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ASSESSING TREE RING TO CLIMATE ASSOCIATIONS: A COMPARISON BETWEEN NATIVE (*Betula pubescens* and *Sorbus aucuparia*) AND EXOTIC SPECIES (*Picea sitchensis*, *Pinus contorta* and *Picea abies*) IN ICELAND

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ABSTRACT

Climate change, which has reached unprecedented levels in recent years, is having clear effects on global ecosystems, and many species are forced to migrate northward to survive global warming. Nowadays, however, the climate is changing rapidly, bringing several species to the extinction risk.

The purpose of this thesis is to study the climate response of several tree species. The study was conducted in Iceland: at this latitude climate conditions are rather limiting for tree growth. Five species were analysed: two native broadleaves (*Betula pubescens* and *Sorbus aucuparia*) and three imported conifers (*Picea abies*, *Picea sitchensis* and *Pinus contorta*). The aim is to examine the association between annual growth and climate in a context where temperature is a strongly limiting factor for growth, both for native and exotic species that have been introduced beyond the limit of their range.

All the analyzed species show a large positive correlation with temperatures during the summer period, confirming the key role of temperatures in heat-limited environments. On the other side, precipitation, which is relatively abundant on the island, does not seem to have a particular effect on growth.

These results suggest that in the Icelandic context at the moment global warming seems not having negative effects on tree growth, and respect to other areas of the globe where summers are becoming extremely hot and dry, in Iceland the increase in temperatures during the summer period might be positive, both for the native and exotic species. The results of this thesis can be useful for understanding the behavior of species in the context of current climate change and hypothesizing its future trend.

RIASSUNTO

Il cambiamento climatico, che negli ultimi anni ha raggiunto valori senza precedenti, sta avendo evidenti effetti sugli ecosistemi a livello globale e molte specie si trovano costrette a migrare verso nord per sopravvivere. Il clima al giorno d'oggi sta, però, cambiando molto rapidamente comportando per diverse specie anche il rischio d'estinzione.

Lo scopo di questo elaborato è studiare la risposta al clima di alcune specie arboree. Lo studio è stato condotto in Islanda: a tali latitudini le condizioni climatiche sono piuttosto limitanti per la crescita degli alberi. Sono state analizzate cinque specie, due latifoglie native (*Betula pubescens* e *Sorbus aucuparia*) e tre conifere importate (*Picea abies*, *Picea sitchensis* e *Pinus contorta*). L'obiettivo è quello di esaminare le relazioni tra crescita annuale e clima in un contesto in cui la temperatura è un fattore fortemente limitante sia per le specie native che per quelle aliene.

Tutti i taxa mostrano una correlazione positiva con le temperature durante il periodo estivo, confermando che temperature più miti favoriscono gli accrescimenti delle specie arboree in luoghi dove la temperatura è effettivamente un fattore limitante. Al contrario le precipitazioni, che sono relativamente abbondanti sull'isola, non sembrano avere nel complesso particolarmente effetto.

I risultati ottenuti fanno ipotizzare che, al momento, nel contesto islandese il riscaldamento globale non stia producendo effetti negativi sulle specie arboree, ma al contrario di quanto sta avvenendo in altre aree del pianeta in cui le estati stanno diventando estremamente calde e aride, in Islanda l'aumento delle temperature sta evidenziando effetti positivi sulla crescita, sia per quanto riguarda le specie native sia per quelle esotiche. Le osservazioni effettuate in questa ricerca possono essere utili per comprendere il comportamento delle specie nel contesto del cambiamento climatico corrente e ipotizzarne possibili traiettorie future.

1. INTRODUCTION

Nowadays we are increasingly witnessing the effects of human activities on climate system. As reported by the IPCC in the Sixth Assessment Report on climate change (2022), anthropogenic greenhouse gas emissions have increased since the pre-industrial era driven largely by economic and population growth. Anthropogenic climate change has exposed ecosystems to conditions that are unprecedented over millennia. Models suggest that warming of the climate system is unequivocal (IPCC, 2022), and since the 1950s, many of the observed changes are unprecedented over decades to millennia: greenhouse gases emissions resulted in a global mean surface warming likely to be about 0.87°C from the preindustrial levels to the decade 2006–2015 (IPCC, 2018), with further contributions from other anthropogenic forcings. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen. According to experiments, observations and models that are used to estimate future impacts and risks, prolonged emission of greenhouse gases will cause further warming of continental surface and oceans over the 21st century, long-lasting changes in all components of the climate system, increasing the likelihood of severe and irreversible impacts for people and ecosystems; global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. Such alterations imply mostly negative impacts for biodiversity, ecosystem services and economic development and amplify risks for livelihoods and for food and human security (IPCC, 2022).

Worldwide, forests are strongly affected by climate change: according to IPCC (2022) warmer and drier conditions have increased tree mortality and forest disturbances in many temperate and boreal biomes; a large amount of species is facing increased extinction risk, especially when climate change interacts with other stressors, such as the modification of ecosystems by humans (IPCC, 2022); short-term warming will continue to interfere with plants and animals' phenology. Trees, as many other organisms, will need to shift their geographic range to track climate change moving northward (IPCC, 2022; Taggart & Cross, 2009). However, the pace of actual climate changes is much faster than any other change that occurred in the past (Leech et al., 2011; Malcolm et al., 2002) and plant species will likely struggle to shift their geographical ranges fast enough to track current and projected rates of climate change in most landscapes (Taggart & Cross, 2009).

Some of the world's forest ecosystems are already showing contrasting responses to climate change and forests might become more and more vulnerable to future warming and drought, even in environments that are not normally considered moisture-limited (Craig et al., 2010). However, it is important to point out that the effects of climate change on forests (even if just in the short term and for some species) can include both positive (e.g. increases in forest vigor and growth from CO_2 fertilization, increased water use efficiency, and longer growing seasons) and negative effects (e.g. reduced growth and increases in stress and mortality) (Bachelet et al., 2003; Craig et al., 2010; Scholze et al., 2006).

Since physiological adaptations and growing strategies of different species have resulted in considerable differences in response to past climatic variability (Cook et al., 2001), we can assess the influence of future climatic changes on forest growth only if species-specific responses are well understood (Friedrichs et al., 2009). Furthermore, information regarding tree growth and its relationship with climatic and environmental factors can be useful to provide information on present and past growing conditions and to understand the variability of climate and other factors over time (Fritts, 1976).

Since trees record any environmental factor that directly or indirectly limits a process that affects the growth of ring structures from one season to the next, they can be a useful monitor for a variety of events: the discipline of dendrochronology examines events through time that are recorded in the tree-ring structure or can be dated by tree rings (Speer, 2010).

1.1. Dendrochronology and tree growth

Dendrochronology is a discipline that uses tree rings for dating past events and reconstructing past environmental conditions (Dean, 1997). Firmly grounded in the principle of crossdating - using aspects of ring morphology to identify contemporaneous rings in different trees - dendrochronology provides absolute dates accurate to the calendar year and qualitative and quantitative reconstructions of environmental variations on seasonal to century scales (Dean, 1997).

The word dendrochronology has its roots in Greek: “dendro” means tree and “chronology” means the study of time: this discipline is used to mark time or record environmental variability in the structure of the wood from trees growing in seasonal climates, such as in the mid-latitudes, high latitudes, and some tropical trees growing in environments with a pronounced wet or dry season (Speer, 2010). It is considered as one of the most important environmental recording techniques for a variety of natural environmental processes and a monitor for human caused changes to the environment such as pollution and contamination (Speer, 2010).

Since tree-ring width can vary with anything that affects growth, through the analysis of tree ring it is possible to develop annual records of many natural phenomena. Among them, tree growth is highly affected by variations in climates: more precisely, tree-ring width mirrors the environmental factors that limit tree growth. In this sense, climate can be considered as primary limiting factor affecting the growth (Fritts, 1976).

In dendrochronology, the Principle of Limiting Factors states that the most limiting factor will control the growth of the tree and therefore will be the most likely to be recorded in the tree-ring sequence. For example, trees growing at high elevation or at higher latitudes tend to be limited by temperature. This means that lower temperatures during the vegetative season are likely to cause a reduction in growth and therefore a narrow annual ring-width, and, vice versa, higher temperatures will result in increased annual growth and wider tree rings (Fritts, 1976).

Hence, there is a strong correlation between annual tree growth and temperature at high latitudes and altitudes; on the opposite, in many cases the association between growth and precipitation can be low or negligible (Fritts, 1976).

The common year-to-year variability in tree ring-width among different samples is the factor that permits crossdating defined as the definition of the exact calendar years for each tree ring in a sample (Speer, 2010).

1.2. Iceland: history and particularities of the forestry sector

Iceland, with an area of 103,000 km^2, is the second-largest island in Europe after Great Britain (Levanič & Eggertsson, 2008). It is a volcanic island located in the North Atlantic within 63°23’ N and 66°32’ N latitude, just below the Arctic Circle. Average altitude reaches 500 m a.s.l., and only a quarter of the country lies below 200 m. Ocean masses significantly influences weather and climate, causing high amounts of precipitation. Cyclones are frequent, especially in winter, and the weather depends to a great extent on their trajectory (Einarsson, 1984).

The climate of Iceland is oceanic with relatively cool summers and mild winters. Due to the Gulf Stream, despite its latitude temperatures are relatively mild compared to other areas located at the same latitude. July is generally the warmest month in most parts of the island, with a mean temperature of of around 10° C, while in the coldest month (January) the average temperatures are generally just below 0°C, with the exception of some areas where they exceed 0°C. Temperature generally decreases towards the interior in the Highlands, partly because of an increase in latitude and partly because temperature in winter decreases with increasing distance from the shore (Einarsson, 1984).

According to the Köppen climate classification, Iceland belongs to the Sub-Arctic region, with a subpolar climate (Arnfield, 2020). The northernmost part of the country and the highlands are comprised in the Arctic region (mean temperature of the warmest month less than 10° C), with a tundra climate (Einarsson, 1984; Arnfield, 2020).

According to the Icelandic Forest Service, fossil evidence indicates that Iceland was covered with forests during the mid to late Tertiary (5-15 million years ago), with tree genera including Sequoia, Magnolia, Sassafras, Pterocarya and many others, indicating that the climate was warm-temperate. Beech (*Fagus* sp.) forests were very common during this period. By the late Pliocene, shortly before the onset of Pleistocene glaciations, boreal-type forests of pine, spruce, birch and alder predominated, indicative of a cooler climate. With succeeding glaciations, the Icelandic flora became poorer. The temperature increase after the last glacial peak started 15000-18000 years ago: the glaciers generally retreated and the sea level rose. After some fluctuations, about 10000 years ago temperature began to rise more stably and it is believed that the Ice Age glacier completely disappeared 2000 years later. The vegetation which had survived began to spread. Iceland was settled between 874 and 930 A.D., in relatively favorable climate conditions (Einarsson, 1984). At that time, birch forests and woodlands covered 25-40% of Iceland. Over time, the original forest cover diminished by 95%, especially at the expense of birch stands (Eysteinsson, 2017; Icelandic Forest Service), due to the settlers need for fuel, charcoal, fodder, fields and grazing land (Blöndal, 1987; Icelandic Forest Service). The extent of birchwoods in Iceland probably reached a minimum of less than 1% of total land area around the mid-20th century (Eysteinsson, 2017).

