations in the period 1940-60. Then it comes to a stabilization where the curves are flatter. In PRA we can see a different behavior of jack pine thanks to the partial cutting in the '70. From that period, we can see a new increase of the growth rate, losing the stabilization phase we were talking about for PIG in AUN.

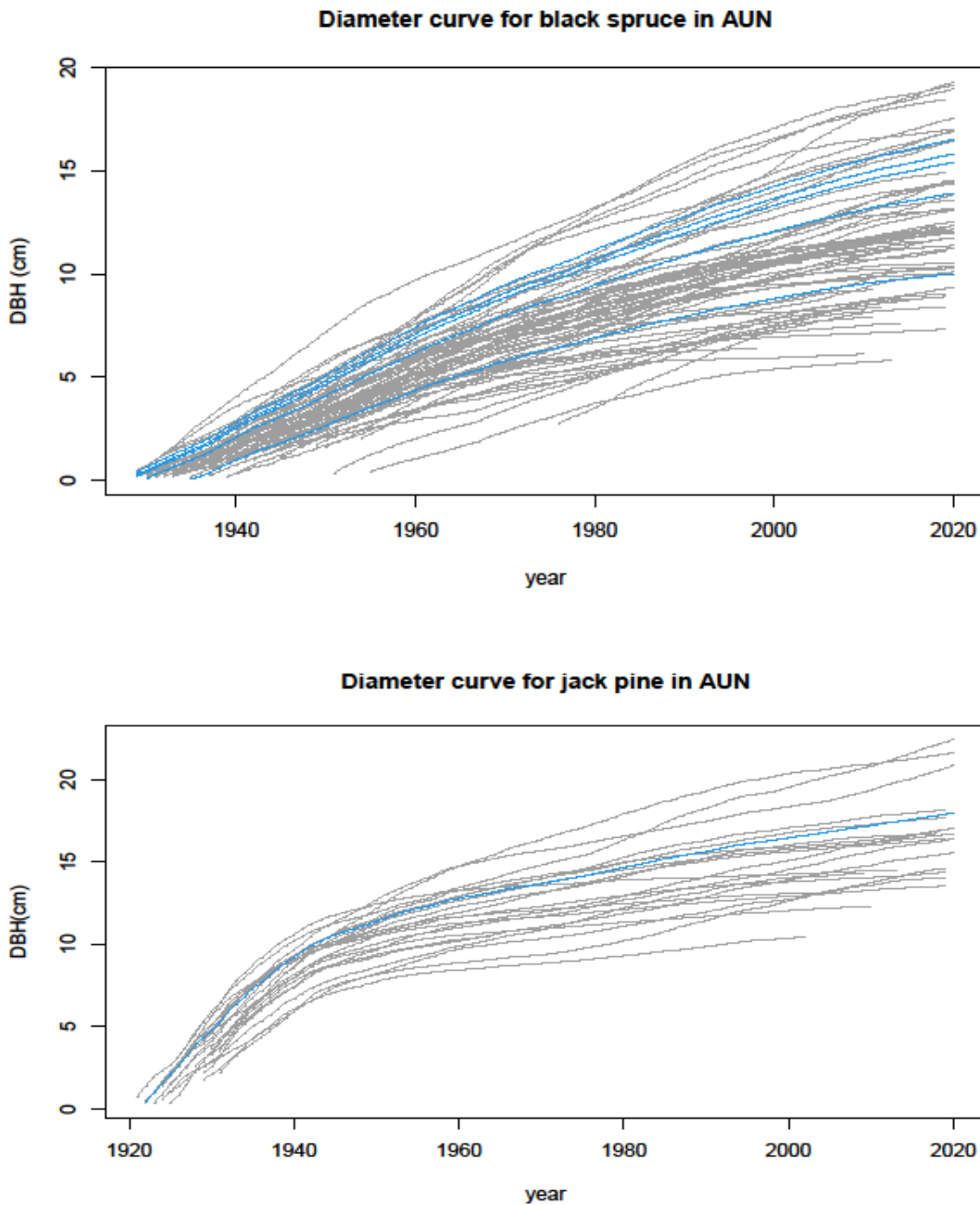
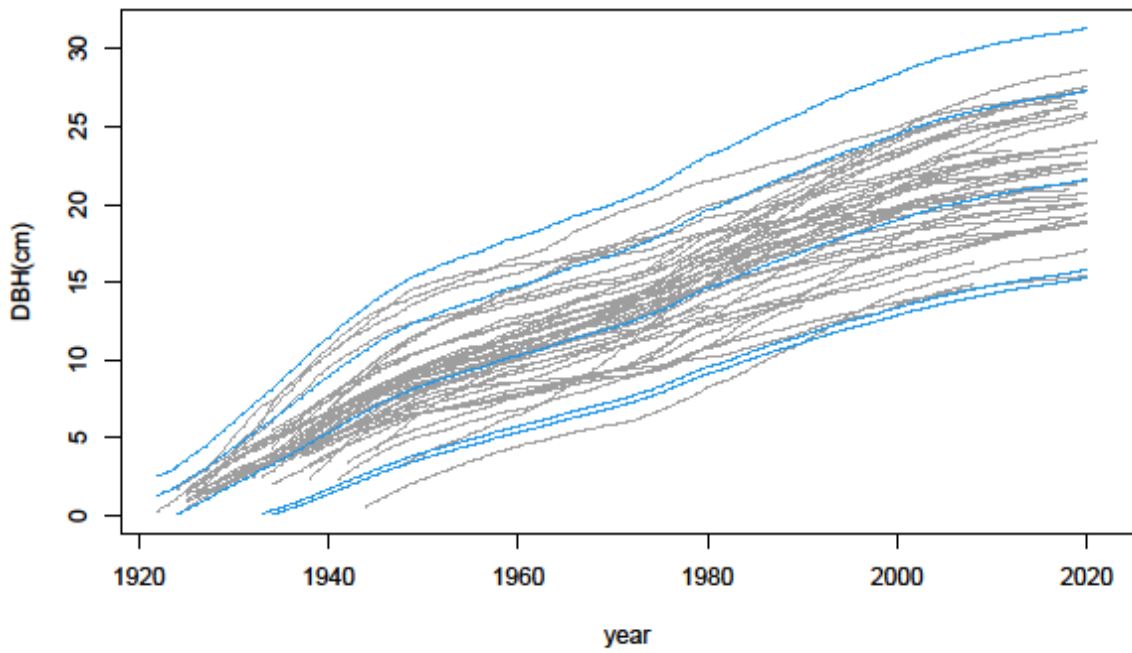


