The potential of using Pinus sylvestris L. from the High Coast region as a climate proxy for studying hydroclimatic variability

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Abstract

It is of importance to get more detailed information on past spatio-temporal hydroclimatic changes in northern latitudes to understand the hydroclimatic regimes working there. This can be done by studying proxy data from tree rings. One place suitable for such research is the High Coast region which has many sites with thin soil cover on bedrock and therefore has low water storage capacity. Thus, trees growing here are dependent on precipitation and sensitive to drought events. Furthermore, the most common tree species here is Scots pine (*Pinus sylvestris* L.*)* which is a drought sensitive species and commonly used within the field of dendrochronology. The aim of this thesis was to examine the potential of using Scots pine from the High Coast region as a climate proxy. This was done by dating and measuring the tree-ring widths and calibrating these against precipitation, temperature, and the drought index *Standardised Precipitation-Evapotranspiration index* (SPEI). The dated samples expanded the existing swed324 chronology that previously stretched between 1448–1998 to 1403–1998 (i.e., 45 years) and further complemented the sample depth by 18 samples which gave it a higher reliability. The sample depth has especially been strengthened between 1480 and 1700 (i.e., 220 years). The results showed the strongest correlation with SPEI in the period of 1901-1998 for the month of June. Furthermore, the calibration between the tree-ring width, temperature and precipitation (1860-1998) showed a slightly lower correlation, although a significant climate signal could be found. Lastly the results showed a potential of tree-ring research in this region, which suggests further studies with methods such as blue intensity will be necessary to enhance the signal.

Keywords: Dendrochronology, Tree rings, *Pinus sylvestris* L., Sample depth, Climate correlation

Sammanfattning

Det är viktigt att vidare få mer detaljerad information över den tidsrumsliga historien av hydroklimatiska variationer på de norra breddgraderna för att förstå hur den hydroklimatiska regimen fungerar. Det kan göras genom att studera proxydata från trädringar. En plats som är passande för sådan forskning är Höga Kusten-regionen, som har många platser med ett tunt jordlager ovanpå berggrunden och därmed en låg vattenhållande förmåga. Träden som växer här är därmed beroende av nederbörd och känsliga för torka. Det vanligaste trädslaget som växer i regionen är Tall (*Pinus sylvestris* L.*),* vilket är en torkkänslig art som ofta används inom dendrokronologi. Syftet med denna uppsats var att undersöka potentialen att använda Tall från Höga Kusten-regionen som en klimatproxy. Detta genomfördes genom att datera och mäta trädringsvidd, som sedan kalibrerades mot nederbörd, temperatur och torkindexet: *Standardised Precipitation-Evapotranspiration index (SPEI).* De daterade proverna expanderade den befintliga swed324 kronologin som tidigare sträckte sig mellan 1448–1998 till 1403–1998 (d.v.s. 45 år) och ytterligare kompletterade provdjupet med 18 prover vilket därmed gav den en större trovärdighet. Provdjupet stärktes speciellt mellan 1480–1700 (d.v.s. 220 år). Resultaten visade den starkaste korrelationen med SPEI under perioden 1901–1998 för juni månad. Vidare visade kalibreringen mellan trädringsvidd, temperatur och nederbörd (1860–1998) en något lägre men ändå signifikant klimatsignal. Slutligen så visar resultatet på en potential av trädringsforskning i denna region, vilket föreslår ytterligare studier med metoder såsom blue intensity för att stärka signalen.

Nyckelord: Dendrokronologi, Trädringar, *Pinus sylvestris* L., Provdjup, Klimatkorrelation

Preface

This thesis ends our three years of Geography studies at the University of Gothenburg. It was through guest lectures in the second year that our interest in dendrochronology first started. When a subject in the field of dendrochronology was proposed for the bachelor's thesis it was an easy choice for both of us.

We would firstly like to thank our supervisor Kristina Seftigen for introducing us to the field of dendrochronology, and pedagogical guidance through this process. We would also like to thank PhD student and assistant supervisor Petter Stridbeck for practical and moral support. To the others at GULD we would also like to give a big thank you for sharing your knowledge in this field. Lastly, thank you to our course leaders Sofia Thorsson and Jonas Lindberg and classmates for helpful seminar discussions.