Nowadays, Iceland’s vegetation cover is mostly formed by grasslands and tundra, and the forest cover is predominantly made of natural birchlands (*Betula pubescens* Ehrh.). Other native tree species found in Icelandic forests are rowan (*Sorbus aucuparia* L.), which, while still native to Iceland, is uncommon and rarely found growing in the wild (Blöndal, 2000), and the extremely rare aspen (*Populus tremula* L.), along with abundant tea-leaved willow (*Salix phylicifolia* L.), which is usually a shrub. All of these species more often grow as shrubs rather than trees in Iceland and none of them ever get very high in nature.

Organized forestry started in Iceland in 1899 (Icelandic Forest Service): since then, an effort has been made to protect the remained native forests from animals grazing and increase the forest cover through afforestation and reforestation with both native and exotic species (Eysteinsson, 2017; Blondal, 1987). The main exotic tree species that have been tested and planted are Siberian larch (*Larix sibirica* Ledeb.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.), Norway spruce (*Picea abies* L.) and Black cottonwood (*Populus trichocarpa* Torr. & A.Gray) (Eysteinsson 2017; Snorrason and Kjartansson 2017).

The total area of forest and woodland in Iceland has at least doubled, possibly quadrupled, since 1950. A recent (2015) remapping of natural woodland extent carried out by the Icelandic Forest Service Research Station indicates that birchwoods are generally expanding and now cover a total of roughly 1.5% of Iceland’s surface. Cultivated forests cover another 0.4% bringing the total forest and woodland cover to nearly 2% of Iceland's land area (Figure 1). Increasing forest coverage is a way of reclaiming biological productivity, preventing soil erosion, enhancing biodiversity and ecosystem resilience and much more. From an economic perspective, it can be a way of meeting certain needs in a sustainable way and decreasing dependence on imports (Eysteinsson, 2017).

Nowadays, the presence of poor and/or shallow soil, soil erosion and sheep grazing are still limiting the possibility of forest expansion (Eysteinsson, 2017).

Iceland represents an environment very sensitive to climatic changes under many aspects (Einarsson, 1984), and since the effects of warming due to climate change (Figure 2) are quite evident on Icelandic nature, predictable warming will have a significant impact on nature and society: glaciers are shrinking rapidly, vegetation productivity and cover has increased, birch forest boundaries are moving upward and new species of birds and insects invade the island (Björnsson et al., 2008).

In forestry, in some cases a global increase in temperature could potentially increase tree growth at high altitudes and decrease at low altitudes, and there might be an increase of the altitude threshold for many species (Sidor et al., 2015); the same concept goes for latitude, and understanding the species behavior in these contexts (Iceland, for example) is becoming increasingly important in the climate change scenario we are facing with.

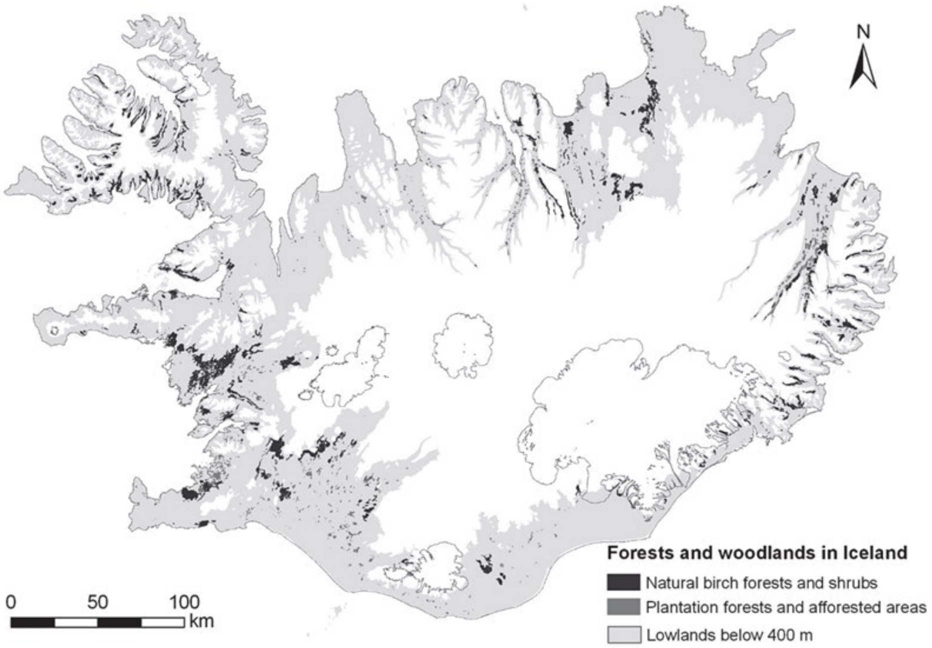


Figure 1. Distribution of forests and woodlands in Iceland (Traustason and Snorrason 2008).

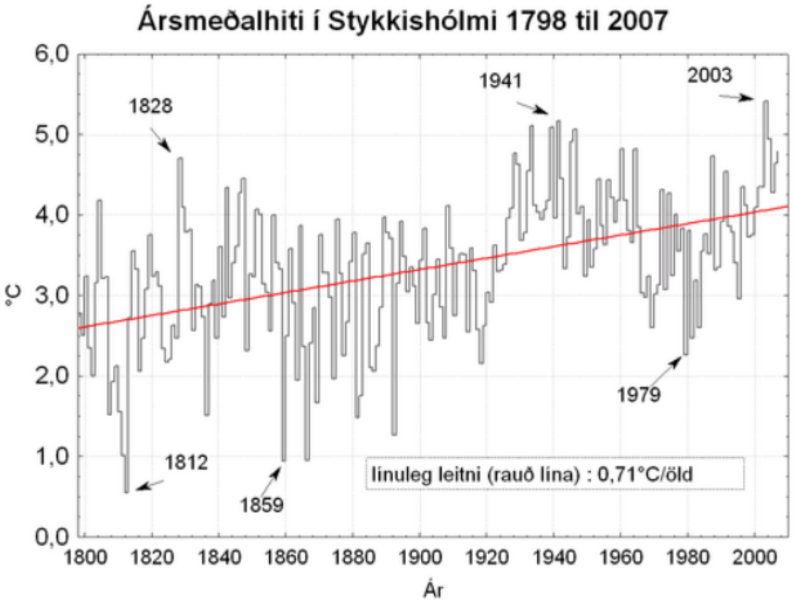


Figure 2. Average annual temperature in Stykkishólmi from 1798 to 2006 (year on the abscissa, temperatures on the ordinate). Arrows indicate some particularly cold and warm years. The red line shows the trend for the entire period (Icelandic Meteorological Office).

2. OBJECTIVES

The aim of this thesis is to study, using dendrochronological techniques, the association between climate and tree growth on both native (*Betula pubescens* and *Sorbus aucuparia*) and exotic species (*Pinus contorta*, *Picea sitchensis* and *Picea abies*) in Iceland. More precisely, the aim is to investigate the correlation between annual tree growth and climate variability, focusing in particular on temperature and precipitation. In this way, I expect to identify which environmental factors are significantly associated to tree growth in Iceland, performing a comparison between native and exotic species, under the effect of climate change.

As reported, temperature can be a strongly limiting factor for tree growth in Iceland (Fritts, 1976). Therefore, I hypothesize a strong correlation with temperatures while, on the other hand, a low correlation with precipitation, that due to the abundant rainfall should not be considered a limiting factor for trees growth in this context.

3. MATERIALS AND METHODS

3.1. Analyzed species

I analyzed the tree-ring width chronologies of five tree species at six different sites. We chose for this study two native broadleaved tree species, Icelandic downy birch (*Betula pubescens* Ehrh.) and rowan (*Sorbus aucuparia* L.), and three non-native coniferous species (*Pinus contorta*, *Picea sitchensis* (Bong.) Carr. and *Picea abies* L.).

Birch is a deciduous broad-leaved tree species; it is light-demanding to semi-shade tolerant and is a frost and wind resistant tree species. It's a typical pioneer species able to spread both through seeds and basal shoots (Kristinsson, 2007). It is spread all across Iceland, except at high elevations (such as in the Highlands). Individuals can reach a height of up to 15 meters, but more often they are shorter (less than 5 meters) or with a shrub-like growth (Eysteinsson, 2017; Kristinsson, 2007).

Rowan is a deciduous semi-shade tolerant hardwood species. It can live in different site and climate conditions, but growth is higher on deep, nutrient-rich soils and sites with abundant incoming solar radiation (Blöndal, 2000). It spreads through seeds, which are usually distributed by birds (Eysteinsson, 2006), but the species is also capable of producing new stems from basal shoots and root sprouts (Blöndal, 2000).

Norway spruce (*Picea abies* L.) is one of the most important trees in Europe both for economic and ecological aspects, with a long tradition of management. It dominates the Boreal forests in Northern Europe and the subalpine areas of the Alps and Carpathian Mountains, but given its good growth performances in different site conditions, it can also be found outside its natural distribution on lower elevations. Norway spruce has been massively planted and cultivated up to its niche limits, even outside its natural range, where it is particularly susceptible to heat and drought, due to its shallow root system. For this reason, it is expected to be severely affected by global warming (Caudullo et al., 2016).

The other two species included in this study are often adopted in Icelandic silviculture (*Picea sitchensis* (Bong.) Carr. and *Pinus contorta* Dougl. ex Loud.) (Blondal 1987; Snorrason and Kjartansson 2017). Sitka spruce is native to North America, where it grows along the west coast, from southern

Alaska to northern California. At the beginning of the twentieth century, it has been planted in Iceland (Houston Durrant et al., 2022) and it's nowadays used for afforestation.

Lodgepole pine is native to US and Canada. Its natural range is limited to the Yukon Territory in the North and in the South by Baja California, and West to East from the Pacific Ocean to the Black Hills of South Dakota, but thank to its pioneer behavior and good colonizing ability, it has been planted all around the world for economical purposes (Lotan & Critchfield, 1990). In Iceland it covers 11% of the forested area (Snorrason & Kjartansson, 2017).

Seed sources for the reported exotic species in Iceland are Skagway area (Alaska) for Sitka spruce and lodgepole pine, and Trysil and Rana (Norway) for Norway spruce.

3.2. Field work

3.2.1. Study areas

The samples of the five analyzed species were collected at six different sites (Figure 3).

