Article

The Use of Basal Area Increment to Preserve the Multi-Decadal Climatic Signal in Shrub Growth Ring Chronologies: A Case Study of *Betula glandulosa* in a Rapidly Warming Environment

Julie-Pascale Labrecque-Foy [1,2,*], Sandra Angers-Blondin [3], Pascale Ropars [4], Martin Simard [2,5,6] and Stéphane Boudreau [1,2]

1 Département de Biologie, Université Laval, Québec City, QC G1V 0A6, Canada
2 Centre for Northern Studies (CEN), Québec City, QC G1V 0A6, Canada
3 School of Biological and Environmental Sciences, Liverpool John Moores University, Liverpool L3 3AF, UK
4 Sentinel North, Université Laval, Québec City, QC G1V 0A6, Canada
5 Département de Géographie, Université Laval, Québec City, QC G1V 0A6, Canada
6 Center for Forest Research (CEF), Québec City, QC G1V 0A6, Canada
* Correspondence: julie-pascale.labrecque-foy.1@ulaval.ca

Abstract: Climate warming at high latitudes has contributed to the growing interest in shrub tree-ring analysis. Shrub architecture presents new challenges for dendrochronology, such as the seemingly lower and inconsistent climatic sensitivity of stems vs. root collars. Shrub stems may thus be considered as sub-optimal to study climate–growth relationships. In this paper, we propose that the lower climatic sensitivity of stems could be caused by the use of unsuitable detrending methods for chronologies spanning decades rather than centuries. We hypothesize that the conversion of the ring width (RW) to basal area increment (BAI) is better suited than traditional detrending methods to removing age/size-related trends without removing multi-decadal climate signals. Using stem and root collar samples collected from three sites in the forest–tundra ecotone of eastern Canada, we compared the climate–growth relationships of these two approaches for stems and root collars using mixed-effects models. The climate sensitivity was, on average, 4.9 and 2.7 times higher with BAI than with detrended (mean-centered) RW chronologies for stems and root collars, respectively. The climatic drivers of radial growth were identical for stems and root collars when using BAI (July temperature and March precipitation), but were inconsistent when using detrended RW series (root collars: July temperature and March precipitation at all sites; stems: April and June temperature, depending on the site). Although the use of BAI showed promising results for studying long-term climate signals in shrub growth chronologies, further studies focusing on different species and locations are needed before the use of BAI can become broadly used in shrub dendrochronology.

Keywords: dendrochronology; shrub; climate sensitivity; radial growth; basal area increment; ring width; detrending; root collar; stem; *Betula glandulosa*

1. Introduction

Harsh climatic conditions and short growing seasons limit plant productivity across the Arctic and subarctic [1–3]. Cold temperatures reduce photosynthetic activity [4] and slow down plant phenological processes such as bud burst and seed development [5–7]. In recent decades, however, warming in Arctic and subarctic regions, which is nearly three times stronger than the global average [8], has substantially reduced the limiting effect of temperature on primary productivity [9–11]. Although some studies have found browning trends in the boreal or lower Arctic regions due to changes in the natural disturbance regime [12–14], the improved climatic conditions during the growing season have resulted in widespread "greening" of the circumpolar region of the Northern Hemisphere [15–17]. The expansion of shrub species, either through the densification of existing stands or

through the colonization of new habitats, contributes to this phenomenon [14,18–20]. In such high-latitude ecosystems, shrub encroachment could alter the surface energy exchange, soil temperature, snow cover, and nutrient cycling, all of which could foster further shrub encroachment [19]. However, shrub encroachment in other ecosystems, such as arid and semi-arid grasslands, could lead to the decline of vegetation cover through its effects on the biophysical and biogeochemical processes affecting the regional climate [21].

North of the treeline, shrubs are the only woody plants [22,23] and their growth rings are a valuable ecological archive with a yearly resolution. Therefore, dendrochronological studies on shrub species can provide precious insights on the drivers of climate and landscape change across the entire circumpolar region. However, shrub growth and architecture present new challenges for dendrochronology. For example, seed-originating individuals of the subarctic shrub *Betula glandulosa* Michx. have a growth form characterized by multiple stems growing from an often-buried root collar, i.e., the interface between the stems and the roots (Figure 1a). From a dendrochronology standpoint, the root collar is thus the anatomical equivalent of the base of the primary axis of a tree as it integrates the growth of all stems. In the field, shrub root collar sampling necessitates shrub excavation, a time-consuming and destructive manipulation that can interfere with the complex logistics of fieldwork in remote areas. For these reasons, many dendrochronological studies have been conducted on samples taken at the base of the dominant stems [23–27]. However, stems can be substantially younger than their root collar as they are continually replaced throughout the shrub's life, resulting in shorter growth chronologies. Moreover, the use of stems instead of root collars could be problematic, as Ropars et al. [28] demonstrated that the climate sensitivity of *B. glandulosa* stems is lower and more variable than that recorded at the root collar just a few centimeters below [28]. Although this has not yet been proven for other shrub species, there is a need to better understand the difference in climate sensitivity between stems and root collars in order to improve shrub dendroclimatology.
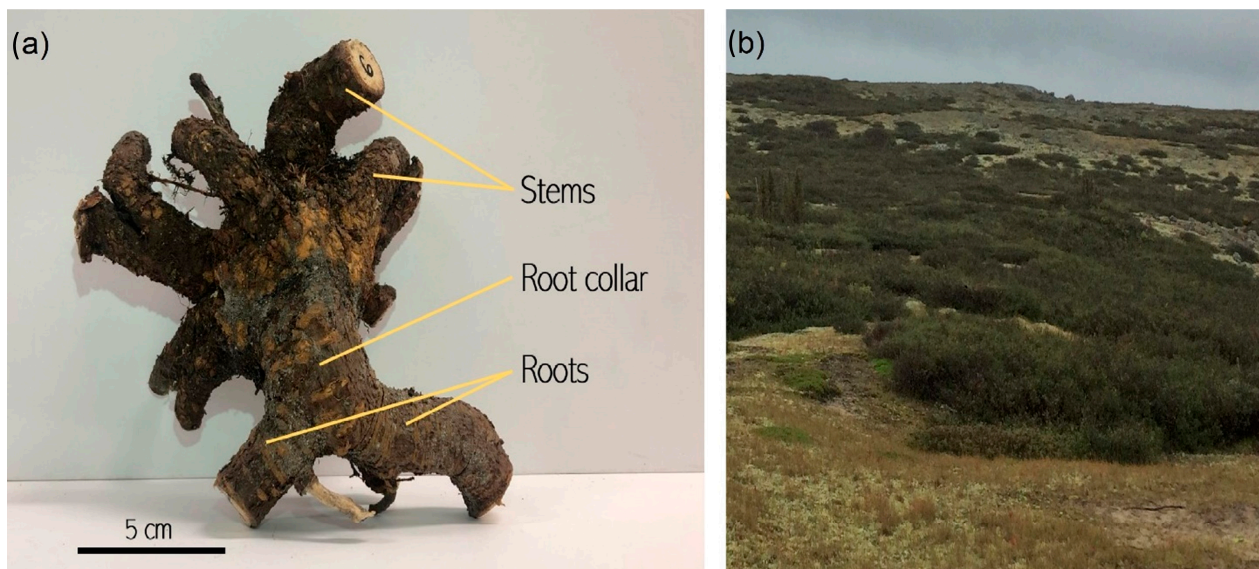

Figure 1. (**a**) Position of the root collar, roots, and stems of an uprooted *Betula glandulosa* individual. Stems and roots were cut and marked in the field to facilitate the transportation of the samples. (**b**) Landscape in the vicinity of the Boniface River research station, with patches of *B. glandulosa* interspersed in a matrix of tundra vegetation.