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Table of contents

1. Introduction **1**

1.1 Aim 2

1.2 Objectives 2

2. Theory **3**

2.1 Dendrochronology 3

2.2 Dating and chronology building 4

2.3 Tree ring-width and dendroclimatology 5

2.4 Hydroclimate 5

3. Study area **6**

4. Methods **9**

4.1 Sampling 9

4.2 Sample preparation 9

4.3 Tree-ring width measuring and crossdating 11

4.4 Standardisation 11

4.5 Climate correlation 12

5. Results **14**

5.1 The SWED2023 chronology. 15

5.2 Tree-ring width and climate 18

5.2.1 Calibration against Härnösand meteorological data 18

5.2.2 Calibration against SPEI 21

5.2.3 Marker years 21

6. Discussion **24**

6.1 Discussion of method 26

7. Conclusions **28**

8. References **29**

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) predicts that temperature extremes will most likely increase in Europe, and the winter temperatures have already been shown to rise in Northern Europe. This will also lead to changes in precipitation and drought as higher temperature increases evapotranspiration as well as the atmosphere's water holding capacity (Chen et al. 2020). IPCC (2021) believes it to be very likely that mean precipitation will increase and have high confidence in more heavy precipitation over Northern Europe. However, there is low confidence in the direction of change when it comes to drought scenarios.

To obtain information about our past climate, where no meteorological observations exist, proxy data such as ice cores, peat sediments and tree rings provide a valuable natural archive (Linderholm et al., 2018; Seftigen, Fuentes, Ljungqvist & Björklund, 2020). Proxy data enables a window to historical climate-change and extreme events (e.g., forest fires, cold/hot spells, storms). Tree rings are the most common proxy for studies of the climate in mid to high latitudes. They provide an annual resolution over the past 1000-2000 year and are considered a reliable method to study climatic variables (Linderholm, Björklund, & Seftigen et al., 2015; Ljungqvist, Pieramattei, & Seim, et al., 2020; Seftigen et al., 2020). Obtaining historical tree-ring proxy data about the past climate will help us understand the future climate (Speer, 2010, p. 4) and its effect on society, for example agriculture and energy (Seftigen, Björklund, Cook & Linderholm, 2014). This is because they provide data which can help to gain a comprehensive understanding of historical climate and natural variability. Such understanding will enable improved tests to develop more reliable models to predict how the future climate might look like (Fritts, 1976; Ljungqvist et al. 2020). Despite tree-rings' high climate sensitivity in Scandinavia, hydroclimatic research using tree-rings have been sparsely conducted on higher latitudes (Fuentes, 2017; St George & Ault, 2014). This is because tree growth is mainly driven by temperature, however, Jönsson and Nilsson (2009) mention a decreased temperature sensitivity on high latitudes since the mid 20th century. There are suggestions that due to a general temperature increase which affects the evapotranspiration, tree growth has become more sensitive to moisture stress. To fully understand these spatio-temporal changes in tree-growth sensitivity to hydroclimate in areas with cool and humid climate regimes, there is need for a denser network of tree-ring proxy data (Seftigen et al., 2020). However, reconstructing and understanding regional hydroclimate is challenging as precipitation and drought have spatial variabilities depending on topography and local features (Ljungqvist et al. 2020). Although studies by Seftigen et al. (2020) shows that there is an unrealised potential to use tree-ring width in the Fennoscandian region for this purpose. One region that possesses the growth-limiting climate factor usable in understanding the hydroclimatic variability on high latitudes is the High Coast region, eastern-central Sweden. The High Coast region consists mainly of exposed bedrock with thin soil layers, thereby not able to store much moisture (Sandström, Edman & Jonsson, 2020). Therefore, the tree growth here is highly dependent on precipitation and available soil moisture during the growing season. Hence, seasonal drought would result in limited tree growth. Scots pine (*Pinus sylvestris* L.) is the most common tree species in the area with characteristics of being drought sensitive, slow growing, often reaching ages of 300 years or more, which makes it a good material for dendrochronological investigations (Eilmann et al., 2010; Jönsson & Nilsson, 2009; Taeger, Zang, Liesebach, et al., 2013).