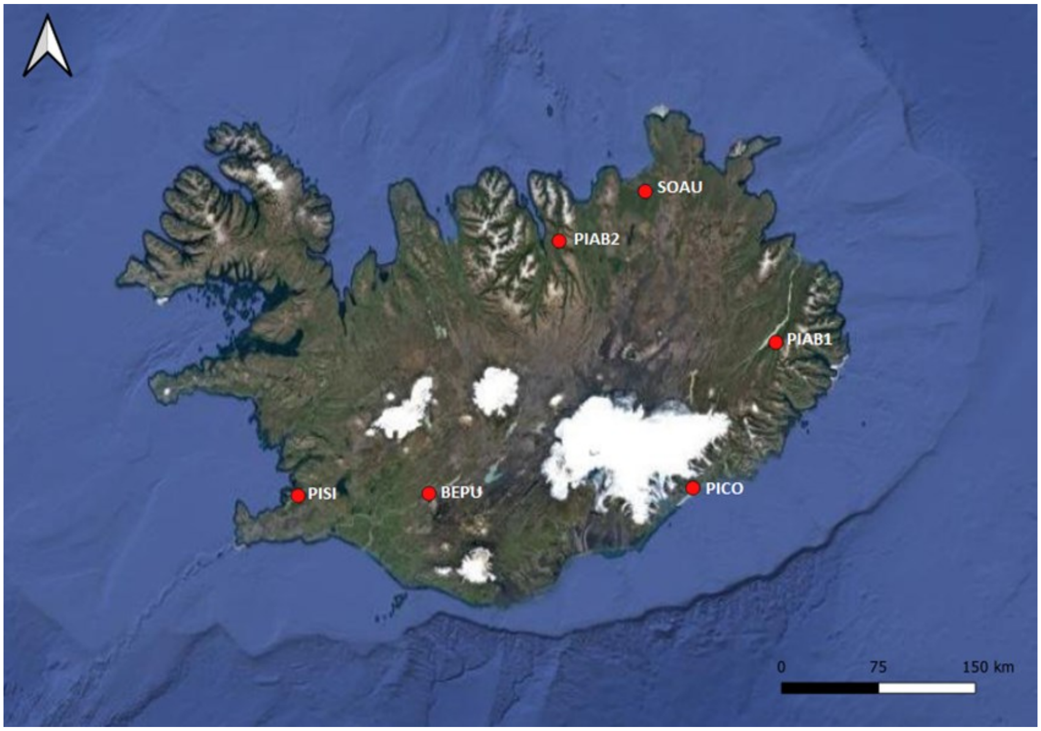


Figure 9. Location of the sites Rauðavatn (PISI), Steinadalur (PICO), Hallormsstaður (PIAB1) Vaglaskógur (PIAB2) Ásbyrgi (SOAU) and Búrfell (BEPU).

A brief description of the sites is given below:

- Site 1 is called Rauðavatn (Figure 4) and will be identified by the abbreviation PISI. It's located in the eastern part of the island, near Reykjavik (64°06'14.63"N, 21°45'46.15"W, 80 m a.s.l.). The stand is divided in two main plantations: one of lodgepole pine and one of Sitka spruce. The lodgepole pine plantation is naturally regenerating at a high rate, faster than Sitka spruce, and closing the gap between the two stands. In the surroundings, it is possible to find a dense birchland (*Betula pubescens*), with a mean height of 2-3 meters. The Sitka spruce plantation presents a high density, without any ground vegetation. The tree crowns are relatively small, however the overall health condition appears good. Initial density after planting was ca. 4000/4500 seedlings/ha; after 1 selective thinning, performed roughly 25 years ago (1995), today the average density is around 800/900 plants/ha. Samples have been collected for a total of 18 Sitka spruce trees (Frigo, 2021).

Figure 4. Rauðavatn (Site 1). Frigo, D. summer 2020.

- Site 2 is called Steinadalur (Figure 5) and it is identified by the abbreviation PICO. It's located in a valley found in the Southeastern part of Iceland (64°10'04.44"N 15°59'45.61"W, 50 m a.s.l.). The plantation was established in 1954 (Guðmundsdóttir, 2012) with an initial area of 0.4 hectares. In 1959 it was extended with lodgepole pine seedlings originating from Alaska and in 1965 and 1969 further 1250 plants of the same species were planted (Guðmundsdóttir, 2012). In addition to lodgepole pine, *Pinus silvestris*, *Larix sibirica*, *Picea abies*, *Picea sitchensis* and *Pinus aristata* were also planted (Guðmundsdóttir, 2012).

In this site, for some reason, the lodgepole pine has had a more rapid natural regeneration and dispersal than has been observed around any other of the oldest plantations in Iceland (Eggertsson et al., 2022). Nowadays, the lodgepole pine forest has an area of about 100 ha (Eggertsson et al., 2022), and the forest looks mature, with a density of ca. 800/900 plants/ha. For the study, 15 lodgepole pine trees were sampled (Frigo, 2021).

Figure 5. Steinadalur (Site 2). Frigo, D. summer 2020.

- Site 3 is located into Hallormsstaður forest (Figure 6), in Eastern Iceland (65°07'21.31"N, 14°41'04.03"W, 126 m a.s.l.), and it's called PIAB1 in this study. As reported by the Icelandic Forest Service, which is the owner, this forest is one of Iceland's biggest forests (740 ha), which expanded from one of the last birch woodlands in Iceland saved from eradication. Since 1905 several exotic conifer species have been planted. Sampling has been done in a dense mixted stand of *Picea abies* (95%) and *Pinus contorta* (5%) with small tree crowns (due to density) and good overall health conditions. After a windthrow, mostly affecting lodgepole pine, it is possible to observe some gaps in the forest cover. In some of these gaps it is possible to find Norway spruce regeneration. A light pre-commercial thinning was conducted around the year 2000 and today the average density is about 1200/1300 plants/ha, while, on average, in the rest of the forest it is about 2000 plants/ha. We sampled 24 Norway spruce individuals, with 10 trees chosen from the thinned part of the forest, to have a picture of the different growth trends in the last 20 years (Frigo, 2021).

Figure 6. Vaglaskógur (Site 4). Frigo, D. summer 2020.

- Site 4 (Figure 7) is located in Vaglaskógur forest at Fnjóskadalur (North Iceland, 65°42'26.77"N, 17°53'13.75"W, 163 m a.s.l.) and it is abbreviated as PIAB2. According to Icelandic Forest Service, Vaglaskógur is part of the largest continuous forest in Iceland, composed of several plantations of exotic conifer species such as *Pinus contorta*, *Picea engelmannii*, *Larix sibirica* and *Picea abies* and a birchwood conservation area of about 690 ha. Samples have been collected from a dense plantation area which is composed of *Picea abies* (95%) and *Pinus contorta* (5%) planted between 1948-1954 (IFS). The average density in this part of the forest is nowadays about 4000/4500 plants/ha. Here a total of 23 Norway spruce trees have been sampled (Frigo, 2021).

Figure 7. Vaglaskógur (Site 4). Frigo, D. summer 2020.

- Site 5 is Ásbyrgi forest (Figure 8) (North Iceland, 66°01'04.1"N, 16°30'29.1"W, about 120 m a.s.l.), which is abbreviated as SOAU. It is located in a large-scale cone-shaped depression which belongs to Vatnajökull National Park. Icelandic Forest Service bought the land in Ásbyrgi in 1927 and started protecting the forest remains, since there was little or no new planting there. Vatnajökull National Park and the Icelandic Forest Service continue nowadays to cooperate on the management of the area.

  On the external part of Ásbyrgi there is peat vegetation, but in the interior there is a diverse and mature birch forest with also rowan and willow. In the years between 1950 and 1980, some imported coniferous tree species were planted in Ásbyrgi.

  Currently, the management strategy is to plant just to maintain a high diversity within the mixed birchland (Icelandic Forest Service). Nowadays, according to some unpublished measurements performed by Dr. Eggertsson, the density varies a lot from 1800 trees/ha to 6000 trees/ha. In the area where the samples have been collected it is close to 3000 stems per hectare.

  Here a total of 17 rowan trees have been sampled.

Figure 8. Ásbyrgi (Site 5). Pagnan, G., summer 2022.

- Búrfellsskógur (Figure 9) is identified with the abbreviation BEPU. It is located in Southern Iceland near Mount Burfell (64°03'43.2"N, 19°51'03.5"W, about 250 m a.s.l.), about 10 km from Hekla volcano, and has an area of about 1,30 km2. According to the information released by Dr. Eggertsson, it is a native birch forest that probably has ancient origins, preserved over time due to its inaccessible position, with a current density of 2200-4800 trees/ha. From this forest 34 birch trees have been sampled.

Figure 9. Búrfellsskógur (Site 6), and Mount Búrfell in the background. Pagnan, G., summer 2022.

3.2.2. Climate data

Climate data (monthly precipitation and temperature series) were downloaded from the Icelandic Meteorological Service website for all sites except BEPU. Data for BEPU has been downloaded from the World Meteorological Organization website, since the Icelandic Meteorological Service website data measurements interrupted in 2015.

Data has been retrieved from the closest station to the sampling site to better represent the local climate:

- for PISI (site 1), the selected station is located in Reykjavik (SW Iceland, 64°07'38.9"N 21°54'10.0"W, 52 m a.s.l). For this station the available series timespan (found by Dr. Frigo) were from 1920 to 2019 (Figure 10). The average annual temperature is 4,87 °C, and the average total annual precipitation is 849,99 mm (Frigo, 2021);

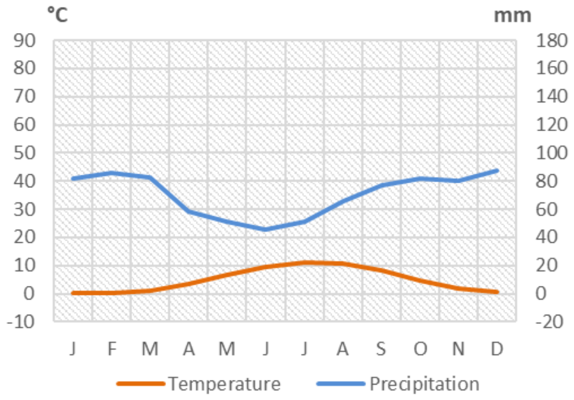


Figure 10. Climograph relative to Reykjavik climate station, representative of the average monthly precipitation and temperature series.

- for PICO (site 2), data were taken from a station located in Höfn í Hornafirði, (SE Iceland, 64°16'08.7"N 15°12'48.7"W, 5.0 m a.s.l.) (Figure 11). Series from 1965 to 2018 were available, but to complete the climate series also data from the nearby stations of Akurnes and Hjardarnes have been considered. The average annual temperature is 4,65 °C, and the average total annual precipitation is 1413,92 mm (Frigo, 2021);

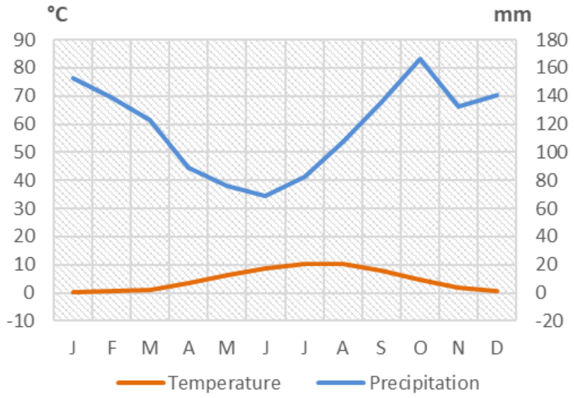


Figure 11. Climograph relative to Höfn í Hornafirði climate station, representative of the average monthly precipitation and temperature series.

