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Article

Climatic Signals on Growth Ring Variation in *Salix herbacea*: Comparing Two Contrasting Sites in Iceland

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Abstract: *Salix herbacea*, being such an adaptive species, has never been studied for its climatic response. The main purpose of this study is to examine the dendrochronological potential of *S. herbacea*. Furthermore, it aims to identify the main environmental factors that are influencing its growth. We selected two sampling sites that are different in terms of morphology and climate. Overall, 40 samples of dwarf willow were collected from two research sites and were analyzed by following the standard dendrochronological methods. The ring width chronology of the dwarf willow from the Afrétt site spans 1953–2017, i.e., 64 years. The correlations between air temperature and the ring width of dwarf willow indicate that this species responds positively to spring and summer temperatures for the Myrdal site. For the Afrétt site, this species responds positively to winter and summer precipitation. These effects may be related to tundra browning, a process that has appeared since the beginning of the 21st century. Our work is the first attempt to create a growth ring chronology of *S. herbacea* and to investigate its climate sensitivity. Despite the differences in local climate in both sites, this species shows its potentiality and a direct imprint of recent environmental changes in its ring width growth pattern.

Keywords: Iceland; arctic; *Salix herbacea*; dendrochronology; climate; drought stress

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1. Introduction

Arctic terrestrial ecosystems are immensely sensitive to modern climate variations and they reflect the effects of changes in air temperature, precipitation, snow cover, permafrost, active geomorphic processes, and the intensity of wildfires. During recent decades, large-scale warming in the Arctic has accelerated and is now occurring at a two-fold rate of the global trend [1]. However, the climatic and inter-annual weather conditions in the Arctic vary dimensionally, as well as the dynamics of biological, biogeochemical, and geomorphic processes in terrestrial ecosystems [2–4]. Climate change has placed plants and animals at high risk, particularly in alpine and Arctic habitats [5–7]. Moreover, due to such radical environmental changes, plants cannot migrate to a new place as easily as animals. The alpine habitat is characterized by severe environments, such as high wind exposure and long winters, which lead to limited nutrient resources. The interactions between wind and topography also create irregularities in the winter snow distribution, resulting in microhabitats with different snow melting times. Global warming is expected to lead to longer growing seasons and lower snow cover in ridge microhabitats. Hence, the ring widths of trees/shrubs comprise the backbone of high-resolution, terrestrial paleoclimatology [8]. Information regarding the growth of trees/shrubs and their response to climatic and environmental factors would be potentially useful. They provide information on the present and past environment and for understanding the variability of climate and other environmental factors, particularly in areas where tree growth is sensitive to limiting climatic factors [9].

Shrub communities are expanding and their growth is also increasing as a response to climate change, and this is occurring at an unprecedented rate in many tundra ecosystems [10,11]. Moreover, they represent a major component of groundcover in the Arctic and alpine tundra; therefore, it becomes very important to understand the effects of climate change on dwarf shrubs and their capacity to respond to environmental changes. Tundra plants growing in Arctic environments are very sensitive to climatic conditions and thus specifically useful for dendroclimatic investigations [12–19]. However, researchers have observed, particularly in recent years, an increase in the environmental importance of Arctic dendrochronology research and studies on complex plant responses to changing environmental conditions [14,16,18,20–25]. Earlier dendroclimatological studies indicated that shrub growth rates were positively sensitive to summer temperatures for most species and at most of the sites [20,26]. However, recent studies of dendroclimatology show that shrub growth/climate relationships are not uniform across the tundra biome [17,21,27]. Thus, these studies conclude that there is still a need to analyze some other species and generate their relations with different climatic parameters in unexplored sites.

Dendrochronological research in Iceland has been limited, probably due to the lack of old trees and tree species that are considered suitable for ring width studies. However, recently, some studies have been carried out on the climate response of some tree species, such as Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and lodgepole pine (*Pinus contorta* Daugl. var. contorta). Both species have shown a good correlation with spring and summer temperatures [28]. Dendroclimatological studies have also been carried out on birch (*Betula pubescens* Ehrh.) in Baejarstadarskogur in Southern Iceland, which showed a strong correlation with the average summer (June–August) temperature [29]. Meanwhile, with the spatial distribution of *Salicaceae* shrubs in the northernmost regions of the Arctic, regional variability in climatic controls on this genus' growth can be assessed. This is further relevant for assessing Salix dwarf shrub's potential and role in future snow redistribution, geomorphic processes' activity, water balance, permafrost thaw, and nutrient availability [10,30], particularly in the most extreme and climatically diverse High Arctic ecosystems. However, up to the present date, no dendroclimatological studies have been implemented for *Salix herbacea* species.