1.1 Aim

The aim of this thesis is to update the existing swed324 chronology from the High Coast region with tree-ring based proxy data of dead Scots pine trees, and to examine the potential of using the updated chronology for hydroclimatic reconstruction purposes. Dendrochronological methods such as measuring the width of the annual tree rings and crossdating will be used in an attempt to expand the current sample depth of the existing chronology for the region. Meteorological data including temperature, precipitation, and the drought-index: *Standardised Precipitation-Evapotranspiration index (SPEI)* will then be calibrated with the tree-ring width data to understand how the growth is affected by the hydroclimate.

1.2 Objectives

- If possible to date the discs, what years can the discs of dead Scots pine trees from the High Coast region be dated to?

- How far back in time can the dated Scots pine tree discs expand the sample depth of the existing swed324 chronology?

- What relationships can be established between the tree-ring width proxy data and climate variables in the High Coast region?

2. Theory

2.1 Dendrochronology

Dendrochronology has many subfields where the *chronology* refers to the dating of tree rings which then can be related to different events. Depending on what is being studied, the dendro-field can be categorised as dendro *-climatology, -archaeology, -geomorphology, -ecology,* and so forth (Fritts, 1976, p. 10). The basics in any of these fields are the formation of tree rings, a phenomenon that relies upon the changes of season which usually occurs in the mid- and high latitudes (Frank, Fang & Fonti, 2022; Linderholm et al. 2018). These switches between growing and dormant states result in visible and microscopical delineations that reflect the environmental conditions of the year. It is this feature that makes dendrochronology and its subfields a useful method when for example acquiring paleoclimatic information. Factors that can be measured are the width, density, and isotopic composition as well as the total number of rings through crossdating (Frank et al., 2022; Linderholm et al., 2018). In the beginning of the growing season the trees produce *earlywood*, which are characterised by large, thin-walled cells. At the end of the growing season the trees instead produce *latewood*, which have smaller, more thick-walled cells making it appear darker (Fig. 1) (Fritts, 1976, p. 13, 20; Speer, 2010, p. 17, 43). In Fig. 1, the tree grows from left to right where the abrupt boundary between the latewood and the new cells of the earlywood therefore marks one annual ring.

Figure 1. A sectional cut of a Pinus sylvestris L. *showing the cell structure, earlywood, and latewood. Source: Authors own.*

Figur 1. Tvärsnitt av en Pinus sylvestris L. *som visar cellstruktur, vårved och höstved. Källa: Författarnas egna.*

2.2 Dating and chronology building

Crossdating is one of the fundamental methods within the dendrochronological field. It is the process of identifying the exact calendar year for each tree ring. In living trees an anchor in time can usually be set to the last formed tree ring (Stokes & Smiley, 1996, p. 48-49). However, chronologies from living trees can only be expanded to the maximum living period of the tree. (Scots pine approximately 300-400 years) (Sandström, 2020). To further expand a chronology back in time, there is a need for samples of dead trees. These samples need to be overlapped and anchored with living tree samples or an already established chronology from the same/nearby site (Speer, 2010, p. 12; Stokes & Smiley, p. 5, 51). The dating can for example be achieved with methods of measuring the width of each ring, or studying pointer years (Sandström, 2020; Speer, 2010, p. 11). The width of the rings reflects the environmental conditions of where the tree has grown. Therefore, it can be expected that the majority of the trees in a population have similar growth patterns for each year which can be seen in the ring structures (Fritts 1976, p. 20-21; Speer 2010, p. 11-12). It is important to compare several samples to each other in order to confirm the principle of uniformitarianism, and to find anomalies such as missing rings or false rings. An average of 20 trees and two samples from each tree is generally considered sufficient, however, depending on the quality of the samples, additional or fewer samples may be required for statistical credibility (Fritts 1976, p. 248; Speer 2010, p. 23). Sample depth is the number of samples that represent a phenomenon back through time and should always be considered. Sampled living trees are most likely not the same age, and the further back the chronology stretches the more likely the sample depth gets thinner. When falling below 10 to 20 trees there might be stronger signals from individual trees' growth variation than from the common growth (Speer, 2010, p. 176). The adequacy of the sample depth needs to be estimated by the researcher for each sample site and particular study (Fritts, 1976, p. 323). To measure the reliability of the sample depth Expressed Population Signal (EPS) can be used. EPS gives an indication on the strength of the unknown population signal (Buras, 2017) described as an EPS value, adopted at 0.85. If dropping below this value, it is an indication that the signal comes from individual trees rather than the population's common stand. This does not mean the samples are not correctly dated however, since the credibility might be too low for a reliable climate signal. Furthermore, EPS is a chronology measure that is commonly used among dendrochronologists (Speer, 2010, p. 109).