- for PIAB1 (site 3), data from a station located in Egilsstaðaflugvöllur (E Iceland, 65°16'58.8"N, 14°24'09.0"W, 23.0 m a.s.l.) (Figure 12) has been used, and to complete the climate series it has also been used another nearby station (ID 4271), by simply adding lacking data to the series. Series timespan goes from 1954 to 2019. The average annual temperature is 3,43 °C, and the average total annual precipitation is 612,37 mm (Frigo, 2021);

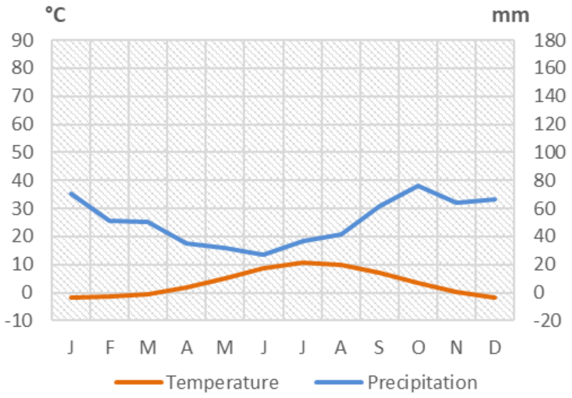


Figure 12. Climograph relative to Egilsstaðaflugvöllur climate station, representative of the average monthly precipitation and temperature series.

- for PIAB2 (site 4) and SOAU (site 5) data has been taken from Akureyri station (NE Iceland, 65°41'08.1"N, 18°06'00.8"W, 23.0 m a.s.l) (Figure 13). Series from 1949 to 2019 were available. The average annual temperature is 3,71 °C, and the average total annual precipitation is 521,17 mm (Frigo, 2021);

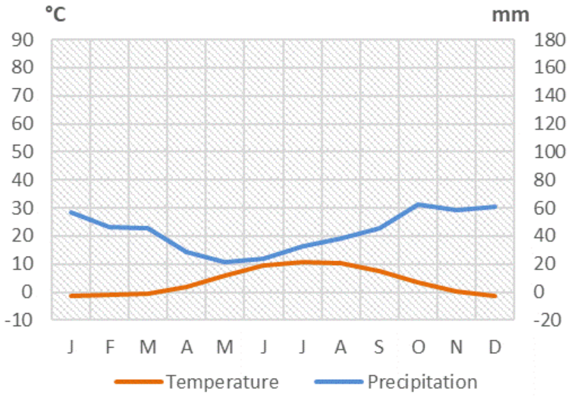


Figure 13. Climograph relative to Akureyri climate station, representative of the average monthly precipitation and temperature series.

- for BEPU (site 6), data were retrieved from the World Meteorological Organization website for the specific position of the site (Figure 14). Series spans from 1949 to 2018. The average annual temperature is 2,69 °C, and the average total annual precipitation is 1025,37 mm.

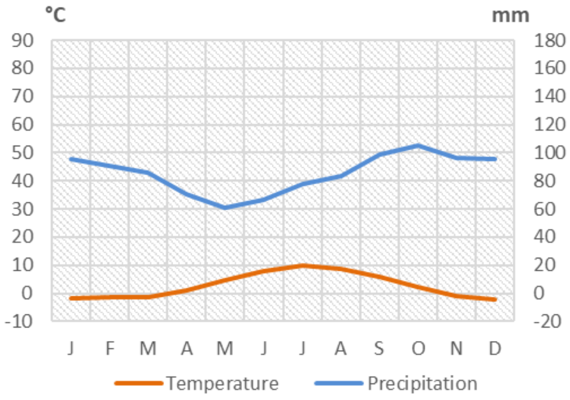


Figure 14. Climograph relative to the site Búrfellsskógur, representative of the average monthly precipitation and temperature series.

3.2.3. Field sampling, sample preparation and rings measurement

To collect the core samples we used an increment borer. We selected possibly the oldest dominant or codominant trees, according to size and general appearance. These trees can provide longer data series and permit our analysis on a longer time scale, while dominant tree-ring growth should have a stronger response to climate as the growth is less limited by non-climatic factors such as competition (Fritts, 1976).

In order to obtain a representative picture of the stand, trees have been selected randomly both on the edge and inside the stand.

Figure 15. Coring of a tree with an increment borer. Pagnan, G. summer 2022.

Samples have been collected at knee height, which means 50 cm from the ground (Figure 15) to extend the series length as much as possible.

A total of 14 rowan trees and 34 birch trees were sampled in two different moments, collecting two perpendicular cores from each tree, and for trees with more than one stem, the main stem (with the largest diameter) has been cored.

The samples have been stored in plastic holders that have been sealed and labelled with a code reporting the location name and date of sampling.

Once back at the institute, the samples were taken out of the containers and left to dry for a few days. Each sample was assigned an 8-digitcode, providing site information (site initial and site number), the sample number and the species. Finally, they were glued onto wooden core mounts, with the transverse section (the cross-section of the stem with visible tree-rings) facing upward (Figure 11). The top of the cores was cut off with a scalpel, using water and talcum powder to make tree-rings more visible.

As last step, each sample's ring widths were measured using LINTAB and the software TSAP (TSAP-win, Rinntech). LINTAB is a digital positioning table for tree-ring analysis, where the measuring stage is a linear encoder (precise to 0.01 mm) hooked to the measurement capture button, which is connected to a computer through USB or serial port connector (Figure 16). TSAP is a software that allows to save and process tree-ring measurements, and it is compatible with LINTAB.

The tree-ring widths were measured at 0.01 mm precision. The measurement was performed starting from the pith when visible, and it was concluded when reaching the outermost complete ring, close to the bark, or at the last clear ring.

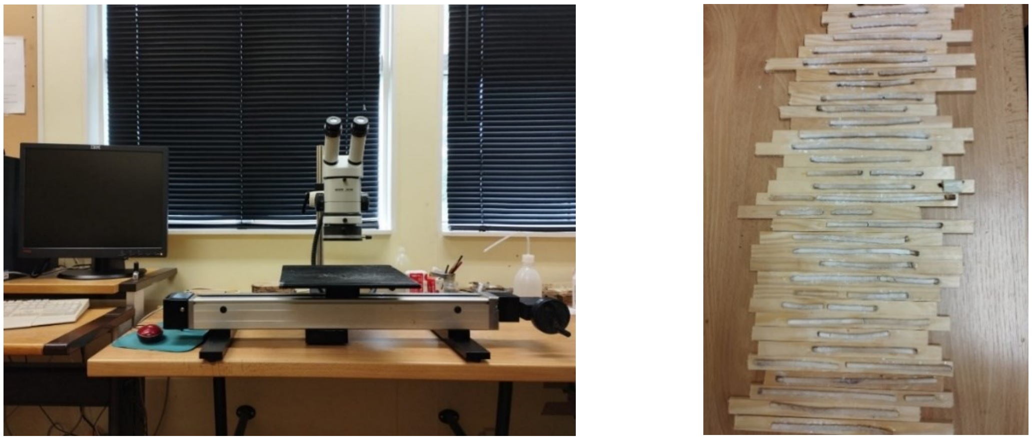


Figure 16. Rinntech LINTAB measuring apparatus (on the left) at the dendro lab of the Icelandic Forest Research (division of the Icelandic Forest Service (Skógræktin)), in Mógilsá, Reykjavik; some of the birch core samples (on the right) glued on wooden supports.

An individual ring-width chronology was produced for each core. In case of the presence of two cores per tree a mean series was created.

Some (2 rowan and 7 birch) core samples could not be measured due to cracks or irregularities in the wood. To make sites chronologies more robust, we added 13 birch and 8 rowan individual series that had been collected (respectively in Búrfell and Ásbyrgi) and previously measured by Dr Ólafur Eggertsson. The rowan samples had been collected in 2007 (therefore reaching up to 2006), while the birch ones in 2015.

3.2.4. Crossdating

Crossdating was carried out in two steps: first, using the program TSAPWin for a visual comparison of the series represented by line graphs, and then with COFECHA, which is a statistical program (Holmes 1983) used to verify the accuracy of the visual crossdating (Speer, 2010).

Cores with the clearest rings or with the least number of narrow or unclear rings were chosen and visually crossdated in TSAPWin. Pointer years (individual rings or series of rings that are significantly wider or narrower than neighboring rings or all other rings) were identified (Schweingruber, 1992) and used to compare the core-series.

In TSAPWin, the two core series of each tree were averaged, to produce an individual series. Working with two averaged core series from an individual rather than the single core series is better, since it prevents the overrepresentation of individual tree-signals and distortion of the stand-level signal in the master chronology, and because it allows a better insight into the growth of individual trees (Speer, 2010).

A first check was visually made for the individual series of each species on the graph provided by TSAPWin.

After the visual crossdating, a file including the single series of each species were analyzed using COFECHA: the program runs a correlation analysis to calculate the intercorrelation of all series and to identify or “flag” segments of series which do not match or have a significantly lower correlation with all the other series. Flagged segments due to apparent missing or false rings or with very correlation values were re-measured.

The raw chronologies were again uploaded on COFECHA, to identify any further error or low correlation. This was done until a good output from COFECHA was obtained, gradually eliminating the samples which after several checking had low correlation values with the mean chronology. In some cases, we inserted as input only one of the two cores of a tree, removing the one with reaction wood or any other faults.

At this point, the remained series have been standardized with ARSTAN, a program used in dendrochronology procedures to remove the age/size trends in ring width raw chronologies (Speer, 2010). Different standardization techniques can be used to maximize climate signal and remove the noise from the final chronology (Speer, 2010). In the previous study (Frigo, 2021), after comparing different spline flexibilities, the 20-year cubic smoothing spline was selected as the most efficient in extracting the climate signal and in removing both the long-term trend and the effects of localized disturbance events.

In this study, to remain in line with previous investigation and to allow a correct comparison of the data, I selected the same spline flexibility.

Finally, ARSTAN also provides several descriptive statistics commonly adopted in dendrochronology to compare raw and indexed chronologies of the analyzed sites, i.e.:

- the number of cores (N);
- the length of the master series (L);
- the mean ring width (MRW), which is the average between all the ring width values of all the samples;
- the mean sensitivity (MS), which is a measurement of the year-to-year variability in tree-ring width ranging from 0 to 1: if every ring were the same width, the series would have a mean sensitivity of 0 and if every other ring were absent then the mean sensitivity would approach 1 (Speer, 2010);
- the standard deviation (SD), to assess the high-frequency variations (Fritts, 1976);
- the first-order serial autocorrelation (AC) to detect eventual low-frequency persistence retained after the standardization (Carrer & Urbinati, 2004).

3.2.5. Climate-growth relationships

Climate-growth relationships were performed on a period of 52 years, from 1967 to 2018, as well as in the previous study (Frigo, 2021). Such range has been chosen based on the shortest site chronologies.

The relationship between each site's standardized master chronology and climate variables (temperature and precipitation) has been tested using Pearson correlation. In particular, the indexed chronology of each site was contrasted again average temperatures and the precipitation sum, both monthly and seasonally (as, for example, the summer period) to find the correlation value with dated tree annual rings. The correlation has been also calculated for 7 some months (June-December) of the previous year, to attest a potential effect of those months on the following tree growth.

A significance threshold has been set using the critical values for correlation coefficient according to the number of years n = 52, with p<0,05 and p<0,01.

4. RESULTS

4.1. Descriptive statistics

We included in the analyses a total of 22 rowan individuals (14 collected in the current summer, and the others previously collected by Dr. Eggertsson), 28 birch individuals (18 collected in the current summer, and the others previously collected by Dr. Eggertsson). As regards conifers, 17 Sitka spruce, 12 lodgepole pine and a total of 46 Norway spruce (24 from site PIAB1, and 22 from site PIAB2) individuals were included.

The Table 1 shows some descriptive statistics for each site.