Therefore, in this study, the dwarf shrub *Salix herbacea* L. (dwarf willow) was analyzed. *Salix herbacea* is well distributed in the Arctic areas, as in northern regions of Europe, Western Siberia, and North America, and also in the mountainous regions of Central Europe, e.g., the Alps [5–7,31]. *Salix herbacea* is regarded as an optimal species for studying the effect of climate change in the Arctic and alpine tundra due to its ecological characteristics and the Arctic–alpine distribution range [32–34]. *Salix herbacea* is commonly found in snow beds and also occurs on wind-exposed mountain ridges and screes, where snow cover disappears early in the spring [6]. *Salix herbacea* has been found at a maximum age of 43 years using dendrochronology [35]. However, the highest age reported for *S. herbacea* was determined by using some different methods. In a study done by [36], the clone age of *S. herbacea* was estimated to be at least 450 years by using some calculation of clones, while most other individuals were less than 100 years old. However, being such an adaptive species in such diverse environments and climatic conditions, its climatic response has never been generated. The main objective of this study was therefore to examine the dendrochronological potential of *Salix herbacea* at two climatologically contrasting sites in Iceland. Furthermore, we wanted to identify the main environmental factors that are influencing its growth. The research questions we examined were: (a) Is it possible to construct *Salix herbacea* chronology? and, if so, (b) How does this species respond to the climatic parameters? We hypothesized that specimens from sites with varying amounts of rainfall will potentially differ in dendroclimatic sensitivity. We here assess the potential influence of varying site conditions on growth rings by analyzing climate signals and growth trends of dwarf willow collected in northernmost and southernmost located sites, which is important to further estimate the potential of this species for studies of past climatic conditions.

2. Materials and Methods

2.1. Study Area

Two sampling sites were chosen for detailed research that are different in terms of morphology and climatic conditions (Figure 1A). The Mýrdal site (Figure 1B) is located in the southern part of Iceland, south of the Mýrdalsjökull ice cup. The landscape is dominated by ridges and plateaus built of Upper Pleistocene (younger than 0.8 Ma) hyaloclastite, pillow lava, and associated sediments and belongs to the Móberg Formation [37]. These subglacially and intraglacially created landforms are currently being intensively eroded, especially in its eastern part at the Mýrdalssandur edge. This part of Iceland receives a large amount of precipitation (2363 mm/year) and is relatively warm (avg. 5.5 °C) (Figure 1B).

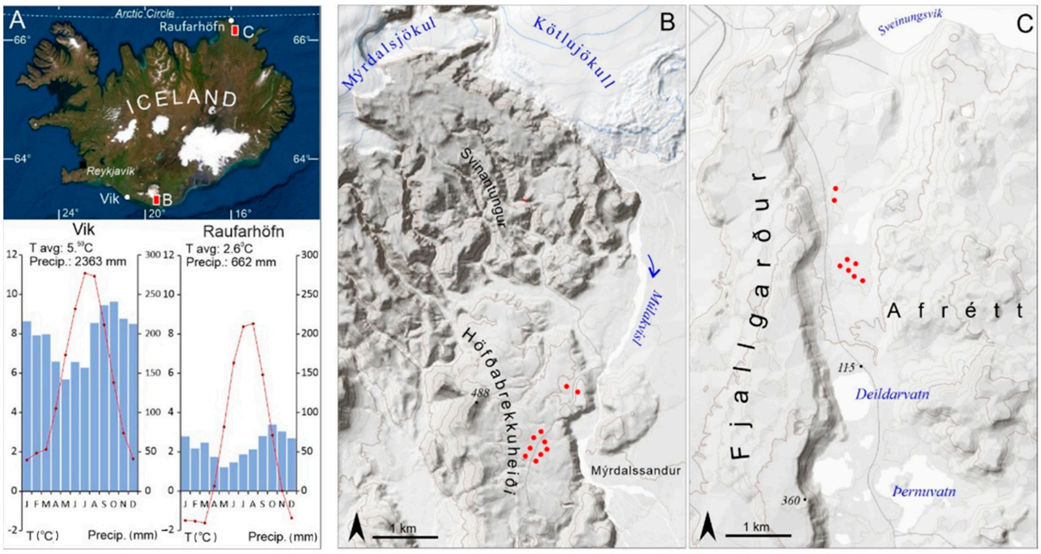

Figure 1. (**A**) Location of the study areas and meteorological stations with climatographs from Southern (Vik) and Northeastern (Raufarhöfn) Iceland; detailed locations (red points) of sampling sites at (**B**) the Mýrdal site and (**C**) the Afrétt site (source of background maps: National Land Survey of Iceland, https://www.lmi.is/, accessed on 15 November 2021).