Although Ropars et al. [28] argued that the weaker climatic signal registered by stems could arise from competition between the different stems of a single individual, another likely explanation relies on a technical issue associated with the detrending of growth ring chronologies. Detrending, sometimes also called standardization, is necessary to remove age/size-related trends from tree-ring series in order to isolate and amplify signals of

interest, such as high-frequency or low-frequency climatic trends, forest disturbances, or stand dynamics [29]. One of the trends that is almost systematically removed is the age/size effect, observed as a gradual decrease in ring width from the center of the stem towards the bark. This trend, which results from the increasing perimeter of the cambium as new rings are produced, is removed using a variety of detrending approaches that each have their benefits and drawbacks [30–32]. One of the challenges of detrending is to be able to remove the age/size trend while keeping the low-frequency (long term) variations associated with climate change, as both operate at a multi-decadal scale. For example, in time series spanning decades rather than centuries, detrending to remove any age/size-related trends will likely also remove at least part of the long-term increase in ring width associated with climate warming. This appears to be exacerbated under rapid climate change.

The conversion of ring width (RW) to ring area, or basal area increment (BAI), is a robust detrending approach that compensates for the ever-increasing perimeter of the cambium [33,34]. BAI has been used in studies aiming to characterize tree responses to environmental changes, and some of these studies confirm the effectiveness of converting RW into BAI as a detrending method [35–38]. Leblanc [39] demonstrated that RW measurements of pine and spruce species tend to cloud the relationship between a growth trend and its potential cause, and that BAI measurements are more closely related to the stem volume increment than RW data. Moreover, based on the results of Baral et al. [40], who demonstrated that climate–tree growth relationships were stronger when using BAI rather than standardized RW in short chronologies, we believe that the use of BAI might be of high interest when analyzing shrub species' growth rings. Indeed, even though BAI measurement has been used mainly with trees, it remains only marginally used for shrub species [22,23,41–43].

In this study, conducted in Nunavik (subarctic Québec, Canada), our main objective was to determine if the conversion of RW to BAI can reduce the discrepancies found in *B. glandulosa* detrended chronologies built from shrub stems vs. root collars, both in terms of growth patterns and the relationship with multi-decadal climate trends. If so, the climatic drivers and climatic sensitivity of growth chronologies should be comparable, regardless of the nature of the sample (stem or root collar), when using BAI data instead of detrended RW data (mean-centered or spline detrended). A secondary objective was to determine if BAI estimations (i.e., calculated from raw ring width measurements) are correlated with the actual measurements of BAI (i.e., measured on scanned cross-sections using image analysis) for *B. glandulosa*. Indeed, both approaches have been used in previous studies but have never been compared (calculated: [37,40,42]; measured: [22,41]). Calculating BAI from RW measurements is significantly faster, but might generate inaccurate values in the presence of eccentric growth forms or irregular rings [23].

2. Materials and Methods

Using the same dataset as Ropars et al. [28,44], we calculated BAI values to perform a direct climate sensitivity comparison between growth ring chronologies built with either detrended RW or BAI for both stems and root collars.

2.1. Study Area

The samples were collected in the vicinity of the Boniface River research station (57°45′ N, 76°10′ W) in Nunavik (subarctic Québec, Canada). Located in the forest–tundra ecotone, approximately 10 km south of the treeline [28], this region showed a significant greening trend between 1984 and 2012 [16]. The landscape is dominated by shrub tundra, with *B. glandulosa* being the dominant shrub species (Figure 1b). Open lichen woodlands dominated by black spruce (*Picea mariana* Miller) cover ca. 30% of the landscape. Wetlands, exposed hilltops, and sandy terraces are also common. The fire frequency in the region is very low, with a fire rotation period of 1800 years [45]. The study area is also located at the southern limit of the summer range of the Leaf River Caribou Herd, but the caribou density is low and evidence of grazing has mostly been found on *Salix* species [46].

The closest meteorological station is located 130 km northwest of the Boniface River research station, at Inukjuak Airport (Environment Canada, 58°28′ N, 78°05′ W). The mean annual air temperature was −6.8 °C for the 1950−1994 period, but increased to −5.2 °C in the 1995–2019 period. Over the 1995–2019 period, the total annual precipitation was 500 mm on average, 42% of which fell as snow [47].

2.2. Field Sampling

Field sampling was conducted in the summer of 2010 [28,44]. Samples were collected at three sites in each of the following environment types: sandy terraces, exposed hilltops, and snowbeds. Sandy terraces, located on well-drained sites next to the river, are dominated by lichens, graminoids, and large patches of shrub species [28], whereas exposed hilltops are dominated by arctic–alpine vegetation and mineral soil as a result of harsher winter conditions [44]. Snowbeds are characterized by greater snow accumulation during winter and later snowmelt in the spring, resulting in shorter growing seasons [48]. At each site, 20 large, circular, and isolated *B. glandulosa* individuals were selected as they were believed to represent older individuals that originated from seed. Each shrub was excavated to collect the root collar, as well as two of its main stems. If the root collar of an individual could not easily be identified, it was discarded, and another shrub was excavated. Samples were cleaned and left to dry at room temperature for further analysis. Ropars et al. [28] randomly selected one site per environment type (sandy terrace, exposed hilltop, and snowbed) to conduct their analyses. We used the same sites and samples in this study.

2.3. Dendrochronological Analysis

Root collars and stems were boiled for 3 h before being sliced (25 μm) with a microtome. Thin sections were stained with 1% safranine, and were dried and mounted on microscope glass slides with a 66% toluene solution. Root collars that could not be sliced perpendicularly or that were rotten were discarded, along with their corresponding stems. At the end of this process, 46 shrubs were kept in the study, for a total of 138 analyzed cross-sections (46 root collars and 92 stems). The mean diameter of the stems and root collars was 7 and 21 mm, respectively.

Digital pictures of each sample were taken with a camera mounted on binoculars at 40× magnification. Most samples showed little to no eccentricity. Ring width measurements were conducted with the LIGNOVISION software (v. 1.36, Rinntech, Heidelberg, Germany) on two opposite radii for each sample. The RW series were crossdated using COFECHA software [49] and were standardized in the Dendro 2019 software (v. 3.2.8, Centre for northern studies, Université Laval, Québec, Canada) to produce RWI chronologies. During our analyses, we realized that the detrending methods applied in Ropars et al. [28] sometimes varied between samples and sites. Therefore, we decided to redo the detrending process using the same detrending methods for all of the samples. Uniformity in the detrending process is in fact necessary to show how traditional detrending methods can remove climatic trends in dendrochronological series. Consequently, the results shown in this paper are slightly different from those published in Ropars et al. [28]. The first detrending method used was the mean-centering method as it is the most commonly used method when studying multi-decadal growth trends. However, to show how other detrending methods can alter climatic signals, we also detrended RW data with cubic splines of different wavelengths (20-year, 30-year, and 66% of the length of the series). Only the comparison between BAI and RWI obtained from the mean-centering method is shown in the text, but the results obtained with the various spline lengths are presented in the Supplemental Material (Tables S1–S3).

BAI was first calculated using raw (non-standardized) RW measurements according to the following equation, which assumes that all growth rings are perfectly circular and concentric:

$$\text{Calculated BAI} = (\pi \times r^2 \text{ of current year}) - (\pi \times r^2 \text{ of previous year}) \quad (1)$$

BAI was also measured by image vectorization with Image J software. For this part of the study, only samples for which the complete thin section could fit on a microscope slide were used, resulting in the measurement of 56 samples, mostly stems (terrace: 18; hilltop: 18; snowbed: 20) with a mean and maximum diameter of 5.0 and 11.5 mm, respectively. Each outer ring was delineated by hand, and the annual ring area was computed by subtracting the cumulative ring area of the previous year from the cumulative ring area of the current year.

Expressed population signal (EPS) values were computed in Dendro 2019, and rbar and AR1 values were computed using the dplR package in R [50]. All individual RWI and calculated BAI chronologies are available as Supplemental Material (Figures S1–S3), as well as mean chronologies divided by age cohorts (Figures S4–S6).

2.4. Statistical Analyses

To determine whether the BAI values calculated from the raw RW were representatives of the BAI values measured by image vectorization, two mean chronologies were produced for each site using the calculated and measured BAI data. The similarity of the chronologies was then evaluated with the Pearson correlation coefficients (r).