Table 1. Statistics for each site chronology: the number of cores (N), the length of the master series (L), the year from which site chronology consists of at least 5 individuals (Y_5), the mean ring width (MRW), the standard deviation (SD), the first-order serial autocorrelation (AC), the mean sensitivity (MS) are represented. Statistics have been done both on raw and indexed tree-ring series (except for N, L, Y_5 and MRW).

	N	**L** (years)	**Y_5**	**MRW** (mm)	**MS**		**SD**		**AC**	
					Raw chronologies	**Indexed chronologies**	**Raw chronologies**	**Indexed chronologies**	**Raw chronologies**	**Indexed chronologies**
PISI	17	62	1963	2.57	0.202	0.160	0.945	0.167	0.826	0.148
PICO	12	53	1970	3.69	0.083	0.069	0.867	0.075	0.877	0.286
PIAB1	24	56	1965	2.39	0.203	0.173	0.731	0.170	0.694	0.202
PIAB2	22	56	1970	1.73	0.175	0.150	0.397	0.150	0.644	0.173
SOAC	22	81	1945	1.09	0.186	0.178	0.335	0.160	0.739	0.007
BEPU	28	111	1919	0.76	0.318	0.295	0.255	0.270	0.377	0.160

The longest series obtained is the one from BEPU (111 years) and it's the one with the smallest tree-ring width, followed by the other site of native species considered (SOAU), where the longest series had 81 years. At PISI, PICO, PIAB1 and PIAB2 the maximum series length detected was respectively of 62, 53, 56 and again 56 years. PICO is the site with the greatest average tree-ring width. In general, non-native species have wider tree-rings than native ones. The column "Y_5" shows the year from which the chronology consists of at least 5 individuals, and thus begins gaining firmness.

4.2. Growth trend comparison

The graph in Figure 17 shows the average series for each site: we can appreciate the different series length and ring width in the six sites. Furthermore, it shows that for some years, such as 1964, 1967, 1970, 2011 and 2015, several sites had low growth rates. Similarly, we can observe high growth rates across all the sites in 2010, for example.

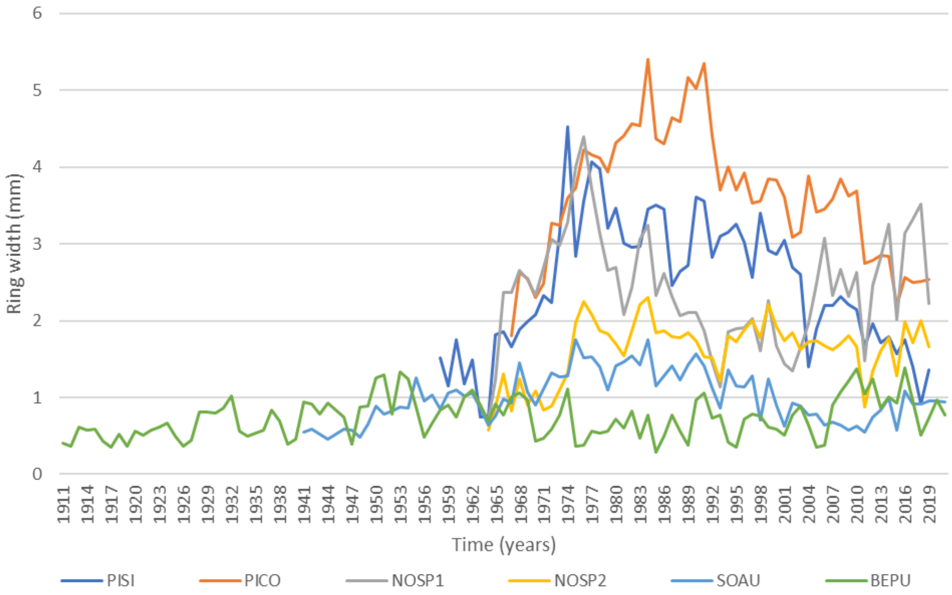


Figure 17. Average tree-ring width chronologies of each analyzed site.

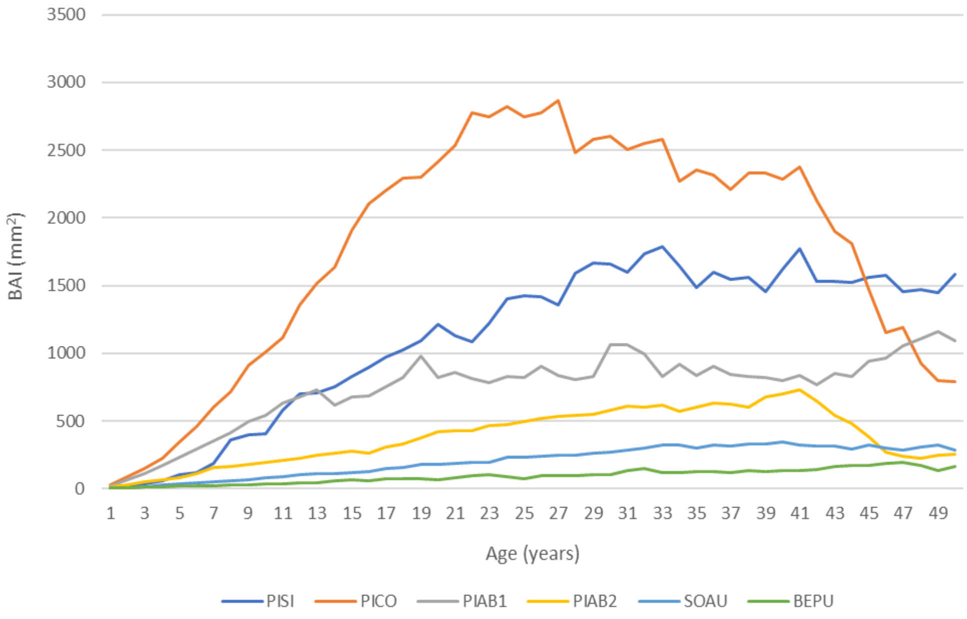


Figure 18. Average Basal Area Increment (BAI) of the first 50 years of trees life, for the six different sites.

The graph in Figure 18 shows, instead, the growth trend in terms of Basal Area Increment: again, we notice differences in growth between the five species.

In Figure 19 we can appreciate the effect of standardization, i.e. the difference between the chronology with the raw data and the indexed chronology created fitting the 20-year cubic smoothing spline, which reduces the autocorrelation value (Table 1) and removes most of the age/size and disturbances effect.

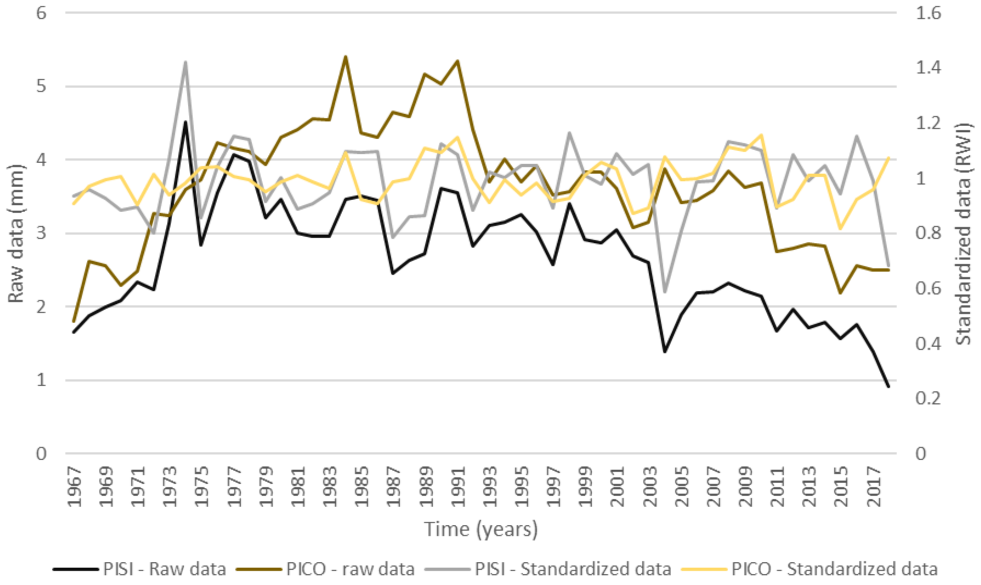


Figure 19. Comparison between raw data (mm) and standardized data for PISI (Picea sitchensis) and PICO (Pinus contorta).

4.3. Associations between growth and climate

The graphs in Figure 20 describe the correlation between the annual tree-ring width and temperatures, for each month from June of the previous year to September of the current year (when the ring was formed), showing also the significance threshold for p=0.01 and p=0.05.

It's clear a convergence towards positive correlation for all sites during the summer months and May. In particular, there is a significant positive correlation for PICO in May and July, for Norway spruce in both sites (PIAB1 and PIAB2) in June, July and August, and for Sitka spruce in July, which, however, has a significant negative correlation with June and August of the previous year. It is also interesting to observe that Norway spruce seems to be negatively influenced by April temperatures. The growth of the two native species seems to feature a positive response to summer temperatures of the current year, but negative to those of previous year growing season.