The Afrétt site (Figure 1C) is located in the northeastern part of Iceland in a hilly volcanic upland, on the northeastern edge of the Þistilfjörður fjord. The landscape is dominated by dome-shaped eroded hills of a maximum height of 334 m a.s.l. (Selfjöll) cut by deep river valleys. The eastern and central part of the upland is built of Upper Pliocene and Lower Pleistocene (0.8–3.3 Ma) basaltic lavas [38]. The Afrétt Upland is widely varied—dry, hummocky terrain that is actively undergoing solifluction. Erosion forms associated with severe soil degradation are a typical feature of the landscape [39–41]. This area is one of the driest (658 mm/year) and coldest (avg. 2.6 °C) parts of the country (Figure 1C).

Based on the phytogeographical and ecological data, Iceland may be recognized as a region located in the Arctic and sub-Arctic zone [42–44]. Moreover, its climate is firmly controlled by different atmospheric circulation patterns and dynamics in oceanic current and sea ice extent [29,45,46]. Due to the influence of the warm North Atlantic Current, the climate in Iceland is not as cold as we would expect from the high latitude.

Vegetation cover in Iceland represents less than one fifth of its area; the rest of the country consists of barren mountains, deserts, and glaciers. Arctic–alpine tundra, dominated by dwarf shrubs, is the predominant vegetation in Iceland. Most of the land surface at the study sites is sparsely vegetated or un-vegetated. North Atlantic boreo-alpine heath and Icelandic lichen *Racomitrium* heath communities occur in lower-elevation areas, depressions, and valleys. Arctic dwarf shrubs, such as dwarf willow (*Salix herbacea* L.), mountain avens (*Dryas octopetala* L.), and crowberry (*Empetrum nigrum* L.), are common in these habitats.

All of these habitats are in various stages of degradation, from small openings to bare patches [47].

2.2. Field Sampling

Salix herbacea, commonly growing with other species such as *Salix arctica* (Afrétt site) and *Dryas octopetala* (Mýrdal site), were used in this study. Vegetation cover is not dense and ranges from 30 to 50%, and is characterized by patches of varying size, often forming isolated covers. The samples of *Salix herbacea* were collected from the elevation 90–105 m a.s.l. (Afrétt) (Figure 2A) and 250–270 m a.s.l. (Mýrdal). This plant is a deciduous, prostrate, creeping dwarf shrub, usually less than 15 cm tall. Branches of *S. herbacea* are dense, often forming mats or small pillows. Complete individuals of *S. herbacea*, including exposed roots, root collars, and branches (Figure 2B), were collected in 2017. Overall, 40 samples of dwarf willow were collected from the two research sites.