2.3 Tree ring-width and dendroclimatology

In the sub-field of dendroclimatology, the dendrochronologist searches for information about the past and future climate (Fritts, 1976, p. 10). When looking for climate signals it is important to minimise noise from non-climatic disturbance. Therefore, it is central to choose sites where the limiting environmental factor can be expected to be found (Jönsson & Nilsson, 2009). The variation of the tree-ring widths is mainly driven by these factors. This principle of limiting factors, stated by Fritts (1976, p. 15) means that "a biological process, such as growth, cannot proceed faster than is allowed by the most limiting factor". This could be precipitation, temperature, or nutrients in the soil (Speer, 2010, p. 16). Tree rings of drought sensitive trees record dry years with a narrower ring and a rainy year with a wider ring, however, the width is not necessarily uniformal (Stokes & Smiley, 1996, p. 3). A tree can have the same limiting factor throughout the years, or it might change, and other factors can become limiting. The more a tree is limited by the factor, the stronger a signal can be found in variations in the tree-ring widths (Fritts 1976, p. 15-16, 19; Speer, p. 16). Reconstructions of the past climate can be made by comparing the tree-ring widths to meteorological data to create a statistical equation, which can then be used on the ring widths that reach further back in time than meteorological records can. The reconstruction of the past climate can thereby give estimates about what the future climate might look like (Fritts, 1976, p. 2, 10 -11; Speer, 2010, p. 4-5, 174-175). It is of importance to improve past hydroclimatic records to create more reliable models and reconstructions, which are important for a deeper understanding of the past, present and future hydroclimate (Ljungqvist et al., 2020).

2.4 Hydroclimate

Hydroclimate refers to the hydrological cycle's relation to the climate. The hydrological cycle consists of many processes on different scales such as evaporation, condensation and precipitation to water storage, stream flow and run-off patterns (National Weather Service, n.d.). To understand the hydroclimate in a region, there is need to identify the baseline conditions (Teale, 2020). However, these are complex systems which requires extensive studies that exceeds the time frame for this study. Therefore, only precipitation, temperature and drought patterns will be examined.

3. Study area

The study area is located in the High Coast region (62.65°N, 18.08°E to 63.20°N, 19.06° E), Västernorrland county, Sweden.