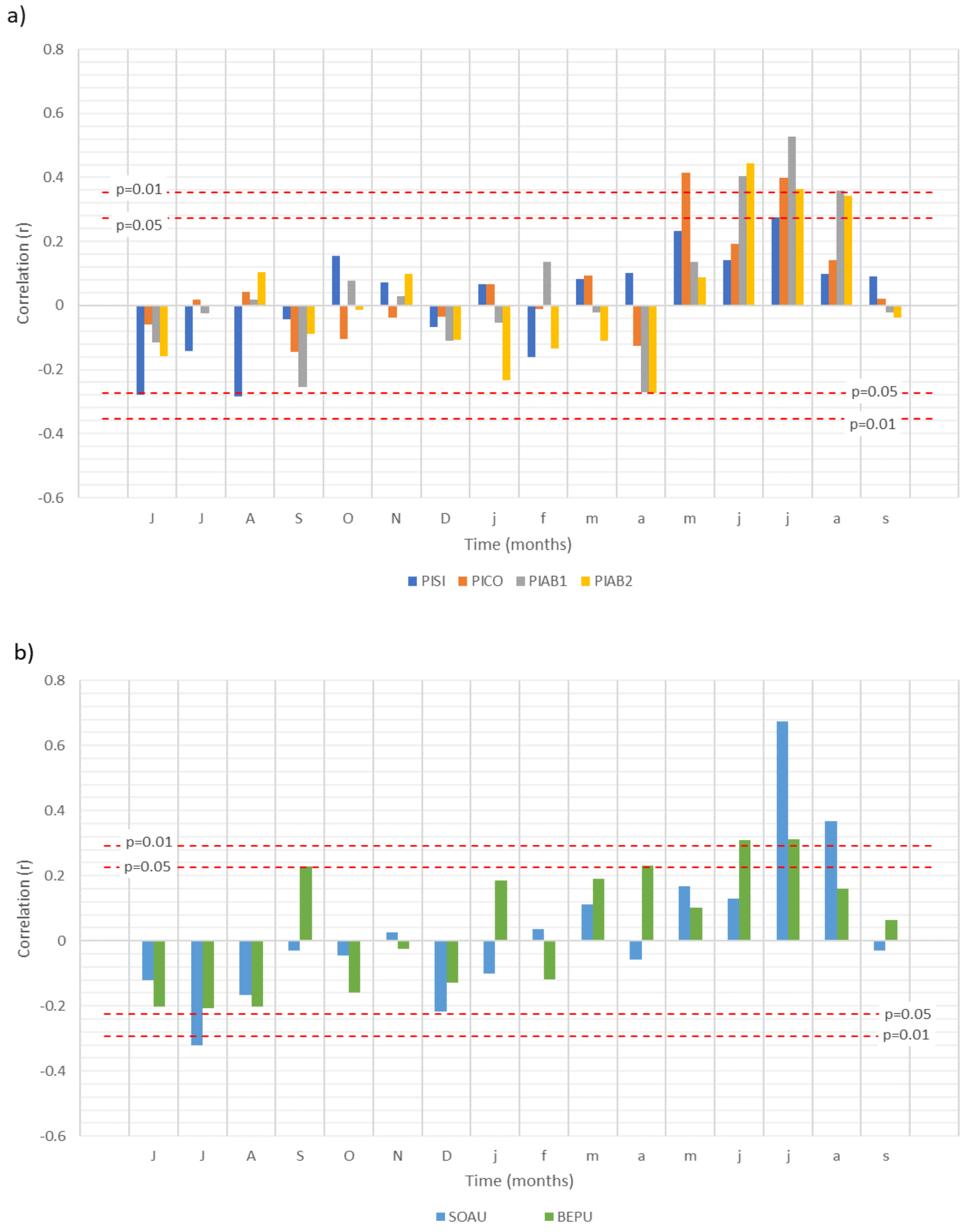


Figure 20. Correlation values among monthly mean temperature and tree-ring width standardized chronologies for the alien (graph a) and native (graph b) species. The correlation has been done for monthly temperatures (1967–2018) of the previous year (from June to December, indicated with capital letter on the abscissa) and to September of the current year (lowercase letter on the abscissa). Values above the threshold |0.2732| are significant at $p < 0.05$ while values above |0.3542| are significant at $p < 0.01$.

In Figure 21 the correlation for pairs of summer months, as well as for the period from June to August (summer period) and from April to June (spring period) are represented. For all sites the correlation is positive for these periods, and in many cases it trespasses the significancy threshold.

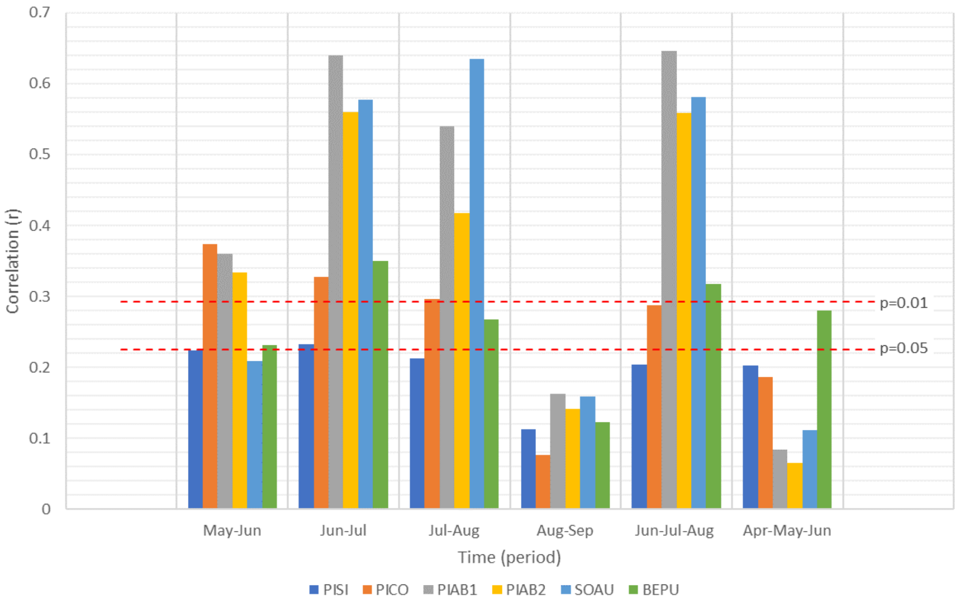
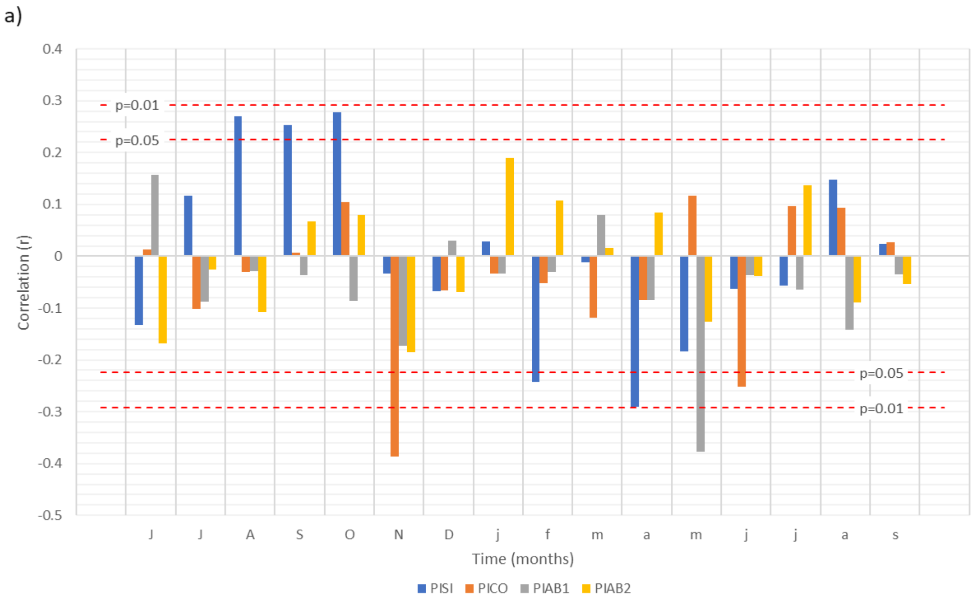


Figure 21. Correlation values among birch and rowan tree-ring width standardized chronologies and temperatures in the periods: May-June, June-July, July-August, August-September, June-July-August and April-June-July. Values above the threshold |0.2732| are significant at p < 0.05 while values above |0.3542| are significant at p < 0.01.

The associations among tree growth and precipitation are shown in the graphs in Figure 22.



b)

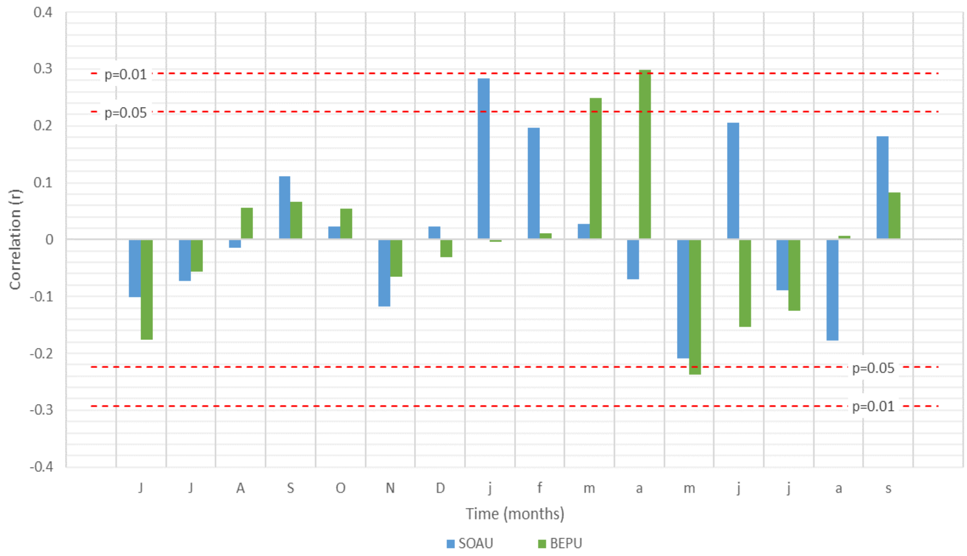


Figure 22. Correlation values among monthly precipitation and tree-ring width standardized chronologies for the analyzed alien (graph a) and native (graph b) species. The correlation has been done for monthly precipitation (1967–2018) of the previous year (from June to December, indicated with capital letter on the abscissa) and to September of the current year (lowercase letter on the abscissa). Values above the threshold |0.2732| are significant at p < 0.05 while values above |0.3542| are significant at p < 0.01.

For what concerns exotic species, in many cases there is a low correlation. It seems that just the precipitations in August, September and October of the previous year could have a positive effect on PISI growth only. A significant negative correlation is shown for PICO in November of the previous year, and for PIAB1 in May of the current year. For the native species, correlations are still generally low, however there are significant positive correlations in January for SOAU, and in April for BEPU. Precipitation negatively affects both the species in May, even though not reaching the significancy threshold.

The correlation with seasonal windows (Figure 23) are generally low and mainly negative in all sites. However, PISI shows a significant negative correlation during spring months, and all sites seem to be affected negatively by precipitation during spring. BEPU shows a strong significant positive correlation with precipitation during the two-months period March-April.

Finally, the correlation analysis was repeated over a longer time window, to see if there were any consistent changes in the results (Figures 24, 25, 27 and 27). This was done for rowan and birch (because, being the longest series, they are also the only ones that allow a relatively long-time window to be added to the analyses), adding 23 years to the time window (which is therefore 75 years, from 1945 to 2019).

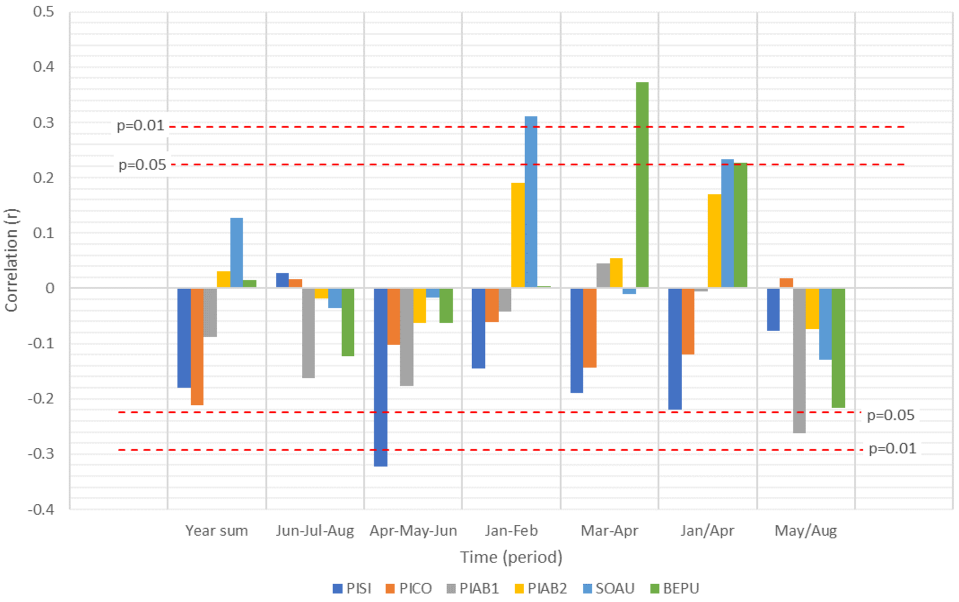


Figure 23. Correlation values among tree-ring width standardized chronologies and the total precipitations of the year, the summer precipitation (June, July, August), the spring precipitation (April, May, June), the couples of months January-February and March-April, the period from January to April and the period from May to August. Values above the threshold |0.2732| are significant at p < 0.05 while values above |0.3542| are significant at p < 0.01.