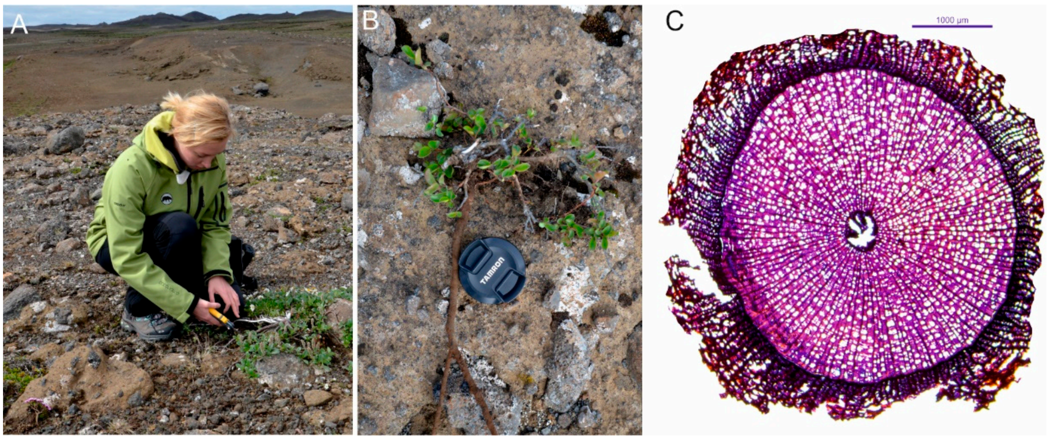

Figure 2. (**A**) Polar willow sampling in the Afrétt site, Northeastern Iceland; (**B**) dwarf willow specimen containing the root, root collar, and wooden branches collected for laboratory analysis; (**C**) example of a microscopic cross-section of dwarf willow.

2.3. Microscopic Preparation

We used microscopic techniques adapted to the specificity of dwarf shrubs [27,48–50]. In correspondence to the serial sectioning technique, sampling and measurement of cross-sections were performed at several locations below and above ground on the same individual, implementing the proper age determination and more accurate growth chronology construction [14,51]. This sectioning procedure consists of the extraction of 1-cm-long fragments from the main root and up to two main aboveground shoots at a mean distance of 2–3 cm from each other. In the field, the bent or injured shrub parts were not sectioned. In the further steps, microscopic slides were prepared by following the standard procedures used for dwarf shrub preparation [35,48].

Before cross-sectioning, the samples were soaked in water to rehydrate desiccated tissue. From each plant sample, a thin section of around 15–20 µm in thickness was cut with a sledge GSL1-microtome, and later on, it was stained by a mixture of Safranin and Astra Blue [52]. This was done to highlight lignified and un-lignified tissues, as well as to enable the identification of narrow and irregular ring boundaries. Hence, these staining solutions further enhance the contrast between cell walls and lumens. In total, 125 stained micro-slides were prepared from the samples of Iceland.

2.4. Growth Ring Measurements

For measuring the growth rings in the prepared micro cross-sections, digitalized photographs were taken (Figure 2C). The photographs of each sample were taken from each micro-slide under 10× magnification for regular cross-sections and under 20 × 20 magnification for irregular individuals. This enabled the detection and measurement of narrow growth rings either directly under a light microscope or from digital images taken from the sections. This all was performed using a Leica FLEXACAM C1 camera connected to a Leica DM1000LED microscope. Then, all the individual images for each micro-slide were stitched together in Adobe Photoshop (Adobe Systems Incorporated, San Jose, CA, USA) to form a single high-resolution image for the cross-section, required for accurate annual ring border recognition and ring width measurements.

Measurements were done along multiple radii extending from the center of the stem cross-section towards the cambium to account for growth irregularities. However, due to a large number of wedging and missing rings, at least two radii were measured for each micro-section under visual control, using the WinDENDRO tree-ring measuring system [53]. Therefore, in our analysis, based on the clear visibility of ring widths in the prepared micro-slides, we took a minimum of two and a maximum of 4 measurements from each slide. Then, all radii from one disc were cross-dated to assign the correct calendar year to each ring based on the matching patterns of ring development before being further analyzed [9,54].

2.5. Cross-Dating and Chronology Development

All the growth ring measurements were visually cross-dated and then they were tested statistically by using COFECHA software [55]. Moreover, all the poor-quality samples with a large number of missing rings, significant eccentricity, numerous wedging rings, scars, or visible reaction wood were excluded from further analyses. The cross-dating of the tree ring series was carried out in two parts: a visual comparison of the series in the form of line graphs in TSAPWin, and performing a statistical comparison in COFECHA to verify the accuracy of the visual cross-dating [56].

Cross-dating of raw ring width measurements of the *Salix herbacea* shrub species was performed. Firstly, the radial measurement series were cross-dated within cross-sections. This was augmented by a careful visual inspection of irregular and partially missing rings within a complete cross-section. Moreover, quality control was applied using the COFECHA program to check for measuring mistakes [57]. If necessary, some measurements were repeated and re-checked with COFECHA and removed from further processing if recognized as unusable.

2.6. Data Standardization

Raw growth ring width measurements after cross-dating were standardized to remove all noise from datasets, including the possible non-climatic age-related and/or biologically induced growth trends. To evaluate the climate–growth responses of shrubs completely, the chronology was standardized. As some samples did not present any apparent age-related growth trend, we, therefore, applied individual series standardization including linear regression and horizontal means, with the choice of function based on the best fit for each series, as an approach that is commonly used in dwarf shrub detrending [27,58]. Well correlated with each other ($r > 0.4$), individual radial growth curves were then transformed into the dimensionless ring width indices as ratios, averaged, and a pre-whitened overall site chronology was constructed for subsequent analyses.