Figure 5-2 Diameter at breast height (DBH) over time per each tree in Authier-Nord. Black spruce on the top and jack pine on the bottom. In blue the trees for which the DBH increments were modelled (see chapter 3.4.3.1.1)

Diameter curve for jack pine in PRA



Diameter curve for white spruce in PRA

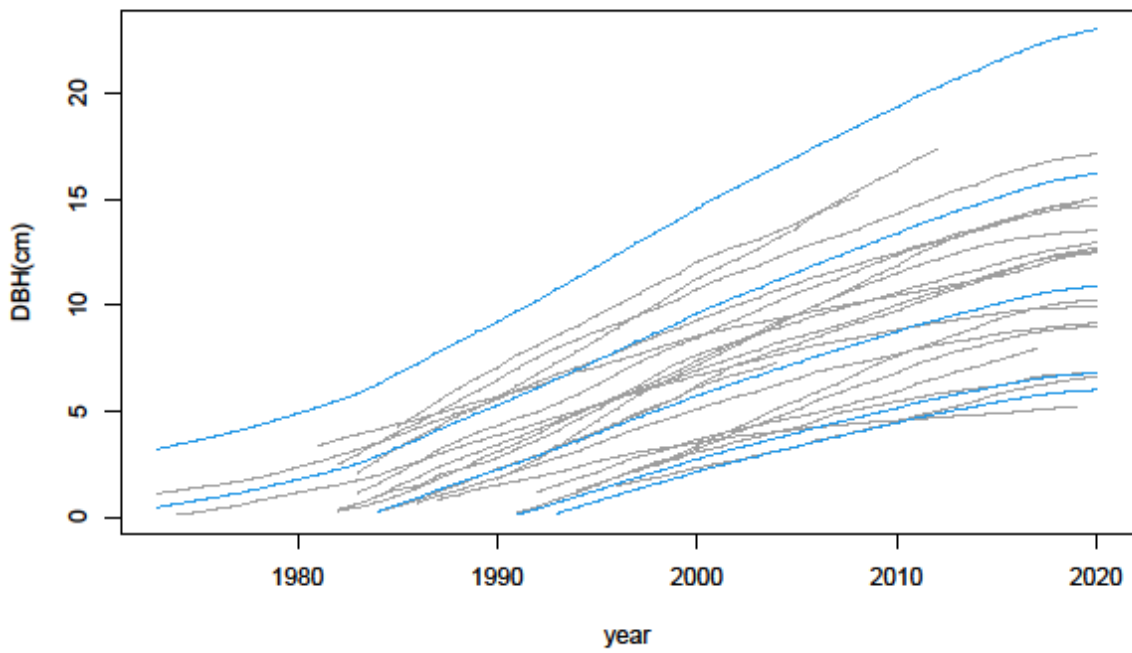


Figure 5-3 Same as figure 4.2 but for the site PRA. Jack pine on the top and white spruce on the bottom. In blue the modelled trees with the linear mixed-effects (Equation 4-2)

5.3 TREE AND STAND LEVEL ABOVEGROUND C STOCKS AND INCREMENTS

The estimated density shows the first difference about conditions in which trees at the different sites growth. In fact, in the first site (AUN) we have 2406 (1779+627) units per hectares more than the double of the approximated 1137 (390+747) units in PRA (Figure 5-1). We must say that the current density may not well represent the density at the settle time. We lose some trees during the century because of a big competition especially for pioneer species like jack pine. Also, the main species changes. In Authier Nord jack pine represent about the 25%, black spruce is the more plentiful. In PRA jack pine is more than the 65%, fulfilled by the white spruce. In terms of average diameter, the jack pine has the highest values (10.11 cm for AUN, 12.7 cm in PRA) the less variable in both stands having a standard deviation always less than 50% considering the average. A similar case is for the black spruce while for the EPB the standard deviation is the 80%. In contrast it has the biggest average concerning the tree ring width (TRW) with 1.45 mm nearly threefold than the second value (0.56 mm for PIG in PRA). Talking about the basal area increment (BAI) in the second site both species reveal similar averages (3.21 and 3.32 cm²) and more than the double of the species in the other stand (1.28 and 1.34 cm²).

Table 5-2- Tree density and tree average growth and C increment at our study sites.

SITE	SPECIES	DENSITY (n/ha)	AVERAGE DIAMETER (cm)	Average carbon stock (Kg)	AVERAGE TRW (mm year-1)	AVERAGE annual C increment (g C tree-1 year-1)
Authier- Nord (AUN)	Black spruce (EPN)	1779	6.6 ± 3.42	21,83 ± 15,03	0.36 ± 0.13	39.32 ± 18.23
	Jack pine (PIG)	627	10.11 ± 3.62	43.89 ± 18.78	0.29 ± 0.13	24.58 ± 8.34
	Trembling aspen	24	15.55 ± 0		0.76 ± 0.47	
Near Amos (PRA)	White spruce (EPB)	390	5.07 ± 4.08	21.09 ± 17.69	1.45 ± 0.41	8.70 ± 12.57
	Jack pine (PIG)	747	12.07 ± 6.21	91.52 ± 36.60	0.56 ± 0.31	68.78 ± 37.24
	Balsam fir	32	10.47 ± 5.6		1.04 ± 0.34	
	Black spruce	16	14.68 ± 0		1.83 ± 0,5	

TRW= tree ring width, BAI= basal area increment.