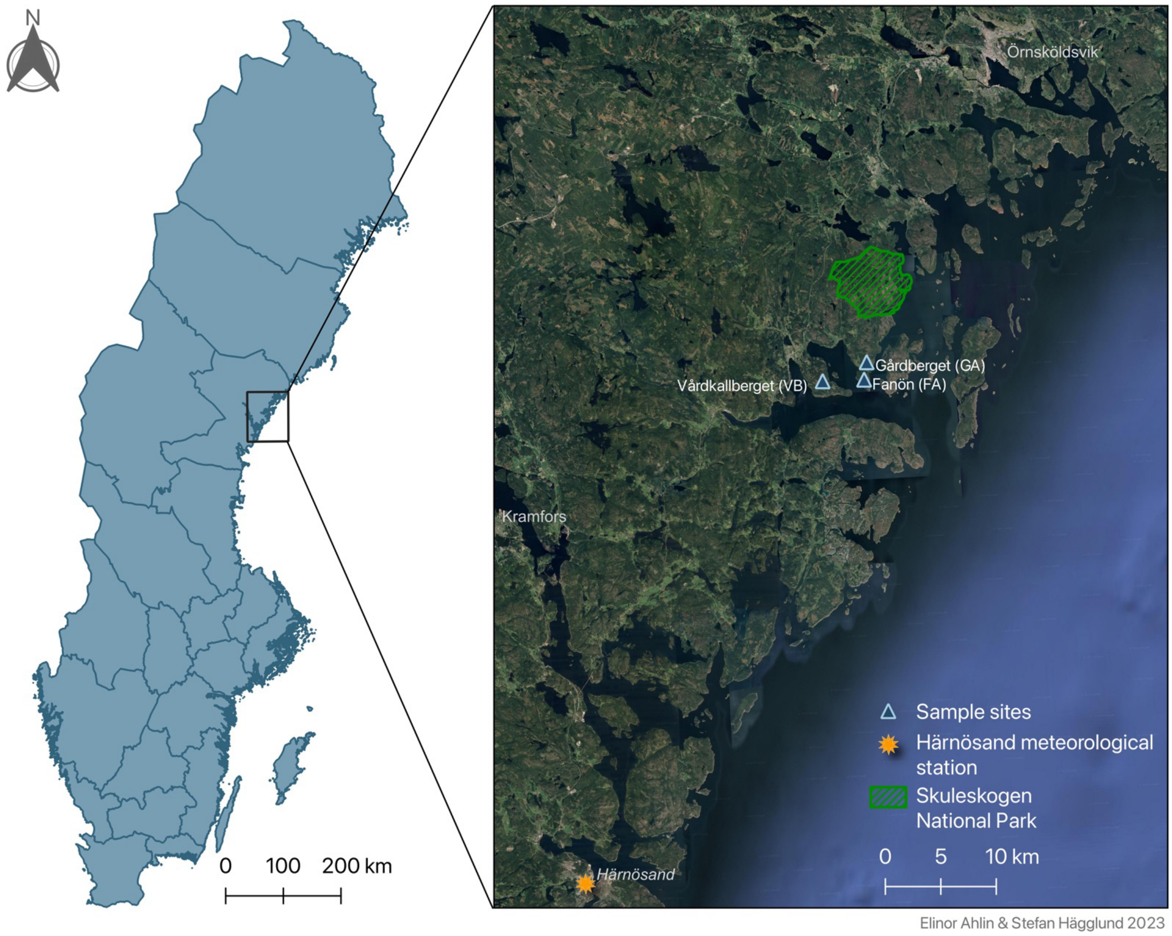

Figure 2. Location of the High Coast region and the three sampling sites; Gårdberget (GA), Vårdkallberget (VB) and Fanön (FA), Härnösand meteorological station and Skuleskogen National Park. Data source: Google Satellite, The Swedish Environmental Protection agency and Statistics Sweden (SCB)

Figur 2. Lokalisering av Höga kusten regionen och de tre provtagningplatserna; Gårdberget (GA), Vårdkallberget (VB) och Fanön (FA), Härnösands meteorologiska station och Skuleskogens nationalpark. Datakälla: Google Satellite, Naturvårdsverket och Statistikmyndigheten (SCB).

The region is characterised by a steep hilly topography largely influenced by the retreat of the last glacial period 10 400 years ago. This triggered a land uplift still ongoing today with a pace of 8 mm lifting per year (Geological Survey of Sweden (SGU), 2005). The historical uplift with its geological processes has left the environment rocky with soils that are nutrient poor in thin layers (Sandström et al., 2020). The soil in the High Coast is according to SGU (2005) classified as exposed rock on the majority of the hilltops in the area, loose gravel and sand, shingle, thin or incoherent soil layer and moraine (Fig. 3). Scots pine (*Pinus sylvestris L.*) is the most common tree species in these rocky forests. Many of the rocky pine forests in the High Coast region are and have not been easily accessible, which makes the forests little affected by human activities. The forests have thereby a high number of old trees and untouched dead trees (Sandström et al. 2020; K. Seftigen, personal communication, March 30, 2023). The sampling site of the Scots pine trees used in this study is located at the coast, just south of Skuleskogens national park. The samples were collected from three different sites in the High Coast region, Vårdkallberget (VB) 63.03°N, 18.38°E, Gårdberget (GA) 63.04°N, 18.46°E, Fanön (FA) 63.03°N, 18.45°E (Fig. 2) (K. Seftigen, personal communication, March 30, 2023).