2.7. Climate Data and Analysis of Climate–Growth Responses

Meteorological data from four stations with long-term monthly temperature and precipitation records were obtained from the Veðurstofa Íslands (Icelandic Meteorological Office) and Rif Field Station, Icelandic Arctic Cooperation Network (Table 1). The Kirkjubæjarklaustur and Vík í Mýrdal stations were located near the southern dendrochronological site, Mýrdal; stations Raufarhöfn and Akureyri were located near the Afrétt site in Northeastern Iceland (Figure 1A). For dendroclimatological analysis, the common period 1961–2013 was used. Pearson's correlation analyses were used to explore the climate–growth relationships. A 95% confidence level criterion was used to determine the statistical significance of the correlations. The ring width chronologies were compared with a 15-month window of climate data spanning the period from May of the previous year through July of the current growing season. Due to insignificant results, only the results for the current year are presented in the text.

Table 1. General information on selected long-term climatological data (mean monthly temperature and monthly precipitation totals) used in the studies.

No.	Station Name	Station Code	Location	Coordinates	Elevation	Distance to the Sampling Site	Timespan
1	Kirkjubæjarklaustur	722	S Iceland	63.79° N, 18.05° W	42 m a.s.l.	51.0 km	1930–2013
2	Vík í Mýrdal	798	S Iceland	63.42° N, 19.01° W	31 m a.s.l.	11.7 km	1961–2013
3	Raufarhöfn	505	NE Iceland	66.45° N, 15.95° W	4 m a.s.l.	12.5 km	1931–2021
4	Akureyri	422	NE Iceland	65.68° N, 18.09° W	23 m a.s.l.	122.5 km	1949–2021

3. Results

3.1. Chronology Development

Salix herbacea sampled in Iceland has well-defined and distinct visible growth rings whose average width ranges from 50 to 250 µm (Figure 3A). The borders between growth rings are highlighted by two to three rows of flattened cells and additionally by larger groups of vessels (Figure 3B). These anatomical features have allowed the construction of dendrochronological scales for this species.

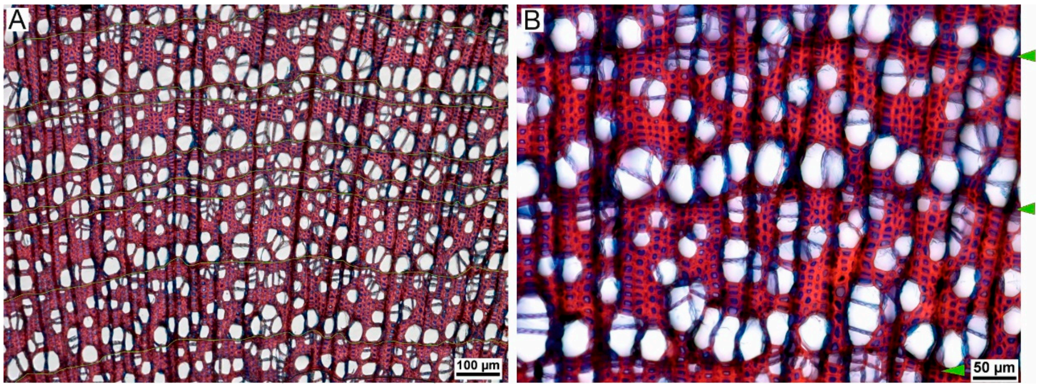

Figure 3. (**A**) Example of growth ring variations of *Salix herbacea* sampled; (**B**) detailed microscopic image showing distinct rings and semi-ring porous wood structure of *S. herbacea*.

From a total of 40 samples that were collected in July 2017 from the two sites with different climatic regimes in Iceland, 30 were included in the chronologies and used for further analysis (Table 2). The remaining sequences were removed due to a large number of missing rings and due to a very low correlation resulting from growth disturbances related to non-climatic factors, such as periglacial processes activity, erosion, and animal grazing. All the included cross-sections were subjected to a proper calendar dating of this woody material. This would not be possible without serial sectioning and cross-dating between the ring growth of different parts of the plant. Hence, this step validates the complete detection of growth rings and shrub dendrochronological dating.