The evolution of the carbon stock per tree though time follows the DBH trends, reminding that the allometric equation are built on diameter values. So, we find the maximum values in the jack pine population in PRA (200 kg) where, obviously, the white spruce continues to be the less efficient in productivity taking in count that is the youngest population analyzed. Jack pine is still the more productive specie also in AUN. We have some trees that arrive at 80 kilograms of carbon content while the maximum estimated for the black spruce is 60 kg. But the plots show

how at the long scale the EPN takes over PIG being a more resilient specie. Benefits from the partial cut occurred in PRA in the 70 is even more evident in the carbon content curve

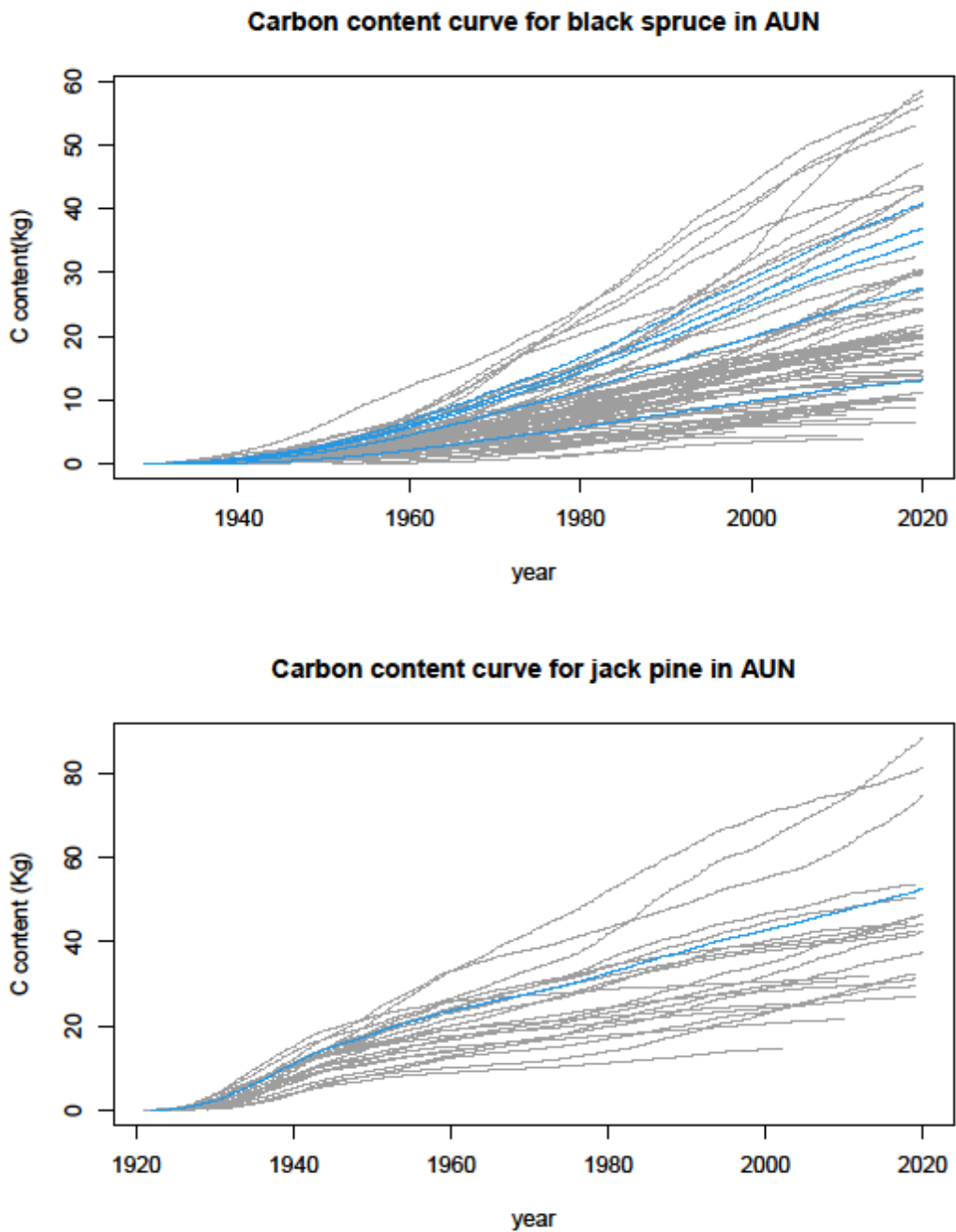
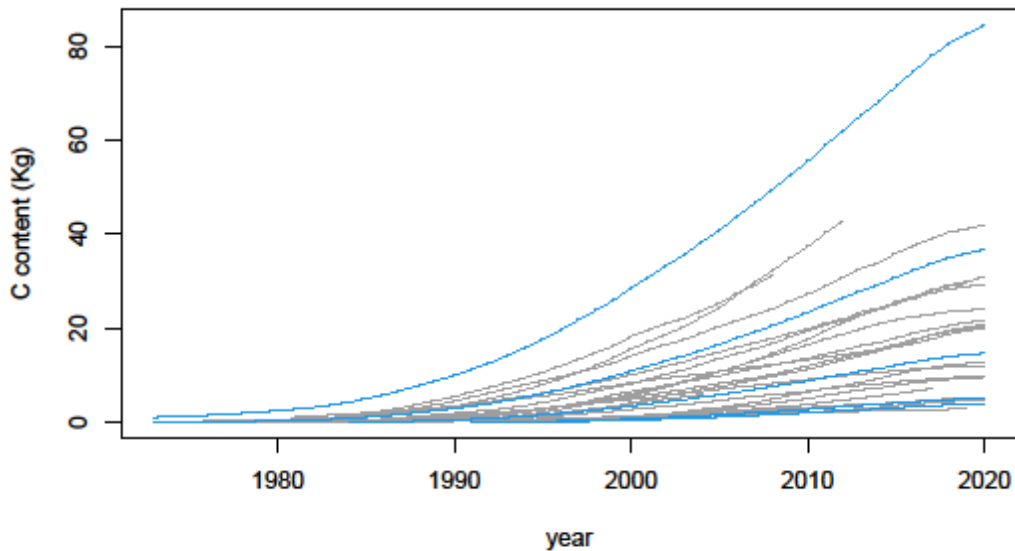


Figure 5-4 Carbon stock per tree (Kg) through time estimated by allometric equation and DBH measurements. Black spruce on the top and jack pine on the bottom. In blue the trees for which the DBH increments were modelled (see chapter 3.4.3.1.1).