To evaluate climate sensitivity, mixed-effects models were created using the lme4 package in R software (v. 4.0.2; [51]). For each environment type (terrace, hilltop, and snowbed), we ran four separate series of models using individual growth series constructed with (1) either root collar or stem data and (2) either RWI (detrended by mean-centering or various spline wavelength) or BAI calculated from raw RW measurements. The RWI and calculated BAI were used as response variables, and monthly total precipitation, monthly mean temperature, and their various combinations were used as fixed effects. Year was considered as a random effect. Null models using only growth measurements (BAI or standardized RW; response variable) and year (random effect) were used as a baseline to calculate the climatic sensitivity. The models were run with data from 1947 to 2009, the period for which both climatic and radial growth data were available.

The Akaike information criterion (AIC) was used to determine the best models and to compare climatic sensitivity [28]. To do so, we calculated the ΔAIC_{null} by subtracting the AIC of each model built with climatic data from the AIC of the corresponding null model. A higher ΔAIC_{null} represents a greater sensitivity to climate [52]. To assess the goodness of fit of the models, the marginal and conditional R^2 were calculated using the MuMIn package and the r.squaredGLMM function [28,53] in R. Marginal R^2 represents the proportion of growth that is influenced by fixed effects (climate), whereas the conditional R^2 represents the proportion of growth that is influenced by both fixed and random effects [53].

3. Results

The RWI results included in the results section come from RW series detrended by the mean-centering method. The climate sensitivity results obtained with RWI detrended by the various spline lengths can be found in the Supplemental Material (Tables S1–S3).

The age of the sampled root collars ranged from 13 to 96 years, with an average age of 41.4 ± 20.5 years (Figure 2). On average, the root collars were 18 years older than their two corresponding stems. The stem age ranged from 10 to 64 years, with an average age of 23.4 ± 13 years (Figure 2). The age distributions were, however, skewed towards younger individuals, with 68.4% of stems being younger than 25 years.
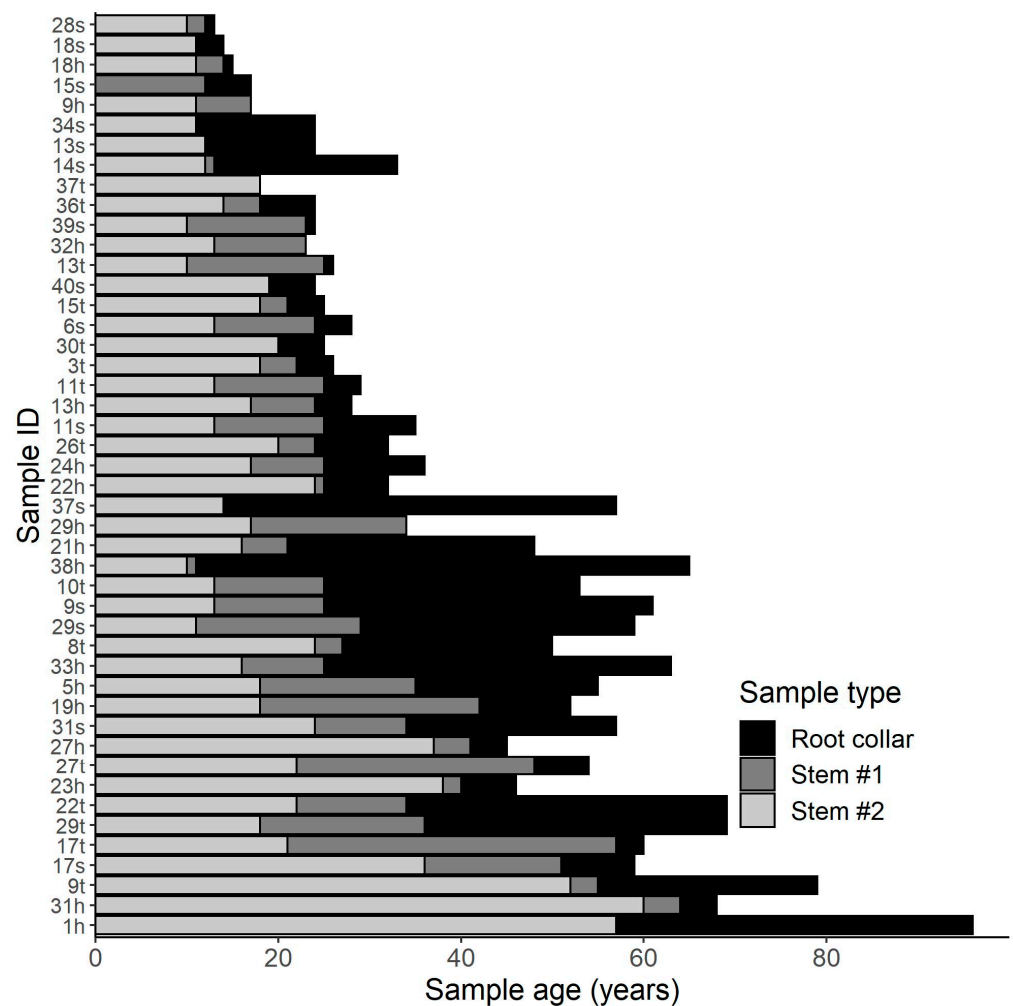
Figure 2. The age of the root collar (black) and stems (grey) of each sampled shrub (horizontal lines). Letters at the end of the shrub IDs represent the site from which they originated (t = terrace, h = hilltop, s = snowbed).

3.1. Growth Chronologies

There was a strong correlation ($p < 0.001$) between the BAI calculated with a perfect circle equation and BAI measured by image vectorization, as revealed by the correlation coefficients > 0.9 (Figure 3).

All of the growth chronologies had high EPS values, between 0.92 and 0.98, with an average of 0.95 (see Table S4 for other growth chronologies statistics). Growth chronologies built from the RW data were characterized by high variability (large confidence intervals) in their oldest portion and a significant radial growth increase in the mid-1990s (Figure 4). Compared with the RW chronologies, the BAI chronologies were much less variable at their onset and showed a similar significant growth increase in the mid-1990s. As a result, the main difference between the RW and BAI chronologies was found in the oldest portion of the chronologies. The examination of individual chronologies (Figures S1–S3) and of the chronologies separated by age groups (Figures S4–S6) suggests that the high variability in the early RW chronology was caused by the age/size effect found in each individual series that are gradually included in the chronologies. Such an effect is not seen in the BAI chronologies because the age/size effect is effectively removed by the transformation of RW to BAI.
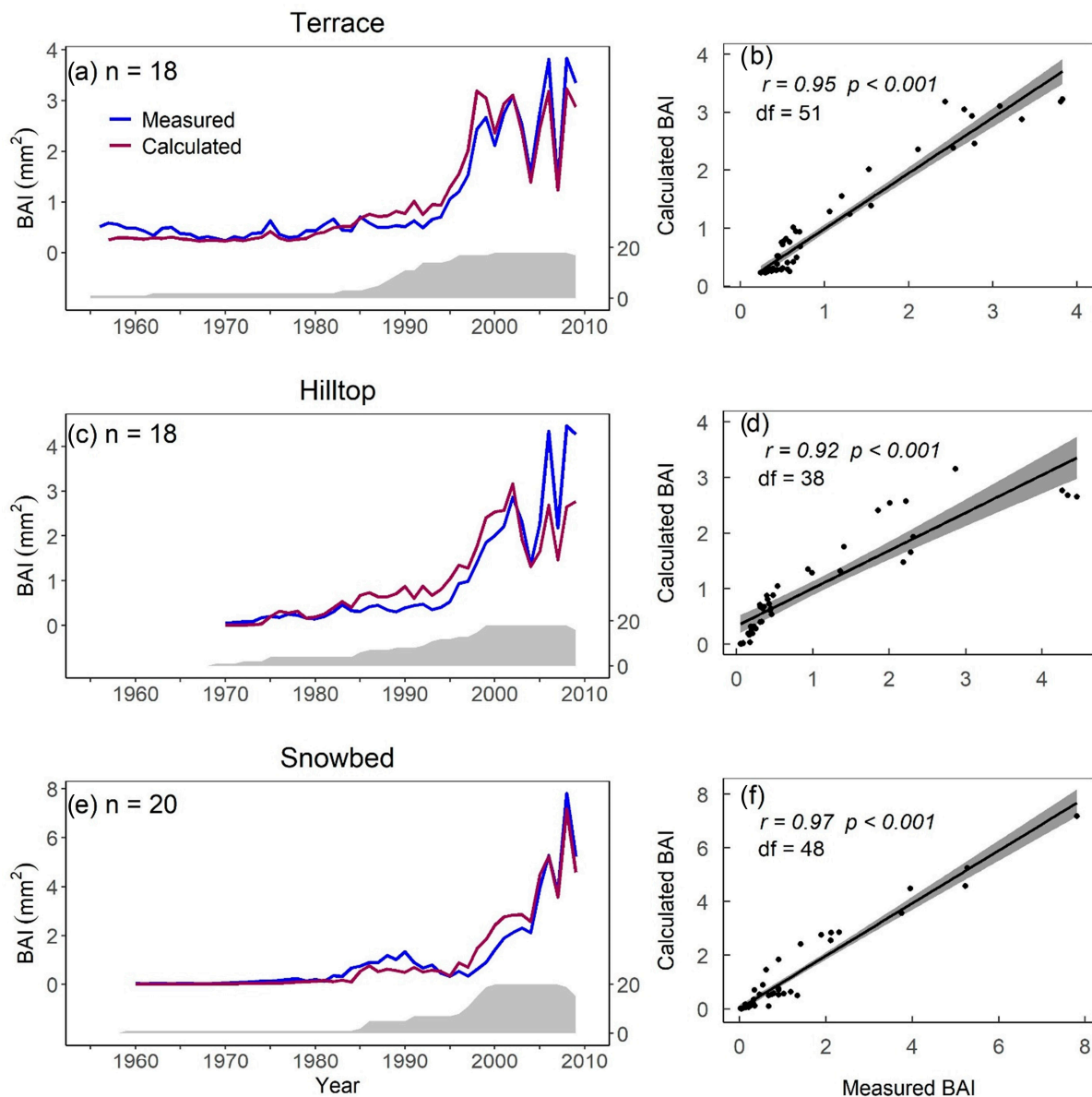
Figure 3. Growth chronologies based on calculated (red) and measured (blue) basal area increment(BAI) data (**a**,**c**,**e**) and graphs showing the correlation between the two data types (**b**,**d**,**f**). The number of cross-sections used (n), correlation coefficients (r), and degree of freedom of the correlations (**d**,**f**) are given for the three sites. The shaded areas on the left panels represent the sample depth of the series (**a**,**c**,**e**).