Table 2. Dwarf willow sites sampled in Iceland and corresponding chronology information.

Parameter/Site	Mýrdal	Afrétt
Number of samples (sampled/cross-dated)	20/12	20/18
Correlation between samples	0.47	0.48
Mean measurement (mm)	32.59	32.72
Mean sensitivity	0.36	0.34
First year	1965	1953
Last year	2016	2016
Coefficient of variation: before/after 1990	26.77/13.90	24.02/19.36
Standard deviation: before/after 1990	0.26/0.13	0.27/0.17
Trend per decade: entire chronology/after 1990	−0.02/−0.02 *	−0.06/−0.18 **

* statistically insignificant, ** $p < 0.001$.

The oldest individuals of *S. herbacea* that were used in the chronology construction were 64 years old. The dwarf willow chronology from the Mýrdal research site spans 55 years, with the longest specimen having 61 years (Figure 4A). The ring width chronology of the dwarf willow from the Afrétt research site spans the period 1953–2017, i.e., 64 years (Figure 4B). A noticeable growth ring fluctuation is observed in the 1960s and 1970s. It is also confirmed by the calculated measures of dispersion. Standard deviation and coefficient of variation are significantly higher in the early part of the chronology (Table 2). After this period, systematically decreasing growth ring widths are visible, especially distinct after 2002 in the Afrétt chronology. At this site, a significant negative trend is observed in the dendrochronological data (Table 2). The high fluctuations in the very beginning are the reason for the smaller sample size, but the declining trend in the previous decade may be the imprint of recent environmental changes.

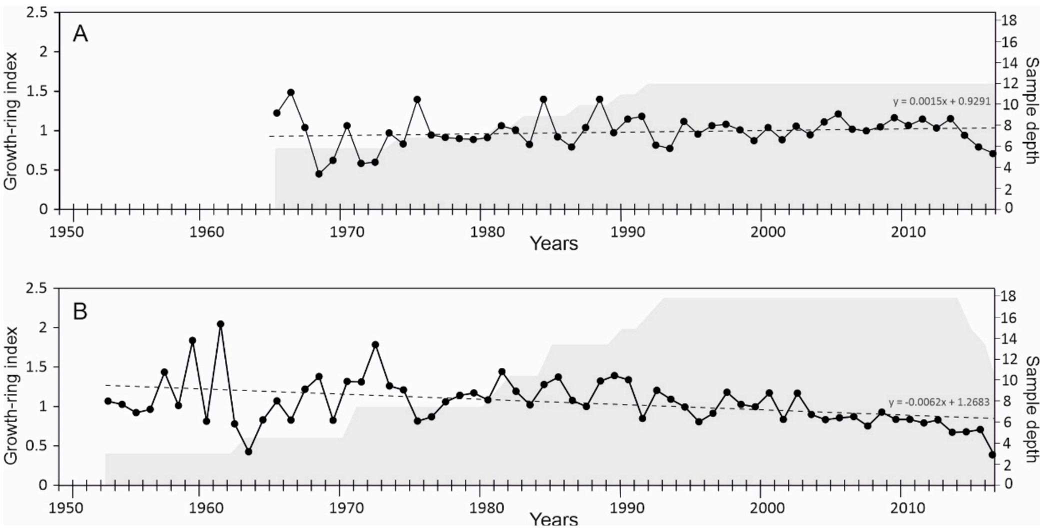

Figure 4. Indexed growth ring chronologies of dwarf willow from (**A**) the Mýrdal site and (**B**) the Afrétt site.

3.2. Correlation Analysis

The dendroclimatic correlations between air temperature and the ring width of dwarf willow indicate that this species positively responds to spring and summer temperatures (Figure 5A) for the Myrdal site. The radial growth of the dwarf willow from the investigated site of Myrdal responds strongly to March temperatures (r = 0.52 for Vík í Mýrdal station, r = 0.49 for the Kirkjubæjarklaustur station) and also shows a statistically significantly positive correlation with the mean temperatures of May (r = 0.37 and r = 0.30, respectively, $p < 0.05$) and July (r = 0.40 and r = 0.39, respectively, $p < 0.05$). Hence, there is a strong influence of spring–summer temperature on the variability of growth of this species

(r_{MAMJJ} = 0.49 for both meteorological stations). In general, no positive correlations with precipitation were found for the Myrdal site (Figure 5B). In fact, for June, even a negative correlation is noticeable (r = −0.33, $p < 0.05$ for Vík í Mýrdal station). The other months are not significant but, following the response function of June, August, and September, are also showing negative responses with precipitation. Hence, as this site is highly precipitated, thus, with an increase in precipitation, the growth does not respond well or it declines. No significant relationships with the climatic conditions of the previous year were found (Figure 5A,B).