Carbon content curve for white spruce in PRA



Carbon content curve for jack pine in PRA

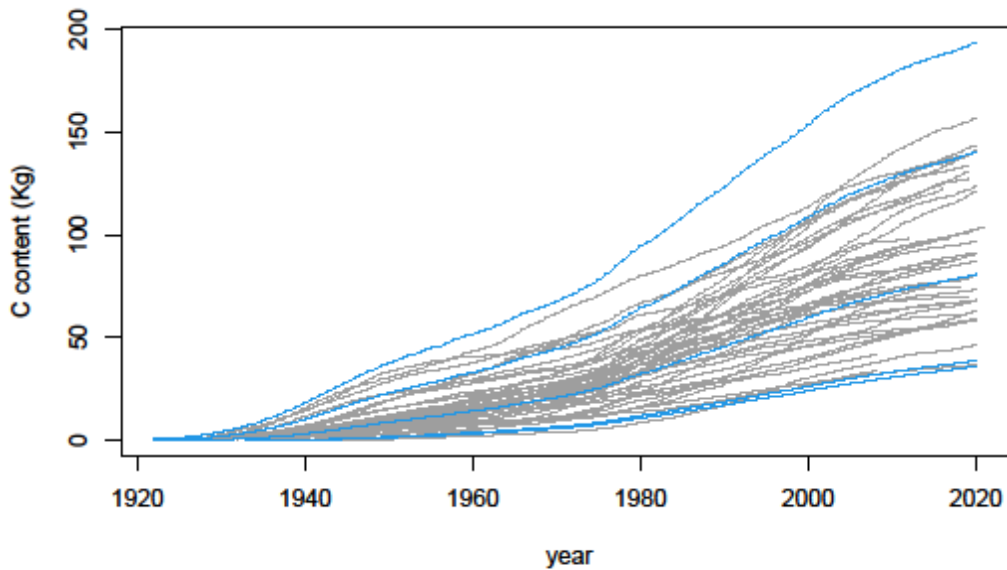


Figure 5-5 Same as figure 4.4 but for the site PRA. On the top white spruce and on the bottom jack pine, in blue trees for which DBH increments were modelled (Eq. XXX)

We assessed the kilograms for meter square for year for each species first and then the increment of the total stand for each site. In AUN after a first setting period of 30 years the increments of the black spruce remain stable between 50 and 60 g/m²*year. The peak of 65 g/m²*year was reached in the 1990 when the population has about 60 years, evidence of the black spruce resilience. For the jack pine the situation is the inverse. It has the maximum of 50 g/m²*year near the 1940, so about 20-year life, for then starts the decreasing due to the

settlement of his colleague. We can see how from the 1950 it has an average of 25 with the minimum of 125 g/m²*year.

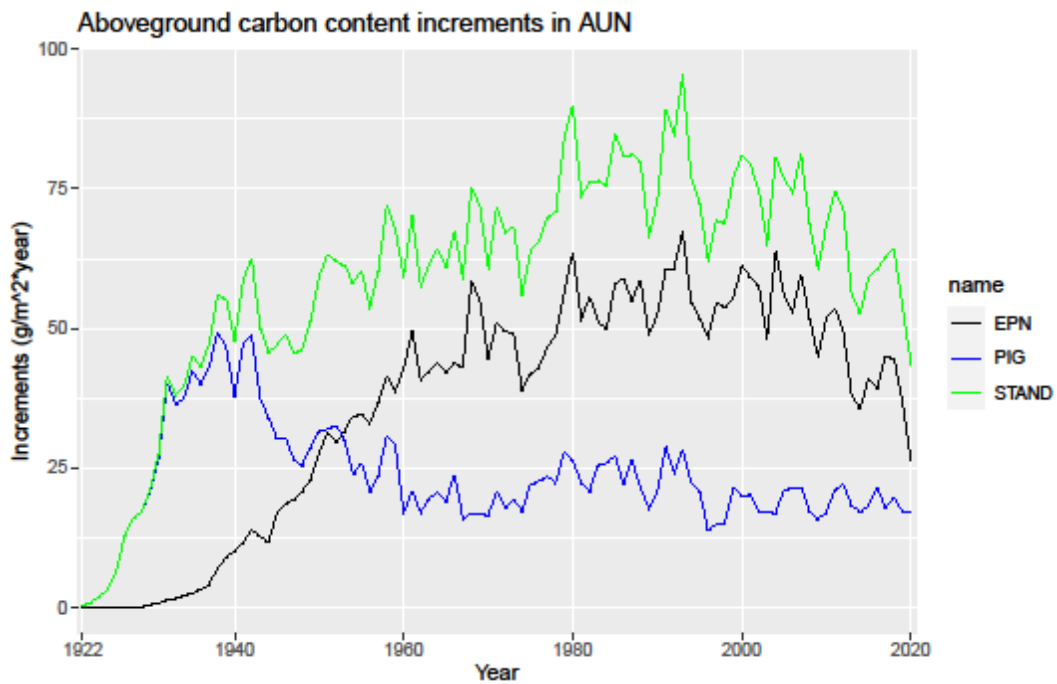


Figure 5-6 Carbon increments at the stand level (g C m⁻² year⁻¹) in Authier Nord. Blue=jack pine, black= black spruce, green= the sum of the species.

In PRA we can see the predominance of the jack pine until an increment higher of 15 g/m²*year after 70 years of the settlement. It is evident the bigger increment of 100g in the '70 thanks to the partial cut. Otherwise, it's clear his decrease started with the came out of the white spruce when the jack pine had the biggest decrease of about 100 g/m²*year in a few year. The latter represents the less productive also in terms of increments having the peak only about 4 g/m²*year. We do not must forget the not favorable condition in which it started to growth with

the jack pine already settled. Even in this case it seems to be the more stable for a twenty-year period between all the species.