Figure 3. Photo from the sample site Gårdberget, showing the typical characteristics of the rocky forest with Scots pine trees. Photographer: Petter Stridbeck, July of 2022.

Figur 3. Fotografi från provtagningsplatsen Gårdberget som visar de typiska karaktärsdragen av den steniga skogen med dess tallar. Fotograf: Petter Stridbeck, juli 2022.

The study area has a boreal climate classified as Dfc according to the Köppen-Geiger climate classification meaning a cold climate with no dry season and cold summers. Smaller areas can also be found at the coastline within the study area that are classified as Dfb, having warm summers in contrast to cold summers in the Dfc classification (Beck et al. 2018; Kottek et al. 2006; Rubel. et. al. 2017) as most clearly visualised in Beck et al. (2018). The average mean monthly temperature at nearby meteorological station Härnösand (approximately 50 km from the sampling site) is in January -5.7 °C, and in July 15.7 °C, over the normal period 1971-2000 with an annual precipitation of 711 mm (Fig. 4) (SMHI, 2023a).

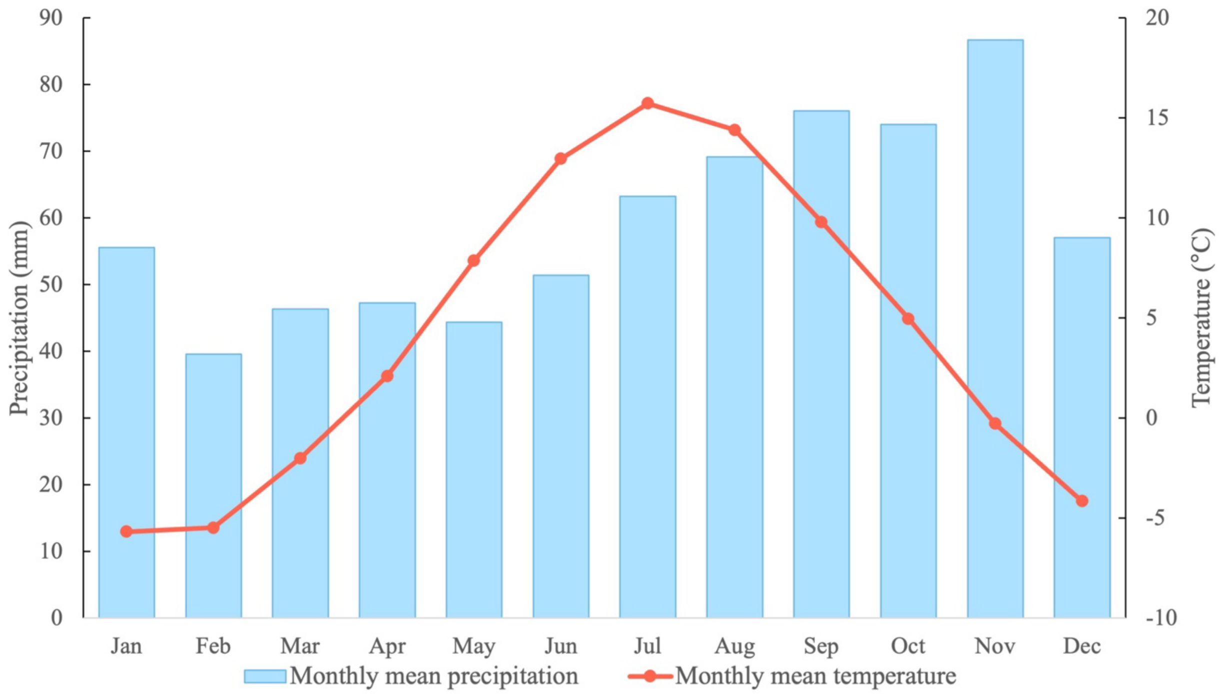

Figure 4. Monthly mean precipitation (1971-2000) and temperature (1971-2000) from Härnösand meteorological station (62°N, 17°N).

Figur 4. Månadsvis nederbörd (1971–2000) och temperatur (1971–2000) från Härnösands meteorologiska station (62°N, 17°N).