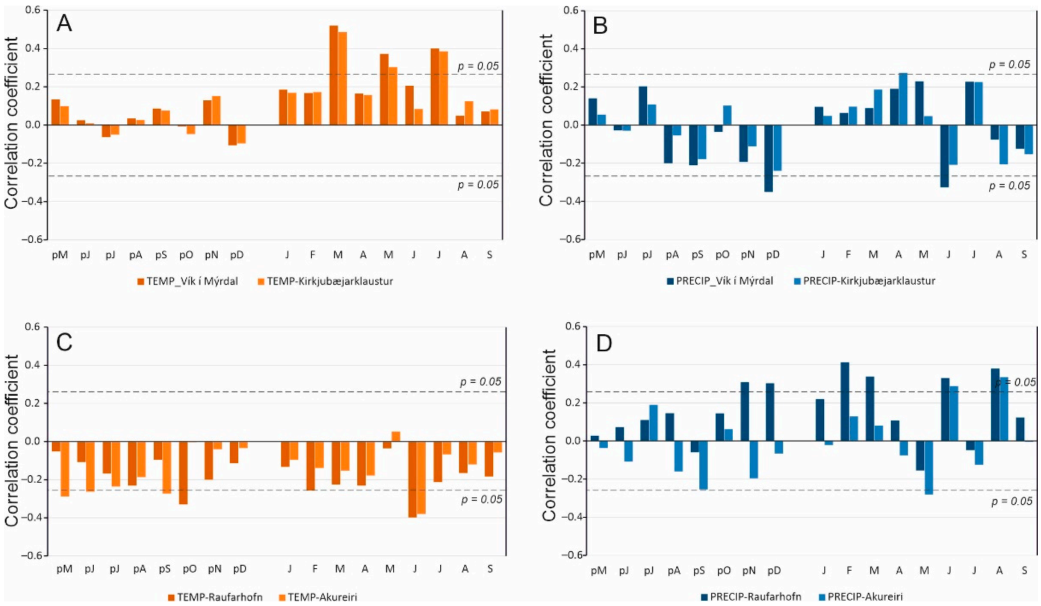

Figure 5. Correlation coefficients of growth ring data at two contrasting sites, Mýrdal (**A**,**B**) and Afrétt (**C**,**D**), to mean temperature and monthly precipitation totals from different meteorological stations.

For the Afrétt site, the climate–growth correlations between climate indices and ring width indicate that this species positively responds to winter (r_{JFM} = 0.46) and summer (r_{JJA} = 0.41) precipitation. High correlations were also calculated for seasonal sums of precipitation noted at the Raufarhöfn station from October of the previous year to March of the current year (r = 0.50). The highest positive correlation with a single month was obtained with February (r = 0.41 for the Raufarhöfn station), followed by March, June, and August precipitation (Figure 5D). Hence, the area is so dry annually that an increase in precipitation favors the growth of this species. Higher correlation values for the Raufarhöfn station result from its closer location to the Afrétt site (Table 1). The measurements from the Raufarhöfn station better reflect the local differentiation of rainfall conditions than Akureiri, which is located at a distance above 100 km. Meanwhile, no highly significant relation is found with the mean temperature apart from the negative correlation with the June temperature (r = −0.40 for Raufarhöfn station and r = −0.39 for Akureyri station), an indication of drought stress at this site (Figure 5C). A negative correlation was also shown for the period from August of the previous year to July of the current year (r = 0.36 for Raufarhöfn station). As this area is the driest, with an increase in warm conditions, the growth is affected inversely.