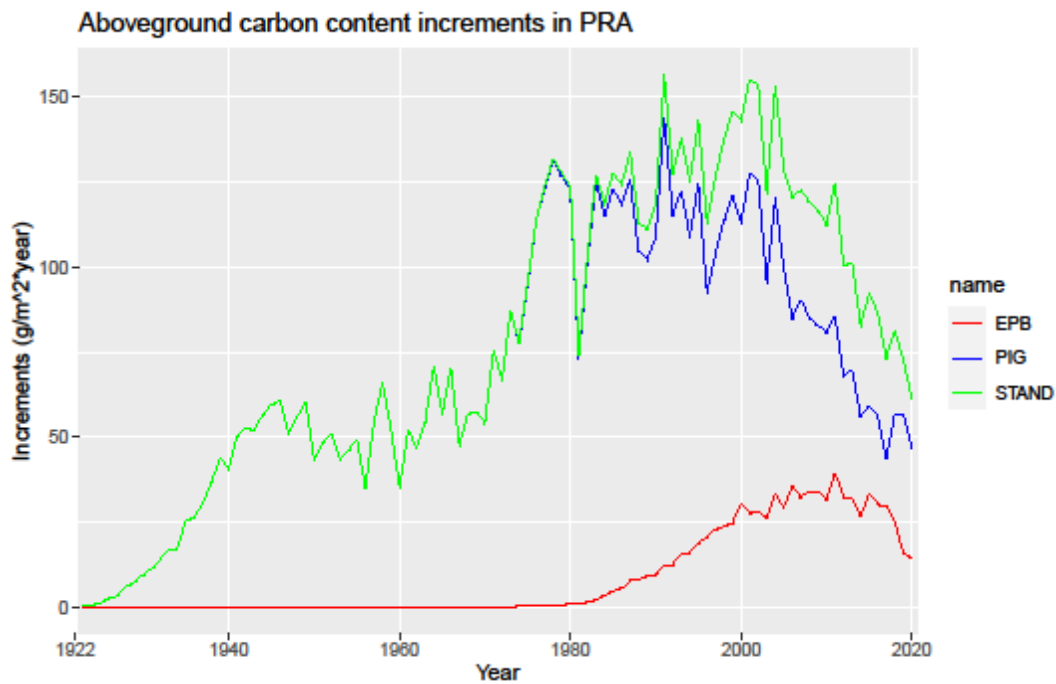


Figure 5-7 Carbon increments at the stand level ($g\ C\ m^{-2}\ year^{-1}$) in the site PRA. Blue=jack pine, red= white spruce, green= the sum of the species.

Finally, we can see the benefits of a mixed stands on the forest productivity thanks to the boxplot in

Figure 5-8. In both stands the median of the bootstrapped coefficient of variation the annual wood carbon increments is always lower for the total stands. In Authier Nord the coefficient of variation median is approximately of the 15% in the stands against 16% and 18% respectively of black spruce and jack pine. Both quartiles are lower making the stands box smaller than both other single species boxes. In the second site the less variability of at the stands level is even more evident. Here the median value in the total stand is less than 20% against the 30% for jack pine and 60% for white spruce. Also, in this case the white spruce result represent an outlier from the other. It has the minimum coefficient variation value (approximately 40%) even bigger than the maximum estimated in the other two population.

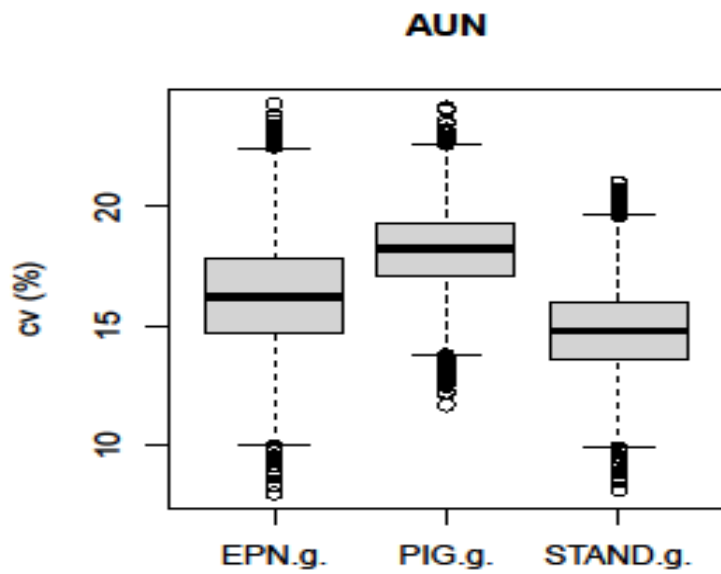


Figure 5-8 Box plot of the in confidence intervals of the bootstrapped coefficients of variation of the annul wood carbon increments ($\text{g}/\text{m}^2 \cdot \text{year}$). $\text{Cv} = \text{coefficient of variation} = (\text{dev.st}/\text{mean}) * 100$