3.2. Climatic Drivers and Sensitivity to Climate

When using RW index data, the model selection found that the climatic drivers were different for the stem and root collar growth chronologies (Table 1). Moreover, the climatic drivers of the stem chronologies were also different between the different habitats. However, when using BAI instead of RW, our analyses generated identical climatic drivers of *B. glandulosa* growth, regardless of the sample type/shrub part and habitat (Table 1). For all BAI chronologies, July temperature and March precipitation were the best predictors and had positive impacts on *B. glandulosa* growth. These results contrasted sharply with those presented by Ropars et al. [28], in which the climatic drivers of stem radial growth varied from site to site.
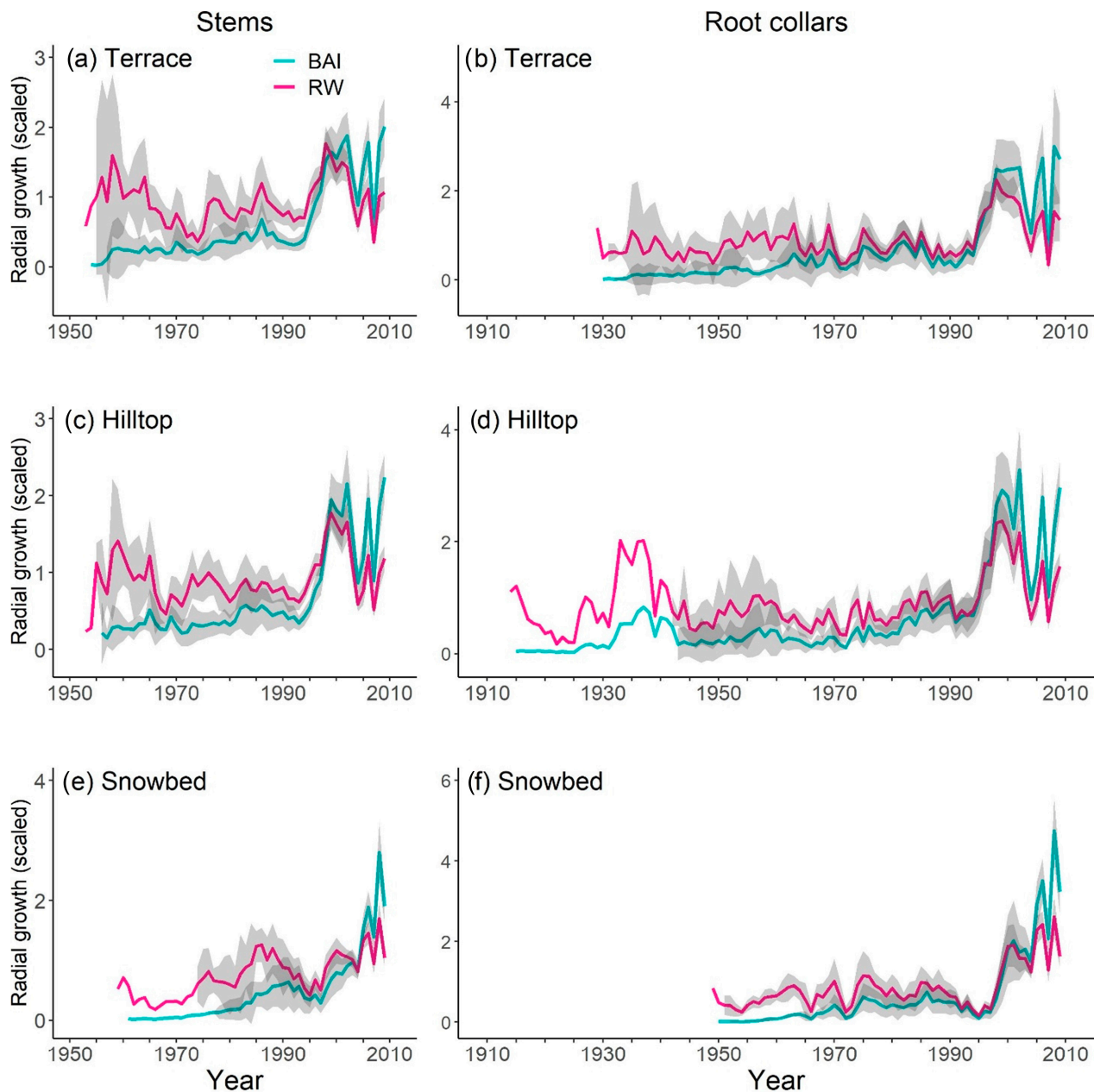
Figure 4. Mean growth chronologies of the stems (**a**,**c**,**e**) and root collars (**b**,**d**,**f**) using mean-centered ring width (RW; pink) and calculated basal area increment (BAI; blue). Shaded areas represent 95% confidence intervals.

The BAI chronologies also showed greater climatic sensitivity than the RWI chronologies (Table 1). For stems, the use of BAI increased climate sensitivity by 5.2 times on terraces, 7.5 on hilltops, and 1.9 in snowbeds (average increase across all environment types: 4.9 times higher). Even the climatic sensitivity of the root collar chronologies appeared to benefit, although to a lesser extent, from the use of BAI (3.6 times higher on terraces, 2.6 on hilltops, and 1.8 in snowbeds; average: 2.7).

Finally, differences in climate sensitivity between root collars and stems were greatly reduced by the use of BAI values. This was exemplified by the overlapping predictive responses of stems and root collar growth to July temperature and March precipitation (Figure 5). Other detrending approaches (spline of various wavelengths) did not have the same positive impact as BAI conversion as they did not reduce the differences in climate sensitivity between root collars and stems and between habitats (Tables S1–S3). Therefore,

the conversion of RW into BAI led to the highest climate sensitivity results among the five detrending methods tested (Figure S7). Lastly, the substantial increases in marginal and conditional R^2 values revealed that climatic variables explained a larger portion of BAI than the RW index (Table 1).