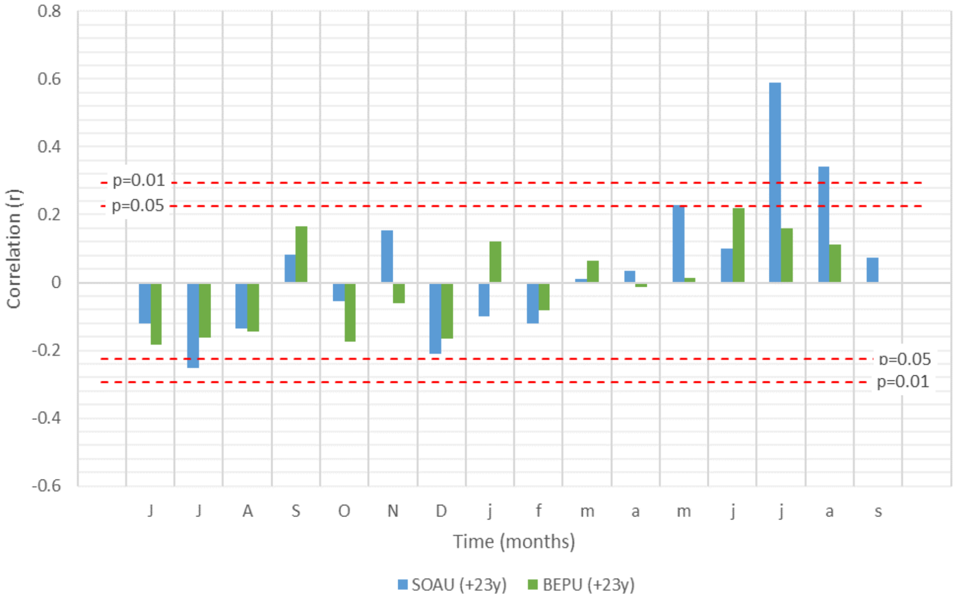


Figure 24. Correlation values among monthly mean temperature and tree-ring width standardized chronologies for the two analyzed native species. The correlation has been done for monthly temperatures (1945–2019) of the previous year (from June to December, indicated with capital letter on the abscissa) and to September of the current year (lowercase letter on the abscissa). Values above the threshold |0.2246| are significant at p < 0.05 while values above |0.2924| are significant at p < 0.01.

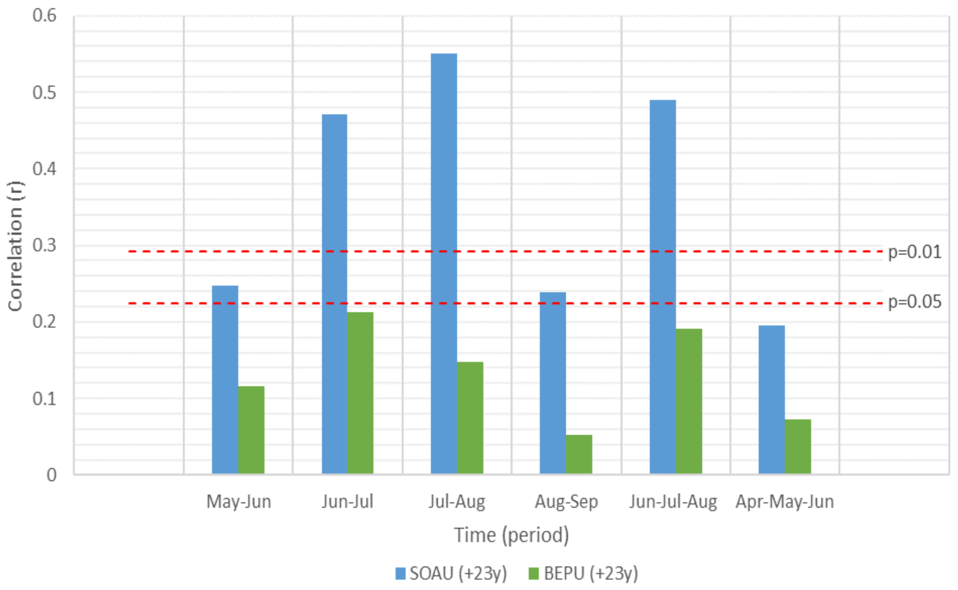


Figure 25. Correlation values among birch and rowan tree-ring width standardized chronologies and temperatures in the periods: May-June, June-July, July-August, August-September, June-July-August and April-June-July. Values above the threshold |0.2246| are significant at p < 0.05 while values above |0.2924| are significant at p < 0.01.

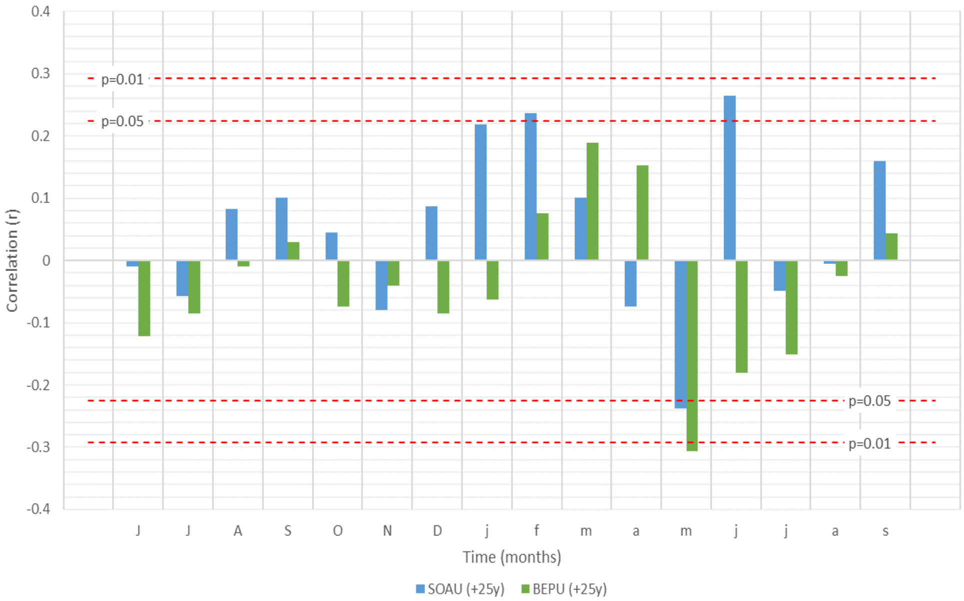


Figure 26. Correlation values among monthly precipitation and tree-ring width standardized chronologies for the two analyzed native species. The correlation has been done for monthly precipitation (1945–2019) of the previous year (from June to December, indicated with capital letter on the abscissa) and to September of the current year (lowercase letter on the abscissa). Values above the threshold |0.2246| are significant at p < 0.05 while values above |0.2924| are significant at p < 0.01.

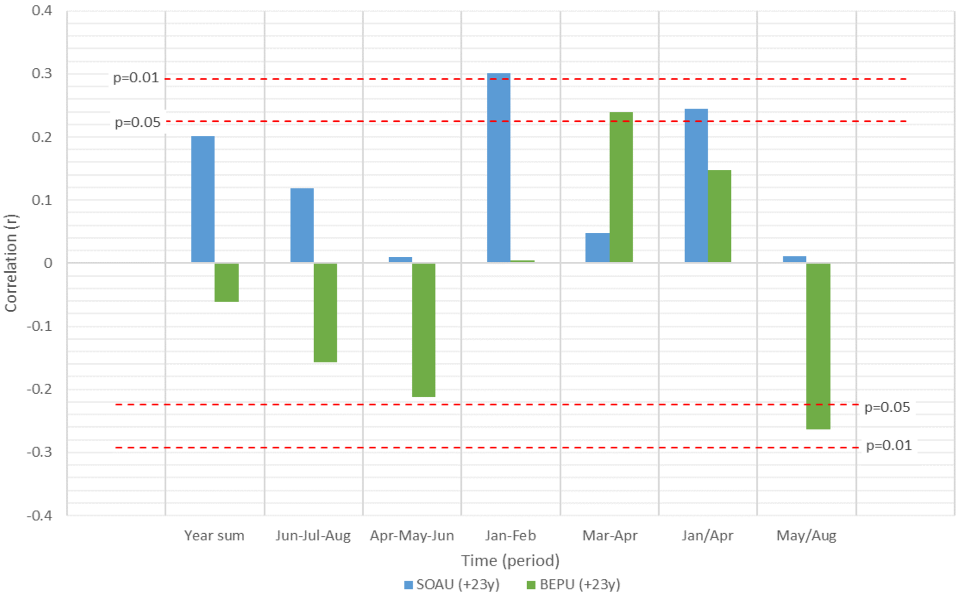


Figure 27. Correlation values among birch and rowan tree-ring width standardized chronologies and the total precipitations of the year, the summer precipitation (June, July, August), the spring precipitation (April, May, June), the couples of months January-February and March-April, the period from January to April and the period from May to August. Values above the threshold |0.2246| are significant at $p < 0.05$ while values above |0.2924| are significant at $p < 0.01$.

5. DISCUSSION

5.1. Descriptive statistics

Table 1 shows that mean sensitivity (MS), standard deviation (SD) and serial autocorrelation (AC) are generally reduced by standardization. Mean sensitivity on indexed chronologies varies from 0.069 to 0.173; according to Speer (2010) it can be difficult to date accurately series which are too complacent or too sensitive: a series with a mean sensitivity around 0.1 might be too complacent that it is difficult to date, and a mean sensitivity greater than 0.4 might be too sensitive, while a mean sensitivity around 0.2 is generally accepted as series that are sensitive enough for climate reconstruction. Standard deviation is generally higher for conifers. Looking at raw chronologies, all sites show a significant amount of serial autocorrelation, which means a strong dependence of current growth on the previous year’s growth; the reduction of the AC value after standardization denotes a removal of the low-frequency persistence present in raw tree-ring series.

5.2. Tree-ring width and growth trend comparison

Observing the graph in Figure 17, which shows the raw chronologies, it is possible to appreciate a clear difference in terms of ring width between the six analyzed sites. We can further notice this diversity also looking at the Mean Ring Width reports in Table 1: site PICO has the highest (3.69 mm), followed by PISI, PIAB1, PIAB2 and SOAU, while BEPU has the lowest value of MRW (0.76 mm). In general, the three exotic species show a higher ring width compared to the native rowan and birch. Moreover, we notice a different growth trend in terms of BAI (Figure 18). This is probably due to species-specific characteristics: the three analyzed conifers are relatively fast-growing species (Caudullo et al., 2022; Houston Durrant et al., 2022; Lotan & Critchfield, 1990). For example, Sitka spruce is the largest of the spruces (Houston Durrant et al., 2022). On the other side, birch and rowan are a relatively small broadleaved tree species (Beck et al., 2022; Räty et al., 2022). However, it is necessary to consider that the choice of different sites determines different local conditions, which might have partly determined the different tree growth rate among sites.