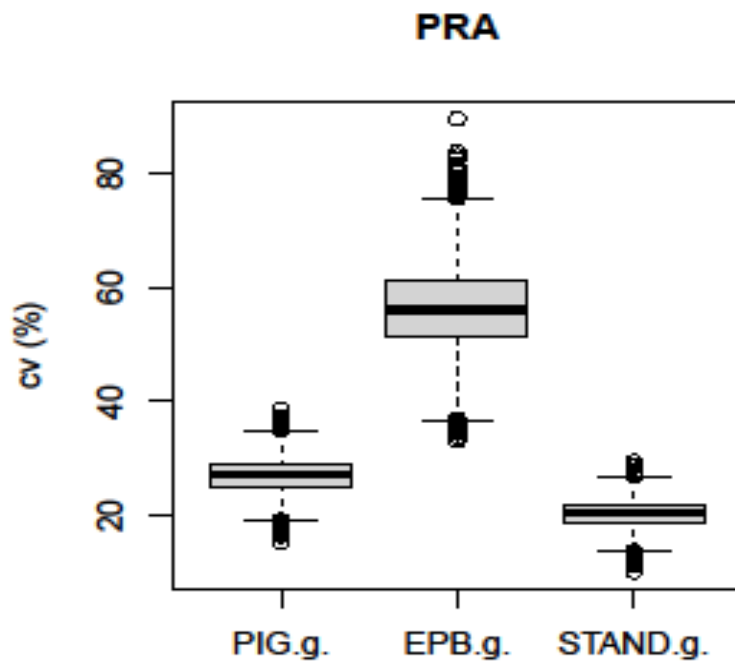
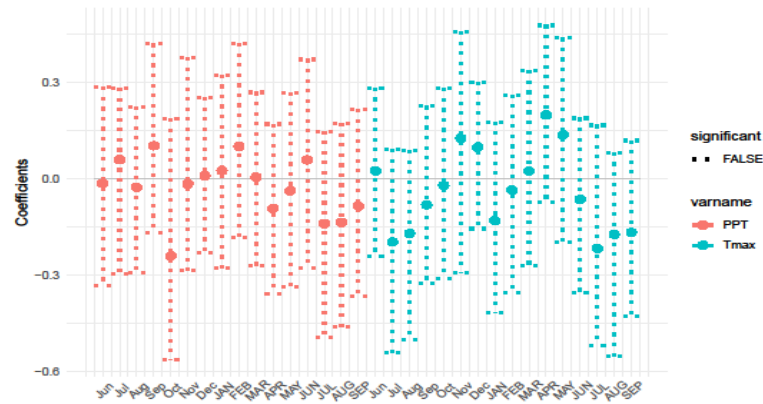


Figure 5-9 Box plot of the in confidence intervals of the bootstrapped coefficients of variation of the annul wood carbon increments ($\text{g}/\text{m}^2 \cdot \text{year}$). $\text{Cv} = \text{coefficient of variation} = (\text{dev.st}/\text{mean}) * 100$

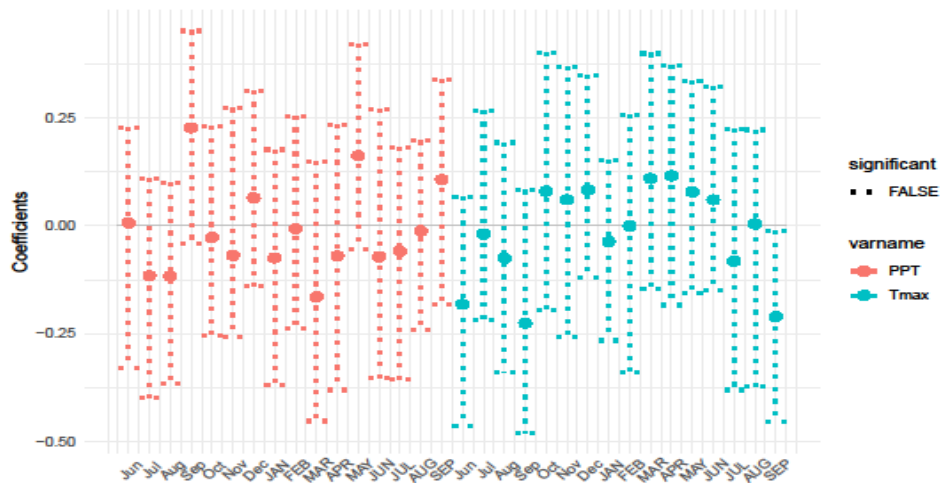
5.4 RESPONSE WITH MONTHLY Tmax AND MONTHLY PRECIPITATION

In Authier Nord there is no significant response between yearly aboveground carbon increments for meter square and monthly precipitation or monthly max temperature. This happen at the single species and stand level



5.5

5.6



5.7

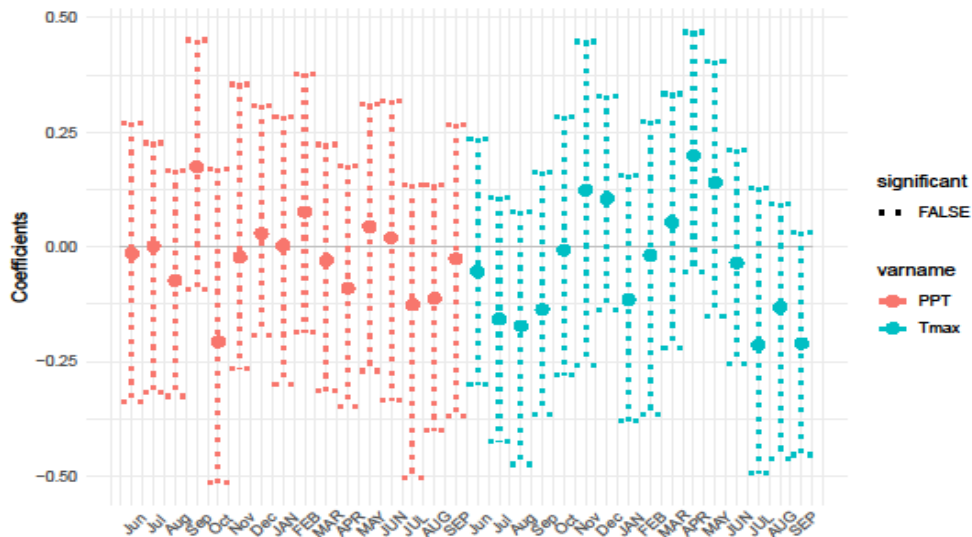


Figure 5-10 Response function analysis between monthly climate variables (Tmax and precipitation) and annual carbon increments in Authier Nord for the last 40 years. Lowercases (uppercases) refer to month of the previous (current) growing season. In order black spruce, jack pine, sum of the species.

In PRA we found a negative significant response only for jack pine with both September (previous and current) maximum temperature.