Table 1. Climate sensitivity values (ΔAIC_{null}), model fit statistics (R^2), and residual degree of freedom (residual df) for the best climatic variables explaining the RW index (detrended by mean-centering) and calculated BAI of *Betula glandulosa* root collars and stems over the 1947–2009 period.

Environment	Data Type	Sample Type	Best Climatic Model	Climatic Sensitivity (ΔAIC_{null})	Marg. R^2	Cond. R^2	Residual df
Terrace	RW index	Root collars	T Jul + P Mar	9.8	0.07	0.14	413
		Stems	T Apr	6.4	0.04	0.06	403
	BAI	Root collars	T Jul + P Mar	34.8	0.29	0.39	400
		Stems	T Jul + P Mar	33.5	0.39	0.46	354
Hilltop	RW index	Root collars	T Jul + P Mar	16.3	0.13	0.25	471
		Stems	T Apr	4.9	0.03	0.08	486
	BAI	Root collars	T Jul + P Mar	43.1	0.43	0.56	458
		Stems	T Jul + P Mar	36.7	0.40	0.48	449
Snowbed	RW index	Root collars	T Jul + P Mar	18.9	0.28	0.50	339
		Stems	T Jun	10.6	0.15	0.24	246
	BAI	Root collars	T Jul + P Mar	33.5	0.52	0.75	325
		Stems	T Jul + P Mar	20.2	0.39	0.52	228
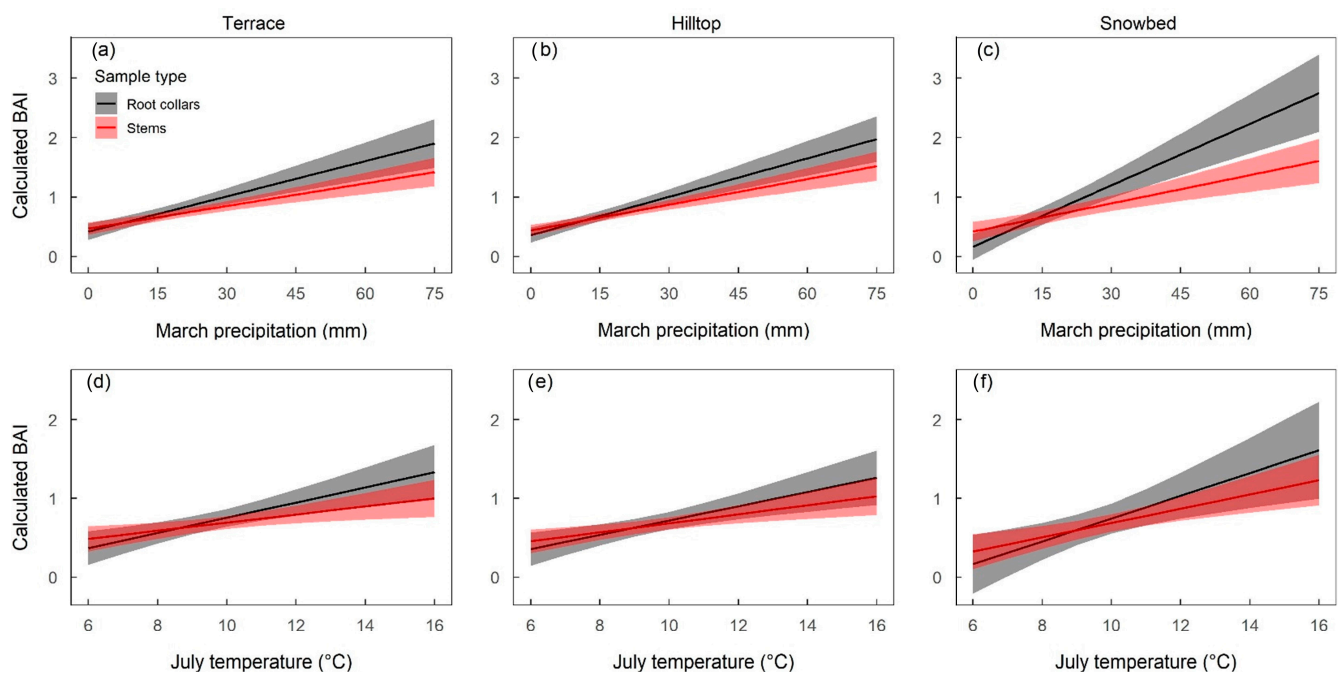
Figure 5. Predicted calculated BAI values for root collars (black) and stems (red) of *Betula glandulosa* according to the best climatic models: March precipitation (**a–c**) and July temperatures (**d–f**) for the 1947–2009 period. Shaded areas represent 95% confidence intervals.

4. Discussion

In this study, we showed that the use of basal area increment (BAI) to remove age/size-related growth trends is an effective detrending procedure for *Betula glandulosa,* as it yielded consistent results regardless of the nature of the samples (stems or root collars). First, the use of BAI allowed us to consistently identify July temperature and March precipitation as the most important climatic drivers of *B. glandulosa* radial growth. Secondly, using BAI increased the climate sensitivity of stem growth to a level comparable to the root collars. Therefore, our results strongly support the use of BAI when considering the impact of climate change on shrub species radial growth at the multi-decadal scale. Although our study was conducted on a single species and further studies are needed to determine if the use of BAI is appropriate for other species, it appears likely that such a procedure will allow low-frequency (long term) variations associated with climate to be found for any shrub species displaying age/size trends.

4.1. Growth Chronologies

4.1.1. Calculated vs. Measured BAI

The calculated BAI values from raw *B. glandulosa* RW measurements were strongly correlated with the measured BAI values. This result suggests that ring width can be used to estimate BAI for species with regular and concentric growth rings like *B. glandulosa* (see Figure S8 for pictures of *B. glandulosa* cross-sections). For such species, it appears thus not necessary to conduct the time-consuming BAI measurements on scanned images, although we would recommend to always verify the strength of the correlation between the calculated and measured BAI before using this short-cut approach with another species as shrubs growing in Arctic and subarctic regions under extreme growth conditions often produce irregular, off-centered, or discontinuous growth rings. For such species, further tests would be needed prior to using the ring width to estimate BAI. A lower correlation between the calculated and measured BAI could necessitate various adjustments. For example, ring width could be measured on at least four radii to improve the accuracy of the BAI estimation [22]. The use of equations considering growth rings as elliptical instead of circular could also be a solution for some species [54]. However, for species with very important eccentric growth, BAI measurements (instead of calculation) would be the most appropriate approach.

4.1.2. BAI Conversion as a Detrending Method for Shrub Chronologies

BAI is already widely used in studies aiming to analyze the relationship between climate and tree growth [33,35,37,40,55–57]. In fact, many studies have demonstrated that the use of BAI instead of RW generates higher correlations to tree biomass and wood volume gain [39,56,58]. Similar results were also reported for some shrub species [26]. In most cases, the conversion of raw RW to calculated BAI values was used as a detrending method to remove non-climatic growth trends related to stem age/size in trees [33,37,38,59]. When both RW and BAI values were compared, the latter systematically yielded better correlations between climate and radial growth [23,31,40,55].

Our results corroborate these previous studies, even though they were mainly conducted on tree species. They strongly suggest that the use of BAI is an efficient method to remove non-climatic growth trends related to the age or size of shrub stems while preserving climatic trends. The conversion of RW to BAI had a noticeable effect in the earliest portion of our growth chronologies, where the BAI series were less variable (narrower confidence intervals) than the RW ones. This greater variability in RW data arose from the different period of establishment of the samples used to build the growth chronologies, resulting in asynchronous age/size growth trends (see Figures S1–S3 for individual chronologies). On the other hand, climatic growth trends are generally synchronous in a given region because they are associated with climatic drivers acting at a regional scale. In our chronologies, these trends, mostly found in the recent period in response to the substantial warming observed in the study region since the mid-1990s [60], were not removed

by the conversion to BAI. Moreover, the reduced variability at the beginning of the BAI chronologies, evidenced by the narrower confidence intervals in BAI chronologies, revealed that the growth estimations were more robust when BAI measurements were used.