4. Discussion

The paper outlines the applicability of a new species in dendrochronology and its potential in the analysis of the Arctic environmental change. *Salix herbacea* has not yet been analyzed to date for its climatic response, while the shrubs of the Willow genus, such as *Salix arctica* [59–61], *Salix alaxensis* [62], *Salix polaris* [16,17,20,22,30], and *Salix uva-ursi* [15], have been widely used as a source of reliable climatic and environmental information for several years. *Salix herbacea* has visible growth ring boundaries that are measurable and correlated to a relatively high degree with climatic variables, allowing this species to be treated as a reliable source of environmental data. Even while growing in extreme site conditions, this studied species has centric and slight eccentric pith positions [63]. Hence, being the smallest woody plant, it attracts attention for several reasons.

Thus far, dendrochronological studies in Iceland have not been numerous, which is related to the extent of the forest cover [64]. Existing dendroclimatological results are limited to the native Iceland tree species, *Betula pubescens* and *Sorbus aucuparia*, from relatively isolated areas. Constructed tree ring chronologies show spring and summer temperature signals, with the maximum length of the records being approximately 130 years [28,29,65–67]. Other studies used dendrochronology for dating geomorphological processes [68], driftwood [69], and volcano eruption [70].

No studies, however, have targeted dwarf shrubs from Iceland as a paleoenvironmental archive. The results of our investigation fill this research gap. Our work is the first attempt to create a growth ring chronology of *Salix herbacea* and to investigate its climate sensitivity. Unlike the results of dendrochronological analyses of tree species from Iceland, *S. herbacea* reflects not only regional temperature signals, but also site-specific microclimatic conditions. This is particularly evident in the dry site in the northeastern part of Iceland. Similar observations, indicating the influence of microsite conditions on differences in the climate–growth response, were made for *Empetrum hermaphroditum*, *Salix glauca*, *Betula nana*, and *Betula pubescens* from the Low Arctic; however, the common growth pattern was reflected at all analyzed microsites [58,71,72]. The analysis of the isotopic composition and tree ring width data of pine from moist and dry microsites in Scandinavia revealed differences in climatic signal strength [73,74].

In the present study, we determined a positive correlation with precipitation during the growing season, which may indicate drought and water deficiency in the soil. This effect may be related to tundra browning, the process that appeared at the beginning of the 21st century, when narrow growth rings became dominant. Such a phenomenon was observed in the Afrétt chronology from 2004. A similar hypothesis was developed and confirmed in multidisciplinary work conducted in the area of Hornsund, SW Spitsbergen [22], and Bear Island [17]. The recent increased interest in Arctic dendrochronology is connected not only with a simple indication that shrub records can track recent temperature warming [20,26,75], but studies on the complex response of tundra plants to changing environmental conditions [14,16,22,25,49]. Direct dendrochronological research from sites with different microclimatic conditions is still needed, as for the correct assessment of climate change-induced shifts in hydrothermal conditions resulting in the transition from tundra greening to browning. Attention should also be paid to processes that can significantly disturb the climate signal recorded in annual rings of Icelandic dwarf shrubs. Volcanic soils and vegetation cover in Iceland are very sensitive to disturbance. Soil erosion and the destruction of vegetation and the root systems of dwarf shrubs are common in Iceland [39,40] and may affect the non-climatic variability of annual growth. Additionally, desertification of large parts of the island has contributed to increased dust storm activity [76,77], which may result in a reduction in annual growth due to dust-covered leaf blades.

5. Conclusions

This study presents the first comparison of the radial growth chronologies of dwarf willow shrubs from two different climate regime sites of the sub-Arctic region. Despite the differences in local climates in both studied sites, this species shows its potential with the recent environmental changes. The studied dwarf shrub *Salix herbacea* is a particularly valuable indicator of drought, which is the case for the dry site in Northeastern Iceland.

Through the application of shrub sampling across a relatively large area, supplemented by serial sectioning and careful detection of locally and completely missing rings, we were able to successfully cross-date species of Arctic shrubs with high environmental potential from two different and contrasting sites in the High Arctic. We suggest that the extension of the chronology lengths and the associated climatic signals is possible through more extensive fieldwork and by increasing the sample size of the species *Salix herbacea*, also from the northernmost polar areas. Moreover, this species shows a direct imprint of recent environmental changes in its ring width growth pattern. Thus, it will be a major tool to understand the recent changes in the environment and will also fill the gap in high-resolution in situ climate data. Thus far, the future research possibilities have increased in various aspects. As this study focused on the response to temperature and precipitation, it also indicates the potential to explore responses with other available environmental datasets. It also shows a need to highlight the main anatomical features that are observed, as these features will be a major representative of other species that are growing in such harsh environments.

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