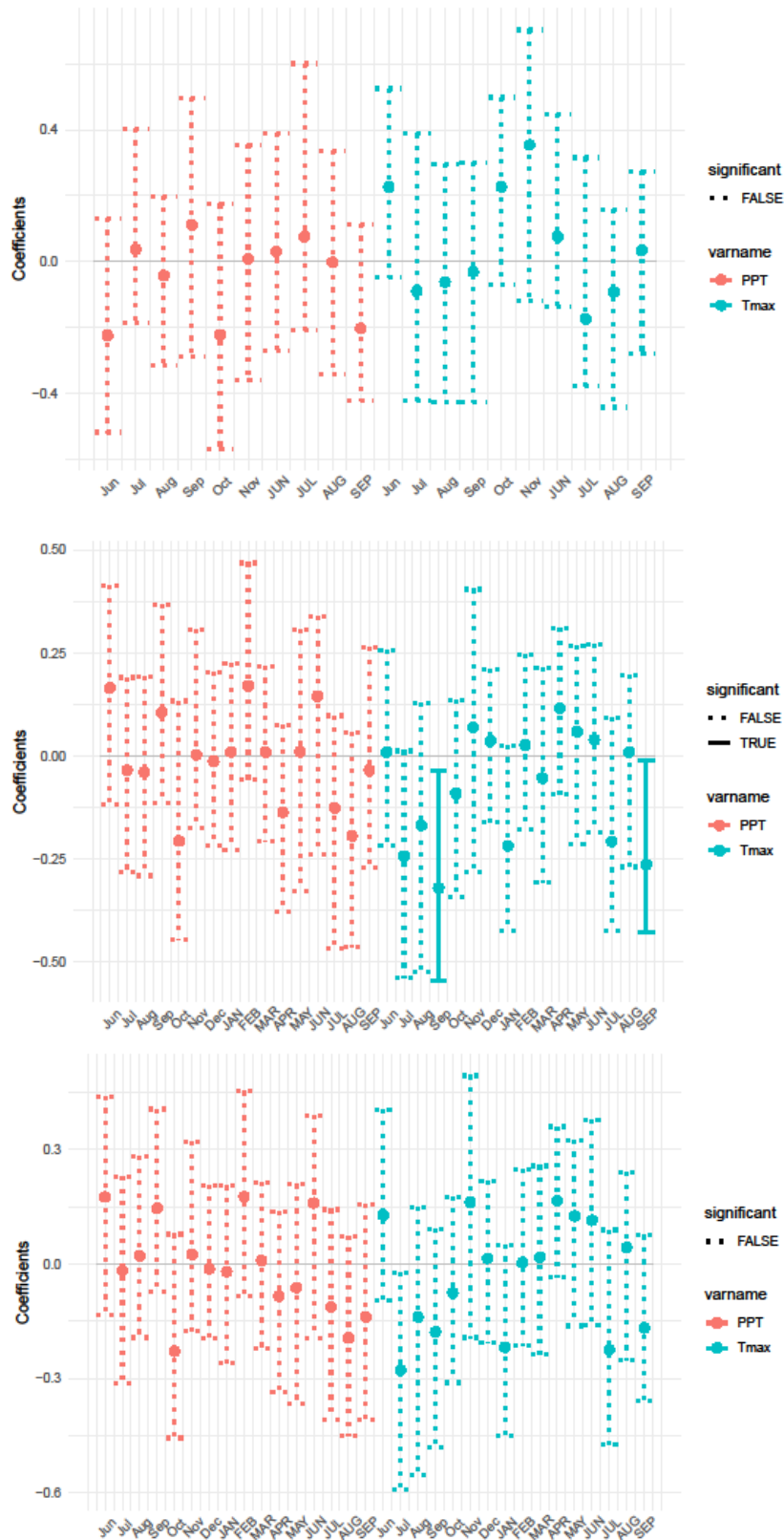


Figure 5-11 Response function analysis between monthly climate variables (Tmax and precipitation) and annual carbon increments in Authier Nord for the last 40 years (jack pine and total stand) and 20 years (white spruce). Lowercases (uppercases) refer to month of the previous (current) growing season. The graphics are sorted with this order: white spruce, jack pine and total stands.

6 Discussion

6.1 IMPACT OF FIRES AND DISTURBANCES ON C STOCKS AND INCREMENTS IN THE BOREAL FOREST

Our DBH and carbon content plots enhance the different growth rate characteristic of each species (Miyamoto et al., 2010). The jack pine confirms a strong pioneer behavior being in both stands the first specie showing a significant productivity. In Authier-Nord the settlement period was the same for both species but the black spruce curves in our plots are always flat for the first 10-20 years. One individual of *Pinus banksiana* and one of *Picea mariana* of the same age could have a difference of 10 centimeter in diameter, especially in the first 30-40 years. Jack pine here was also favored by the fire occurred in 1916. It is not new that his spreading is strongly related with fire thanks to his serotinous cones (Desponts A N D & Payette, n.d.). This also confirms the ecological role of such extreme events in terms of forest productivity (Bergeron & Leduc, 1998; Brandt et al., 2013; Hansen et al., 2010). They contribute to vegetation dynamics by altering interspecific competition and initiating forest gap dynamics especially in the boreal biome. Crown fires tend to kill most vegetation in affected stands, promoting young even-aged communities of fire-adapted tree species, e.g., *Populus* spp., *Betula papyrifera*, *Pinus banksiana* Lamb., and *Picea mariana* (Mill.) B.S.P. However burn severity can vary substantially promoting establishment of less fires adapted species like balsam fir and white spruce. So fires may further contribute in tree regeneration heterogeneity dependently from his frequency and intensity (Taylor et al., 2013). But climate change also induced modifications of frequency and intensity of forest wildfires, outbreaks of insects and pathogens and extreme events (P & A, 2007). Forest burnt area has increase about of 75% during the last 40 years compared with the 20th century with worst prevision for years to come (Resources Canada, n.d.). In 2010 a globally study was conducted to quantify gross forest cover loss (GFCL) from 2000 to 2005 and to compare it among biomes, continents, and countries. They come to the conclusion that the boreal biome has experienced the greatest proportion of forest cover lost of wich 60% caused by fire (Hansen et al., 2010). They can potentially convert boreal forest from a carbon sink state to carbon source(Dieleman et al., 2020).