An alternative hypothesis for the simultaneous increase in growth observed during the 1990s is the manifestation of a strong recruitment pulse with young stems growing rapidly. However, most individuals showed an increase in radial growth during the 1990s, regardless of their establishment year (see Figures S4–S6). Such synchrony between individuals (or stems) of different ages suggests a generalized growth trend that cannot be solely due to a sudden recruitment pulse. Additionally, as the conversion of the RW into BAI is a simple geometric correction removing the effect of the increasing stem diameter [43], it fails to remove the growth fluctuations related to population dynamics and disturbance. This is not an issue in most Arctic and subarctic environments with low inter-individual competition and disturbance regimes. However, in environments where disturbance and competition affect growth trends, researchers should be aware of the limits of the BAI detrending method.

4.2. Climatic Drivers and Sensitivity to Climate: The Influence of BAI

Ropars et al. [28] found that growth chronologies built from stems instead of root collars resulted in inconsistent climatic drivers of *B. glandulosa* and in reduced climatic sensitivity. As many shrubs species, such as *B. glandulosa*, have a multi-stem growth form, Ropars et al. [28] hypothesized that competition between the stems of a single individual could overshadow at least partially the climatic signal. Under this hypothesis, the available resources for growth might be unevenly allocated to the different parts of a single individual according to a competition-like mechanism [61]. It would thus be possible that all stems do not receive their fair share of resources, a pattern that can lead to differential radial growth between stems for any given year. Nonetheless, we would still expect growth trends in stems and root collars to be influenced by the same climatic variables, which was not the case in Ropars et al. [28].

While intra-plant competition is a potential contributor to the observed differences in the climate–growth relationship between stems and root collars, we showed that the detrending method chosen to remove age/size trends could be another factor to consider. In fact, the correlation between climate and woody species growth is strongly influenced by the detrending procedure applied [31,38,59]. For example, in young chronologies (ca. 22 years old on average), Baral et al. [40] found that the use of splines and negative exponential functions tended to eliminate the climatic signal of RW chronologies. When using a smoothing detrending method for shorter chronologies, the use of shorter time windows tends to eliminate mid- and low-frequency variations, which usually comprise most of the long-term climatic signals [62]. Such a detrending procedure could thus explain the lack of radial growth increase in the mid-1990s in our dataset following standardization with cubic splines (Figures S9–S11). Although detrending by mean-centering data enabled us to preserve the multi-decadal climatic trends, it failed to remove, or even amplified, the asynchronous age/size growth trends, which could cloud the climatic signal and strongly influence the results of such an analysis.

The conversion of raw RW to BAI could solve many of the inconsistencies related to the chosen detrending method. In our study, the use of BAI resulted in greater consistency in the identification of the climatic drivers of *B. glandulosa* growth. Using BAI, the best climatic model combined July temperature and March precipitation, regardless of site or sample type (root collar or stem). Analyzing the Inukjuaq meteorological station data, we found that the July temperature increased by 0.14 °C/year between 1980 and 2009 ($p = 0.002$), while no significative trend was observed between 1947 and 1980 ($p = 1$). Before 2000, March precipitation only increased by 0.25 mm/year, while it increased by 4.1 mm/year after 2000 ($p = 0.003$ and $p = 0.1$, respectively). In addition to corroborating the climatic trends in the regions, such results also corroborate previously published dendroclimatological analyses that revealed the importance of summer temperature and winter precipitation for

shrub growth. In fact, a strong relationship was found between *Empetrum hermaphroditum* radial growth and summer temperature [24], and the growing season temperature was found to be the main driver of growth in nine circumpolar countries [52]. At sites located at high latitudes, warmer summer temperatures contributed to the lengthening of the growing season [10], allowing for the formation of more wood cells and an overall increase in radial growth [63]. Snow precipitation was also found to have a positive impact on shrub radial growth [25]. This is in line with our results, as March precipitation falls as snow in our study region. March precipitation could lead to a deeper snow cover that provides greater protection against freeze–thaw cycles in the spring [64], creates higher water availability at the onset of the growing season, and stimulates soil organic matter decomposition [1,25], all of which have positive effects on primary productivity.

Another notable effect of using BAI is the increased climate sensitivity of the chronologies, regardless of the analyzed shrub part/cross-section type (i.e., root collar or stem). Indeed, in Ropars et al. [28], as well as in our study, RWI chronologies built with stem samples had substantially lower climate sensitivity than those using root collar samples. However, when using the calculated BAI values, our results show that these differences almost disappeared. Thus, the use of BAI appears to be a more robust approach for climate sensitivity analyses at the multi-decadal scale than traditional detrending methods (mean-centering or spline), at least for relatively short *B. glandulosa* growth chronologies. Although we only tested this approach on *B. glandulosa*, we believe that the use of BAI would yield similar results for other erected subarctic shrubs species displaying similar concentric growth rings. Further studies should thus focus on other species and could be expanded to include prostrate shrub species growing in the High Arctic.

5. Conclusions

In this study, we demonstrated that the conversion of the raw ring width (RW) to the basal area increment (BAI) should be favored over mean-centering or spline-fitting detrending methods for the dendroclimatological analysis of multi-decadal growth trends in *Betula glandulosa* growth chronologies spanning decades rather than centuries. When using BAI instead of detrended ring width (RWI), chronologies have stronger and more consistent relationships with climate, especially for stems. Our results support the hypothesis that the standardization of short chronologies using unsuitable detrending methods might be responsible for the observed lower climate sensitivity of stems compared with the root collars. As the climate sensitivity of root collars and stems is similar when BAI is used, the only difference remains in the length of the series, which is longer for root collars than for stems. Otherwise, the time-consuming and destructive process of collecting shrub root collars may no longer be necessary for multi-decadal dendroclimatological analysis, as long as BAI values are used. We showed that the calculation of BAI from raw RW is an accurate estimate of the true basal area increment measured on an image for samples whose rings are mostly circular and concentric.

This study contributes significantly to the fast-developing field of shrub dendrochronology. First, from a logistical perspective, the ability to use stems instead of root collars while still obtaining robust and consistent results greatly simplifies and quickens sampling in the field. Second, the use of BAI instead of RW for shrub stems should allow for a more accurate identification of the climatic drivers of shrub growth and expansion across the Arctic and subarctic. In light of these results and as our study was conducted on only one shrub species (*B. glandulosa*), further studies need to investigate the use of BAI with different species and detrending methods before it is broadly used in shrub dendrochronology.