4. Methods

4.1 Sampling

The samples used in this thesis were collected in July 2022 by Gothenburg University Laboratory for Dendrochronology (GULD). The sample sites were chosen according to various factors as described in the study area; thin soil layer, undisturbed rocky forests, presence of old living trees, untouched old dead trees, and an overall moisture-constrained environment. The aim was also to collect living trees as well as dead trees. The latter was selected based on two criteria: 1) as many tree rings as possible (less than 30-50 rings were not sampled), 2) appearing to have been lying on the ground for a long time, where covered in moss, had signs of fire and where most of the trunk was gone (K. Seftigen, personal communication, March 30, 2023). This targeted sampling of choosing samples that are the oldest and the most likely to be stressed by the climate is required when attempting to document climate signals and furthermore create a climate reconstruction (Speer, 2010, p. 21, 76). This is to distinguish variations caused by the climate in the tree rings. The living tree samples were collected using an increment borer with 12 mm diameter, manufactured at Haglöf Sweden AB, while the dead trees were cut into discs using a chainsaw. The samples were later brought to the University of Gothenburg to be processed and catalogued (K. Seftigen, personal communication, March 30, 2023).

4.2 Sample preparation

The tree discs to be used in this study were selected by the estimated number of rings, distinction of the rings and absence of noise (e.g., abnormal growth patterns). A total of 42 discs were selected, 30 from Gårdberget, 10 from Vårdkallberget and 2 from Fanön. Each disc was then cut into smaller samples, from bark to core, by using a band saw following Stokes and Smiley's (1996) recommendations. These cutouts were then sanded to increase visibility of the cells in the cross-sectional view and the tree-ring boundaries. The sanding started with a coarse 80 grit paper on a belt sander, followed by 120, 180, 240, 320, 400 grit laid out on a flat table surface and done manually (Speer 2010, p. 92 - 93; Kristina Seftigen & Petter Stridbeck, personal communication, March 24, 2023). Thereafter the samples were cut thinner, to about 4 mm, and labelled with the id of the sampled tree and site. The samples were then put into a *soxhlet extractor* to remove impurities like resin (Fuentes 2017; Seftigen et al., 2020). A soxhlet extractor is a reflux distillation apparatus containing a distillation flask, a glass chamber with a syphon tube and a condenser. The apparatus is placed on a heater that evenly heats up the extraction liquid, in this case ethanol (97%). The alcohol is then going through the condenser and dripping down over the samples which are placed within the soxhlet chamber. The alcohol extracts impurities from the wood and is then led out of the chamber through the syphon tube (Sella, 2007). The samples were washed in two different batches, both for approximately 27 hours and thereafter dried overnight. When dry, all samples were sanded again with a finer 500 grit fraction.

Figure 5. Sample GAP361 sawn from a disc of a dead Pinus Sylvestris L. *with a high content of resin. Source: authors own.*
Figur 5. Prov GAP361 utsågad del av en disk från en död Pinus Sylvestris L. *med mycket kåda. Källa: författarnas egna.*

Figure 6. Sample GAP361 after being refluxed in 27 hours in 97% ethanol and sanded. Source: authors own.
Figur 6. Prov GAP361 efter att ha refluxats i 27 timmar i 97% etanol och slipats. Källa: författarnas egna.

The next step was to digitalise each sample using *Skippy*, an image-capturing system developed in 2020 at the Swiss Federal Institute of Forest, Snow and Landscape Research, WSL (n.d.). It is integrated with a Sony Alpha 7R IV; 61-megapixel camera which takes high resolution pictures, 6000 dpi, every 6 mm. These picture series were then stitched together in a program called PTGui and cropped to reduce the amount of data for each picture (PTGui, n.d).