In the site near Amos it is evident the benefits from the partial cut (PC) in the seventy's. From the carbon content increments plot we can see that a big decrease in the jack pine curve is followed by a new high peak and the growth start of the white spruce. So, it is obvious the importance of a good silviculture practices in terms of renovation, productivity and so carbon stockage (Saucier & Bégin, 2009). Boreal mixed forests, counting the 50% of Canadian boreal forests (Lee et al., 2002), are prime candidates to sequester atmospheric C because of their extent and because they are often found on the most fertile and productive sites. Further, many mixed stands are currently approaching the point at which harvesting is recommended, thereby affording opportunities to implement innovative C management strategies. Recent works demonstrate that partial cutting aims to increase natural forest productivity and preserve part of the existing forest C stocks (Ameray et al., 2021; Man & MacDonald, 2015). Being classified in the extensive forest management practice, PC is based upon moderate harvesting intensities. Thanks to this it can improve productivity, carbon storage and other ecosystem services keeping the forests in a more natural state (Ameray et al., 2021). PC could bring benefits especially for species like jack pine. As showed in the Figure 5-7 it has had the biggest increments after the harvesting of the 1970. We measured an increment of 100 g/ m² in less than five years. Jack pine

often grows in mixtures with trembling aspen, white spruce and black spruce and as a shade intolerant boreal conifer it is subject to growth loss and mortality under these conditions. Harvested practices of the overstory canopy increases the amount of lights available for jack pine individuals. Moreover, PC could assist natural pruning and promote species and structural biodiversity and ecosystem stability without severely reducing pine survival and growth (Man & MacDonald, 2015)

6.2 BENEFICIAL EFFECTS OF FOREST MIXTURE FOR CARBON MANAGEMENT IN THE BOREAL FOREST

Our results confirm both of our hypothesis: mixed stand has less variability than single species stand, and they are less negatively affected by climate variables. A mixed stands provide a better spatial stratification of roots and leaves increasing use of site resources both below and above ground. Different species means also different resource needs with potential reduction of negative interactions and competition between trees (Lilles, 2013). Black spruce and jack pine examples of such species, also possessing two contrasting, life strategies jack pine being a fast growing and early successional tree, whereas spruce is representative of a slower growing and late successional dominant. In this way they can create an own ecological niche and increase their forest productivity (Chavardès et al., 2022). Also, a different shade intolerance can help a better coexistence between different species(Chavardès et al., 2021b; Chen et al., 2003; Drobyshev et al., 2013) . Following a disturbance like a high-severity stand-replacing fire, black spruce can establish, persist in the subcanopy, and grow slowly, whereas jack pine requires high initial growth rates following establishment to maintain its crown in the rising canopy with access to sunlight. This is the case of the stand near Amos. White spruce often occurs as dominant species but in this case it perform his high shade tolerance. Thanks to this, even if the jack pine was already well settled, it had the capability to grow up and bring profits at the stand productivity level. For the climate response we had the expected results only for the second site. Here we found that carbon content increments for jack pine had a significant negative response with two months if associated with max monthly temperature. This response change in the case of the stand carbon content increments confirming presence of more species more advantageous than pure stand.

6.3 IMPLICATION OF THESE RESULTS FOR FOREST MANAGEMENT IN THE CONTEXT OF CLIMATE CHANGE

Like all the world Canada, especially southwest, is affected by the environmental changes due to human impact (Lorente et al., 2020; X. Zhang & Canadian Councils of Resource Ministers., 2011). Climate has always changed during the history but it never had a significant variation like the one of the last 2 century in so short period due to the increase of the green house gases (GHG) concentration in the atmosphere (Gauthier et al., 2014). One approach to mitigate these effects is to alter the distribution of CO₂ at the earth/atmosphere interface by using forest ecosystems to 'pump' CO₂ out of the atmosphere and into storage in trees. Forest ecosystems, however, are rarely stable. They are often subjected to disturbance (e.g. fires, insects, diseases) or are manipulated and eventually harvested in order to provide a broad range of timber and non-timber values. To realize more of the C sequestration potential of forests, it is critical that a better understanding of the impacts of forestry practices on the C cycle be acquired, so that appropriate forest management strategies aimed to increase carbon stockage and forest productivity. The latter attenuates climate change due to its contribution to the terrestrial C sink and, thus, to the absorption of anthropogenic CO₂ emissions. One third of total global fossil fuel

emissions are taken up by forests (Pan et al., 2011). Photosynthesis allows plants take up from the atmosphere carbon dioxide to produce energy and consequentially stock it in their tissues. In a larger scale if we focus on the boreal forest this data is more meaningful. It's one of the largest biomes on earth occupying the 11% of the terrestrial surface and holding 30% of total forest. For this reason, boreal ecosystems are considered one of the best carbon reservoirs on the planet. Therefore, it's obvious the importance of preserving our forest heritage for the planet balance or at least modify it in a sustainable way. Good silviculture practices can quicken renovation process, increase biodiversity, reduce fire and hydrogeological risks. Further we can earn wood products that could be extremely helpful in the struggle against climate change. Forest products such as Harvested Wood Product (HWP) have direct and indirect effects on the earth climate system because of their substitution of emission-intensive products (Lemprière et al., 2013; Malmshemer, n.d.). Using wood resources in this way can substitute for the use of fossil fuels—in particular for CO₂—and energy-intensive materials like steel and concrete in the construction sector.

7 Conclusions

With this work we help to analyse two of the boreal sites present in the network of SmartForest Canada. Nowadays it is crucial to understand better boreal forests processes. Being part of the largest biome and representing 1/3 of the total world forests it plays a primary role in climate change mitigation. Forest productivity more than other ecological aspects is influenced by multiple factors like soil nutrients availability, extreme events, atmospheric conditions, and human activities. We can confirm the importance of biodiversity. With this study we found the benefits of mixed stands from the diameter at breast high until the aboveground carbon content increments level. We must say that in both our stands we had species complementary to each other. In AUN the pioneer jack pine paved the way to the resilient black spruce. In PRA a shade tolerant species like white spruce had no problem growing under a dominant species like jack pine. The benefits of a mixed stands also came out in the climate response with maximum monthly temperature.

Finally from the results we noticed the importance of the natural forest processes for the ecosystem health. Extreme events like fires help regeneration and so productivity. At the same level human activities could bring profits to the forests. With good forest management we do not alter the natural development of the ecosystem and we contribute to reduce global warming.

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