References

1. Chapin, F.S. Direct and Indirect Effects of Temperature on Arctic Plants. *Polar Biol.* **1983**, *2*, 47–52. [CrossRef]
2. Jia, G.J.; Epstein, H.E.; Walker, D.A. Vegetation Greening in the Canadian Arctic Related to Decadal Warming. *J. Environ. Monit.* **2009**, *11*, 2231–2238. [CrossRef] [PubMed]
3. Vicente-Serrano, S.M.; Martín-Hernández, N.; Camarero, J.J.; Gazol, A.; Sánchez-Salguero, R.; Peña-Gallardo, M.; El Kenawy, A.; Domínguez-Castro, F.; Tomas-Burguera, M.; Gutiérrez, E.; et al. Linking Tree-Ring Growth and Satellite-Derived Gross Primary Growth in Multiple Forest Biomes. Temporal-Scale Matters. *Ecol. Indic.* **2020**, *108*, 105753. [CrossRef]
4. Taiz, L.; Zieger, E.; Moller, I.M.; Murphy, A. *Plant Physiology and Development*, 6th ed.; Sinauer Associates: Sunderland, CT, USA, 2015; 761p.
5. Aerts, R.; Cornelissen, J.H.C.; Dorrepaal, E. Plant Performance in a Warmer World: General Responses of Plants from Cold, Northern Biomes and the Importance of Winter and Spring Events. *Plant Ecol.* **2006**, *182*, 65–77. [CrossRef]
6. Meunier, C.; Sirois, L.; Bégin, Y. Climate and Picea Mariana Seed Maturation Relationships: A Multi-Scale Perspective. *Ecol. Monogr.* **2007**, *77*, 361–376. [CrossRef]
7. Sirois, L.; Bégin, Y.; Parent, J. Female Gametophyte and Embryo Development of Black Spruce along a Shore-Hinterland Climatic Gradient of a Recently Created Reservoir, Northern Quebec. *Can. J. Bot.* **1999**, *77*, 61–69. [CrossRef]
8. Bush, E.; Lemmen, D.S. *Canada's Changing Climate Report*; Gouvernement du Canada: Ottawa, ON, Canada, 2019; 446p.
9. Menzel, A.; Jakobi, G.; Ahas, R.; Scheifinger, H.; Estrella, N. Variations of the Climatological Growing Season (1951–2000) in Germany Compared with Other Countries. *Int. J. Climatol.* **2003**, *23*, 793–812. [CrossRef]
10. Zeng, H.; Jia, G.J.; Epstein, H. Recent Changes in Phenology over the Northern High Latitudes Detected from Multi-Satellite Data. *Environ. Res. Lett.* **2011**, *6*, 045508. [CrossRef]
11. Charron, I. *Élaboration Du Portrait Climatique Régional Du Nunavik*; Ouranos: Montréal, QC, Canada, 2015; 86p.
12. Baird, R.A.; Verbyla, D.; Hollingsworth, T.N. Browning of the Landscape of Interior Alaska Based on 1986–2009 Landsat Sensor NDVI. *Can. J. For. Res.* **2012**, *42*, 1371–1382. [CrossRef]
13. Verbyla, D. The Greening and Browning of Alaska Based on 1982-2003 Satellite Data. *Glob. Ecol. Biogeogr.* **2008**, *17*, 547–555. [CrossRef]
14. Wang, J.A.; Friedl, M.A. The Role of Land Cover Change in Arctic-Boreal Greening and Browning Trends. *Environ. Res. Lett.* **2019**, *14*, 125007. [CrossRef]
15. Bunn, A.G.; Goetz, S.J.; Kimball, J.S.; Zhang, K. Northern High-Latitude Ecosystems Respond to Climate Change. *Eos (Washington DC)* **2007**, *88*, 333–335. [CrossRef]
16. Ju, J.; Masek, J.G. The Vegetation Greenness Trend in Canada and US Alaska from 1984–2012 Landsat Data. *Remote Sens. Environ.* **2016**, *176*, 1–16. [CrossRef]
17. Tape, K.; Sturm, M.; Racine, C. The Evidence for Shrub Expansion in Northern Alaska and the Pan-Arctic. *Glob. Change Biol.* **2006**, *12*, 686–702. [CrossRef]
18. Lemay, M.A.; Provencher-Nolet, L.; Bernier, M.; Lévesque, E.; Boudreau, S. Spatially Explicit Modeling and Prediction of Shrub Cover Increase near Umiujaq, Nunavik. *Ecol. Monogr.* **2018**, *88*, 385–407. [CrossRef]
19. Myers-Smith, I.; Forbes, B.C.; Wilmking, M.; Hallinger, M.; Lantz, T.; Blok, D.; Tape, K.D.; MacIas-Fauria, M.; Sass-Klaassen, U.; Lévesque, E.; et al. Shrub Expansion in Tundra Ecosystems: Dynamics, Impacts and Research Priorities. *Environ. Res. Lett.* **2011**, *6*, 045509. [CrossRef]
20. Ropars, P.; Boudreau, S. Shrub Expansion at the Forest-Tundra Ecotone: Spatial Heterogeneity Linked to Local Topography. *Environ. Res. Lett.* **2012**, *7*, 015501. [CrossRef]
21. Shen, X.; Liu, Y.; Liu, B.; Zhang, J.; Wang, L.; Lu, X.; Jiang, M. Effect of Shrub Encroachment on Land Surface Temperature in Semi-Arid Areas of Temperate Regions of the Northern Hemisphere. *Agric. For. Meteorol.* **2022**, *320*, 108943. [CrossRef]
22. Buras, A.; Wilmking, M. Straight Lines or Eccentric Eggs? A Comparison of Radial and Spatial Ring Width Measurements and Its Implications for Climate Transfer Functions. *Dendrochronologia* **2014**, *32*, 313–326. [CrossRef]
23. Lu, X.; Huang, R.; Wang, Y.; Sigdel, S.R.; Dawadi, B.; Liang, E.; Camarero, J.J. Summer Temperature Drives Radial Growth of Alpine Shrub Willows on the Northeastern Tibetan Plateau. *Arctic Antarct. Alp. Res.* **2016**, *48*, 461–468. [CrossRef]
24. Bär, A.; Pape, R.; Bräuning, A.; Löffler, J. Growth-Ring Variations of Dwarf Shrubs Reflect Regional Climate Signals in Alpine Environments Rather than Topoclimatic Differences. *J. Biogeogr.* **2008**, *35*, 625–636. [CrossRef]
25. Hallinger, M.; Manthey, M.; Wilmking, M. Establishing a Missing Link: Warm Summers and Winter Snow Cover Promote Shrub Expansion into Alpine Tundra in Scandinavia. *New Phytol.* **2010**, *186*, 890–899. [CrossRef]
26. Uyeda, K.A.; Stow, D.A.; O'Leary, J.F.; Tague, C.; Riggan, P.J. Chaparral Growth-Ring Analysis as an Indicator of Stand Biomass Development. *Int. J. Wildl. Fire* **2016**, *25*, 1086–1092. [CrossRef]
27. Weijers, S.; Pape, R.; Löffler, J.; Myers-Smith, I. Contrasting Shrub Species Respond to Early Summer Temperatures Leading to Correspondence of Shrub Growth Patterns. *Environ. Res. Lett.* **2018**, *13*, 034005. [CrossRef]
28. Ropars, P.; Angers-Blondin, S.; Gagnon, M.; Myers-Smith, I.; Lévesque, E.; Boudreau, S. Different Parts, Different Stories: Climate Sensitivity of Growth Is Stronger in Root Collars vs. Stems in Tundra Shrubs. *Glob. Change Biol.* **2017**, *23*, 3281–3291. [CrossRef]
29. Cook, E.; Briffa, K.; Shiyatov, S.; Mazepa, V. Chapter 3.3: Tree-ring standardization and growth-trend estimation. In *Methods of Dendrochronology: Applications in the Environmental Sciences*; Springer Science+Business Media: Berlin, Germany, 1990; pp. 104–123. 394p.

30. Briffa, K.R.; Melvin, T.M. A closer look at regional curve standardization of tree-ring records: Justification of the need, a warning of some pitfalls, and suggested improvements in its application. In *Dendroclimatology: Progress and Prospects*; Springer: Berlin, Germany, 2011; pp. 113–145. 368p.

31. Dietrich, R.; Anand, M. Trees Do Not Always Act Their Age: Size-Deterministic Tree Ring Standardization for Long-Term Trend Estimation in Shade-Tolerant Trees. *Biogeosciences* **2019**, *16*, 4815–4827. [CrossRef]

32. Peters, R.L.; Groenendijk, P.; Vlam, M.; Zuidema, P.A. Detecting Long-Term Growth Trends Using Tree Rings: A Critical Evaluation of Methods. *Glob. Change Biol.* **2015**, *21*, 2040–2054. [CrossRef]

33. Hornbeck, J.W.; Smith, R.B. Documentation of Red Spruce Growth Decline. *Can. J. For. Res.* **1985**, *15*, 1199–1201. [CrossRef]

34. Phipps, R.L. Ring-Width Analysis. In *Air Pollution and the Productivity of the Forest*; Izaak Walton League: Washington, DC, USA, 1984; pp. 225–271.