It is known that seedlings are more sensitive to environmental factors and during the juvenile period trees often produce larger than average growth rings: stem diameter increment tends to peak in the early to mid-life of a tree, and then gradually decline with size and age (Bowman et al., 2013; Speer, 2010): in the graphs in Figure 17 and 18 it is possible to observe this trend.

5.3. Climate effect on annual tree growth

As expected, since in Iceland temperature is a limiting factor for tree growth (Fritts, 1976), from the analysis strong association between annual growth and summer temperatures emerged. During the summer months of the current year, in fact, the correlation between growth and temperatures is positive for all the species (Figure 20): this confirms that higher summer temperature, especially during the vegetative period, allowed higher growth.

Birch and rowan showed a similar response both to temperature and precipitation, even if in slightly different periods. The two species responded significantly positively to the temperatures of June-July and July-August respectively: this difference suggests that the vegetation period of rowan and birch in Iceland is probably July-August and June-July, respectively. The same result for these two species was observed in another study carried out by Hannak and Eggertsson in 2020 in Iceland, and birch responded significantly positively to June and July temperatures also in another study by Levanic and Eggertsson (2008) in Iceland. Similarly, past tree-ring studies in Iceland found that tree-ring growth of birch in Iceland is mainly influenced by summer temperature (June-August) and, occasionally, by pests (e.g. insect outbreaks), while rowan is mainly influenced by summer temperature (Levanic & Eggertsson, 2008; Þórarinsson & Eggertsson, 2012; Eggertsson, 2014; Kaczka et al., 2015; Piermattei et al., 2017). A strong correlation between tree-ring width of *Betula pubescens* and June, July and August temperature was featured in northern Norway (Opała-Owczarek et al., 2015), while in northern Sweden birch chronologies are sensitive to June and July temperature of the current year (Young et al., 2011).

In Figure 28 we can observe how the growth trend of birch follows the trend of the average temperature of June and July.

Figure 28. Growth trend of birch and trend of the average temperature of June and July (1967-2018).

Looking at Figure 28, a consideration could be done also about volcanic eruptions: according to Global Volcanism Program, in 1970, 1980-81, 1991 and 2000 there were eruptions at Hekla volcano, about 26 km far from Búrfellsskógur. Deposits of tephra and ashfalls might have contributed to lower the photosynthetic rates, especially if the eruption occurred right before or during the growing period (such as the 1970 eruption, which started on May 5th 1970, and lasted until July 5th). Furthermore, the reduced atmospheric transparency associated with the dust veil may affect photosynthesis, influencing the local tree-ring growth response. Scuderi (1992) demonstrated an association with atmospheric opacity/solar radiation receipts at high elevation in the Sierra Nevada, however, this kind of relationship between volcanic eruptions and tree-growth should be further explored.

The overall positive correlation between birch growth and September temperatures of the previous year, even though not significant, can be considered fairly important. Since earlywood formation depends partially on stored photosynthates from the previous year(s), whereas latewood formation relies essentially on current year photosynthates (Helle & Schleser, 2004), correlation can be expected with temperatures of periods of the previous year when trees were hypothetically still photosynthesizing.

Both rowan and birch respond negatively to the previous year summer temperature (Figure 20), even though the response is significant only for rowan in July. Significant negative correlations between birch growth and July-August temperatures of the previous year have been also found in northern Norway by Opala-Owczarek et al. (2015). Similarly, in northern Sweden birch growth responded negatively to the previous year June-July temperature (Kaczka et al., 2015).

Precipitation (Figure 22 and 23) seems to significantly positively affect birch and rowan growth on March-April and January-February of the current year. Hannak and Eggertsson (2020) found in Iceland similar results for birch (positive correlations in March, April and May, with the strongest response in May), while rowan had the greatest response to precipitation in June. Thus, their result suggested that for both the species the greatest positive response to precipitation was before the vegetation period.

As demonstrated by Huang et al. (2022), the moisture contribution from winter precipitation to tree growth can persist until the late growing season, providing the isotopic evidence that winter precipitation affects latewood development by the processes of soil moisture.

On the contrary, no precipitation effect on tree growth was observed in northern Norway by Opała-Owczarek et al. (2015).

Lastly, low growth on birch can be, at least in some years, related to insect outbreak years: Levanič and Eggertsson (2008), in fact, stated that insect attacks significantly affect birch wood formation in Iceland.

Norway spruce responds significantly positively to June, July and August temperatures. A similar response to the one we observed for Norway spruce to summer temperature has been showed in a study by Andreassen et al. (2006) where in Norway, at both high altitudes and latitudes, they found that June temperature was the main driver for tree growth. A parallel observation was done on an altitudinal transect in the Alps: in a study by Hartl-Meier et al. (2014) Norway spruce was negatively affected by drought and high temperatures at lower elevations, whereas at higher altitudes, it seemed to be benefitting from warmer climatic conditions. In Norway, the temperature regime in June of the current year influenced the diameter growth of Norway spruce stands located at high elevations in most regions, except for the south-eastern part, where the species is mainly influenced by June precipitation (Andreassen et al., 2006). Similarly, in the Eastern Carpathians in Romania, at high altitudinal level tree growth was found to be strongly limited by summer temperatures (Sidor et al., 2015). The results of these studies confirm that the radial growth of Norway spruce is generally limited by low summer temperature at high latitudes and elevations (Bonan & Shugart, 1989; Makinen et al., 2002; Villalba et al., 1994; Woodward, 1987).

Our results for Norway spruce are thus in line with the other species analyzed in this study regarding the response to temperatures during the summer period, however, in both sites, it also shows a negative correlation during the month of April. Negative effects of warmer temperatures in the pre-vegetative period at high-altitude environments have also been reported by Carrer et al. (1998) in the Italian Eastern Alps: it can be hypothesized that mild temperatures in the months preceding the vegetative period might decompensate Norway spruce, causing excessive respiratory losses in a period where photosynthesis is practically zero. A compliant response to temperatures has been also shown for similar species, *Picea glauca* and *Picea Engelmannii*, in a study by Liepe et al. (2016) in similar latitudes in western Canada. However, it is difficult to transfer these results for Norway spruce in Iceland, also given the lack of studies on the behavior of this species in this peculiar climatic context (Snorrason & Kjartansson, 2017).

The positive response of Sitka spruce and lodgepole pine to summer temperatures confirm the importance of temperatures during the growing season, especially beyond the natural range of the species. The correlation value for Sitka spruce reaches the significance threshold (p=0.05) only in July, while lodgepole pine responds significantly positively to May and July temperatures. Sitka spruce seems more sensitive to previous year summer temperatures than to those of the current year: it is significantly negatively affected by the temperatures of the summer months June and August of the previous year, while June, July and August temperatures of current year does not influence species' growth significantly. For some years, a negative influence of the previous year summer temperature might be due to the accidental introduction in the late 1950s of the green spruce aphid (Elatobium abietinum (Walker), Aphididae), an insect that causes heavy defoliation on Sitka spruce. Some studies found consistent reductions in radial growth on affected trees during the year after the aphid outbreak (Halldórsson et al., 2003; Straw et al., 2000; Thomas & Miller, 1994). Hence, it is possible that the positive effect of temperatures on aphid abundance reflects into a negative effect for Sitka spruce, but this phenomenon could just partially and for only a few years explain the negative relationship with the temperatures of the previous year's growing season. The growth of Sitka spruce seems to be positively influenced by precipitation in the period from August to October (where only the correlation with October is significant) of the previous year. Positive correlations with precipitation can be expected since this species is originally found in areas with a minimum of 1000 mm of rainfall per year, and cannot tolerate even slight drought conditions (Houston Durrant et al. 2022). On the contrary, Lodgepole pine can grow with lower amounts of precipitation: according to Lotan and Critchfield (1990) it grows in restricted areas in the Northern Rocky Mountains (Canada) receiving, in some cases, only 250 mm of mean annual precipitation. This might partially explain the negative response to precipitation during some periods, given the abundance of precipitation that characterizes Icelandic climate.

The correlation profiles between summer temperatures and standardized chronologies for the five species are reinforced by a study (Babst et al., 2013) which evaluated the climate sensitivity of model-based forest productivity using a continental-scale tree-ring network. This work concluded that temperature controls dominate forest productivity at high-elevation and high-latitude areas, while moisture sensitive sites are widespread at low elevation in central and southern Europe.

5.4. Limitations of this study

A first limitation of this study is represented by the relatively short time window analyzed (52 years). However, this time window was the maximum available for this work, since in one of the sites (Rauðavtn, PISI) the tree ring series dated back just to 1948. The same problem was encountered by Levanič and Eggertsson (2008) on their study in Iceland. Increasing the length of the analyzed time window would have allowed the division of the total time window into sub-periods and the analysis of the correlations with the climate period by period. Hannak and Eggertsson (2020), for example, tested correlation values between climate variables and tree growth over different sub-periods of their time window, finding differences in the correlation values between the different sub-periods. Moreover, from the graphs in figures 24, 25, 26 and 27 the correlation values are likely influenced by the length of the chronology, in some cases in a significant way. The positive correlation between birch growth and June-July temperature is not significant looking at the longer chronology. Even when looking at precipitation, there are some differences in the results: comparing Figure 22 and 26, for example, the positive correlation between birch growth and precipitation in March and April becomes significant in the longer series. These discrepancies in the results confirm the importance of having long time interval in this type of analysis.

The results of a study by Carrer and Urbinati (2004) suggest that climate–growth relationships of *Larix decidua* and *Pinus cembra* are partially controlled by age: it might have been interesting to deepen the response of the species analyzed in this study also in relation to the age of the trees.

6. CONCLUSIONS

This study focused on the response to climate of three conifer species, introduced at northern areas respect to their distribution limit, and of two Icelandic native species.

For both native and exotic species, temperature proved to be the most important climatic factor driving tree growth. In particular, in the Icelandic context, a higher temperature during the summer, i.e. during the vegetative period, seems to stimulate the production of wider ring. If we consider the simple response to temperatures, we can hypothesize that a further future increase in temperatures could be favorable to tree growth, also given the abundance of precipitation that characterizes the island. However, to state this we must take into account many factors, many of which are still not fully understood and difficult to predict.

Exotic species (except Sitka spruce) seem sensitive to temperatures for a longer time window (from May to August) than the native ones. Native species are both significantly positively correlated with a two-months summer period, which suggests that their growth is concentrated during this time.

Current climate warming is causing abrupt changes all over the world, and in some areas the rising temperatures (often in combination with droughts) are driving several tree species even to extinction. The analyzed exotic species showed promising growth performances in Iceland, and understanding their behavior might also be useful for assisted migration, that is the movement of species and populations to facilitate natural range expansion as a direct management response to climate change (Vitt et al., 2010). Such strategy has two main positive aspects: it allows the expansion of species in areas where natural migration would otherwise be impossible or extremely slow, and can fulfill with these fast growing species the needs for afforestation and ecosystem services highly present across Iceland.

Precipitation seems to just slightly affect the growth of all the analyzed species, likely on species-specific and site-specific basis.

High latitude and altitude tree growth are usually temperature-limited and thus benefit from warming, however growth trends of tree species within the future perspective of global warming is not just matter of climatic conditions. In fact, together with the change in the climate/growth association, other external factors can occur, such as the introduction of a new pathogenic organism or a significant volcanic eruption, i.e. disturbances. These interactions could be even more complex to predict if we consider that any new disturbance could produce unpredictable effects, and leave many uncertainties about what the future relationships between tree growth and climate.

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