35. Boakye, E.A.; Houle, D.; Bergeron, Y.; Girardin, M.P.; Drobyshev, I. Insect Defoliation Modulates Influence of Climate on the Growth of Tree Species in the Boreal Mixed Forests of Eastern Canada. *Ecol. Evol.* **2022**, *12*, e8656. [CrossRef] [PubMed]

36. Hornbeck, J.W.; Smith, R.B.; Federer, C.A. Growth Decline in Red Spruce and Balsam Fir Relative to Natural Processes. *Water Air Soil Pollut.* **1986**, *31*, 425–430. [CrossRef]

37. Linares, J.C.; Delgado-Huertas, A.; Camarero, J.J.; Merino, J.; Carreira, J.A. Competition and Drought Limit the Response of Water-Use Efficiency to Rising Atmospheric Carbon Dioxide in the Mediterranean Fir Abies Pinsapo. *Oecologia* **2009**, *161*, 611–624. [CrossRef] [PubMed]

38. Sullivan, P.F.; Pattison, R.R.; Brownlee, A.H.; Cahoon, S.M.P.; Hollingsworth, T.N. Effect of Tree-Ring Detrending Method on Apparent Growth Trends of Black and White Spruce in Interior Alaska. *Environ. Res. Lett.* **2016**, *11*, 114007. [CrossRef]

39. LeBlanc, D.C. Using Tree Rings to Study Forest Decline: An Epidemiological Approach Based on Estimated Annual Wood Volume Increment. In Proceedings of the Tree Rings, Environment and Humanity, Tucson, AZ, USA, 17–21 May 1994; pp. 437–449.

40. Baral, S.; Gaire, N.P.; Aryal, S.; Pandey, M.; Rayamajhi, S.; Vacik, H. Growth Ring Measurements of Shorea Robusta Reveal Responses to Climatic Variation. *Forests* **2019**, *10*, 466. [CrossRef]

41. Bär, A.; Bräuning, A.; Löffler, J. Dendroecology of Dwarf Shrubs in the High Mountains of Norway—A Methodological Approach. *Dendrochronologia* **2006**, *24*, 17–27. [CrossRef]

42. Buchkowski, R.W.; Morris, D.W.; Halliday, W.D.; Dupuch, A.; Morrissette-Boileau, C.; Boudreau, S. Warmer Temperatures Promote Shrub Radial Growth but Not Cover in the Central Canadian Arctic. *Arctic Antarct. Alp. Res.* **2020**, *52*, 582–595. [CrossRef]

43. Le Moullec, M.; Sandal, L.; Grøtan, V.; Buchwal, A.; Hansen, B.B. Climate Synchronises Shrub Growth across a High-Arctic Archipelago: Contrasting Implications of Summer and Winter Warming. *Oikos* **2020**, *129*, 1012–1027. [CrossRef]

44. Ropars, P.; Lévesque, E.; Boudreau, S. How Do Climate and Topography Influence the Greening of the Forest-Tundra Ecotone in Northern Québec? A Dendrochronological Analysis of Betula Glandulosa. *J. Ecol.* **2015**, *103*, 679–690. [CrossRef]

45. Payette, S.; Filion, L.; Delwaide, A. Spatially Explicit Fire-Climate History of the Boreal Forest-Tundra (Eastern Canada) over the Last 2000 Years. *Philos. Trans. R. Soc. B Biol. Sci.* **2008**, *363*, 2301–2316. [CrossRef]

46. Dufour-Tremblay, G.; Boudreau, S. Black Spruce Regeneration at the Treeline Ecotone: Synergistic Impacts of Climate Change and Caribou Activity. *Can. J. For. Res.* **2011**, *41*, 460–468. [CrossRef]

47. Environment Canada Inukjuak Station Monthly Data Report. Available online: https://climat.meteo.gc.ca/climate_data/monthly_data_f.html (accessed on 6 March 2020).

48. Payette, S.; Boudreau, F.; Gagnon, R. Gélifluxion Néoglaciaire Dans Une Combe à Neige à La Limite Des Arbres, Québec Nordique. *Géographie Pysique Quat.* **1985**, *39*, 91–97. [CrossRef]

49. Holmes, R. Computer-Assisted Quality Control in Tree-Ring Dating and Measurement. *Tree-ring Bull.* **1983**, *43*, 69–78.

50. Bunn, A.; Korpela, M.; Franco, B.; Campelo, F.; Mérian, P.; Qeadan, F.; Zang, C. DplR: Dendrochronology Program Library in R. Available online: https://cran.r-project.org/package=dplR (accessed on 10 April 2021).

51. R Core Team R: A Language and Environment for Statistical Computing. Available online: https://www.r-project.org/ (accessed on 3 December 2020).

52. Myers-Smith, I.; Elmendorf, S.C.; Beck, P.S.A.; Wilmking, M.; Hallinger, M.; Blok, D.; Tape, K.D.; Rayback, S.A.; Macias-fauria, M.; Forbes, B.C.; et al. Climate Sensitivity of Shrub Growth across the Tundra Biome. *Nat. Clim. Change* **2015**, *5*, 887–891. [CrossRef]

53. Nakagawa, S.; Schielzeth, H. A General and Simple Method for Obtaining R 2 from Generalized Linear Mixed-Effects Models. *Methods Ecol. Evol.* **2013**, *4*, 133–142. [CrossRef]

54. Visser, H. Note on the Relation between Ring Widths and Basal Area Increments. *For. Sci.* **1995**, *41*, 297–304. [CrossRef]

55. Alfaro-Sánchez, R.; Valdés-Correcher, E.; Espelta, J.M.; Hampe, A.; Bert, D. How Do Social Status and Tree Architecture Influence Radial Growth, Wood Density and Drought Response in Spontaneously Established Oak Forests? *Ann. For. Sci.* **2020**, *77*, 49. [CrossRef]

56. Bouriaud, O.; Bréda, N.; Dupouey, J.L.; Granier, A. Is Ring Width a Reliable Proxy for Stem-Biomass Increment? A Case Study in European Beech. *Can. J. For. Res.* **2005**, *35*, 2920–2933. [CrossRef]

57. Rozenberg, P.; Chauvin, T.; Escobar-Sandoval, M.; Huard, F.; Shishov, V.; Charpentier, J.P.; Sergent, A.S.; Vargas-Hernandez, J.J.; Martinez-Meier, A.; Pâques, L. Climate Warming Differently Affects Larix Decidua Ring Formation at Each End of a French Alps Elevational Gradient. *Ann. For. Sci.* **2020**, *77*, 54. [CrossRef]

58. Biondi, F.; Qeadan, F. A Theory-Driven Approach to Tree-Ring Standardization: Defining the Biological Trend from Expected Basal Area Increment. *Tree-Ring Res.* **2008**, *64*, 81–96. [CrossRef]

59. Nehrbass-Ahles, C.; Babst, F.; Klesse, S.; Nötzli, M.; Bouriaud, O.; Neukom, R.; Dobbertin, M.; Frank, D. The Influence of Sampling Design on Tree-Ring-Based Quantification of Forest Growth. *Glob. Change Biol.* **2014**, *20*, 2867–2885. [CrossRef]

60. Chouinard, C.; Fortier, R.; Mareschal, J.C. Recent Climate Variations in the Subarctic Inferred from Three Borehole Temperature Profiles in Northern Quebec, Canada. *Earth Planet. Sci. Lett.* **2007**, *263*, 355–369. [CrossRef]

61. Sadras, V.O.; Denison, R.F. Do Plant Parts Compete for Resources? An Evolutionary Viewpoint. *New Phytol.* **2009**, *183*, 565–574. [CrossRef] [PubMed]

62. Nicault, A.; Bégin, Y.; Guiot, J. Chapitre 8: Standardisation des séries dendrochronologiques. In *La Dendroécologie: Principes, Méthodes et Applications*; Presse de l'Université Laval: Québec City, QC, Canada, 2010; pp. 199–228.

63. Deslauriers, A.; Rossi, S.; Morin, H. Chapitre 3: Analyse et développement intraannuel des cernes de croissance. In *La Dendroécologie: Principes, Méthodes et Applications*; Presse de l'Université Laval: Québec City, QC, Canada, 2010; pp. 61–92.

64. Bokhorst, S.F.; Bjerke, J.W.; Tømmervik, H.; Callaghan, T.V.; Phoenix, G.K. Winter Warming Events Damage Sub-Arctic Vegetation: Consistent Evidence from an Experimental Manipulation and a Natural Event. *J. Ecol.* **2009**, *97*, 1408–1415. [CrossRef]