4.3 Tree-ring width measuring and crossdating

The first step in the process was measuring the tree-ring width. It was done digitally by opening the stitched skippy-photos in *CooRecorder* version 9.4. It is a software designed to mark out coordinates of the earlywood and latewood on an image, and the distance between these coordinates will then be automatically measured (Cybis, 2023). This type of digital measuring-method offers many advantages compared to manual registration such as faster procedures, facilitates quality controls and the advantage of multiple storage and accessibility (Maxwell & Larsson, 2021). The main tool used in CooRecorder was the measure of latewood/earlywood, and each image file was set to 6000 dpi and 4,2-pixel width. After the registration of all rings and measurement of ring width, the coordinate file was saved as a .pos file. The next step was to crossdate the material against a dated master chronology named swed324. The swed324 chronology dates from 1448 to 1998 and consists of 36 core samples from living Scots pine trees. These were sampled in Skuleskogen National Park, which is located at approximately 5 to 10 km from the sample sites of this study (Fig 2.) (Linderholm, Solberg & Lindholm, 2003). The chronology had a strong sample depth for the first 200 years, but the sample depth in the 16^{th} and 15^{th} century consisted of 2 and 1 sample. The .pos files were imported to *CDendro* (Cybis, 2019), where they were correlated one by one to the reference. Thereafter, the files were converted to .rwl-files which was necessary to statistically analyse them in *COFECHA*. COFECHA is one of the most widely used softwares in dendrochronology and provides an estimate on how accurate the crossdating and measurement is (Fuentes, 2017; Holmes, 1983; Zhang, Pretzsch & Rothe, 2012). It does not crossdate but identifies anomalies and gives suggestions on alternative matches to the reference (Grissino-Mayer & Henri, 2001; Holmes, 1983). These suggestions were then followed up by visual controls, both digital and analogue, to identify false and missing rings that might have affected the result. Samples that were successfully crossdated were then used for further analysis while the unsuccessfully crossdated samples were excluded.

4.4 Standardisation

As tree-ring widths can vary due to non-climatic reasons (e.g., tree age, height within the stem and site conditions) standardisation is required to reduce unwanted noise from the climate signal. This makes young, fast-growing wood comparable to old, slow growing wood (Fritts, 1976; Melvin & Briffa 2007; Speer, 2010, p.177). For this study ARSTAN was used which is a software that applies standardisation techniques to mathematically standardise each tree-ring series. The standardisation method chosen in the ARSTAN software was a *cubic smoothing spline* with a 25-year spline-length was fit to each individual ring-width series. ARSTAN then divided the ring-width measurements with the fitted spline, resulting in dimensionless tree-ring indices, visualised as a plot with a straight line of value 1. These indices were then averaged to obtain a site chronology. The site chronology was then calibrated against climate data (see next section). This technique was well suited for the closed-canopy forests with higher stand dynamic signal (Speer, 2010, p. 138-139) similar to the High Coast region. It is important to be aware of how much variance is removed over a temporal scale.

4.5 Climate correlation

The meteorological data used for the climate correlation was obtained from historical meteorological observation data by the Swedish Meteorological and Hydrological institute (SMHI, 2023b). The data regarded monthly mean temperature and precipitation, between the years 1860 and 1998, from the meteorological station Härnösand (station number: 127380) at 62°N and 17°E. The Härnösand station is located approximately 50 km from the sample sites (Fig. 2). The station is also located at a similar distance from the coast as the sample sites. To conduct the climate correlation between the meteorological monthly mean data from Härnösand with the yearly tree-ring width of the Scots pine, Excel was used. The climate correlation was done using the *CORREL* function. The function finds the correlation coefficient between two variables which in this case was the monthly mean temperature (1860–1998), precipitation (1860-1998) and the yearly tree-ring width. The tree-ring width was extracted from ARSTAN in a standardised form and cut to the same 1860–1998 period. The correlation analysis shows which months of the climate data that correlates with the tree-ring width in the whole time period (Speer, 2010, p. 177). The significant months that were found were then divided into 30-year segments, with a running 10-year overlap to investigate how the climate sensitivity of the tree growth changes through time. Furthermore, the drought index *Standardised Precipitation-Evapotranspiration index (SPEI)* (version 2.6) was obtained from KNMI Climate Explorer (2022) in one month timespan over the period 1901-1998 at a 0.5-degree resolution gridded over 62.5°N, 17.5 °E to 63.5°N, 18.5 °E. The index is used to detect, monitor, and analyse droughts by representing the climatic water balance. SPEI is calculated by taking the monthly precipitation minus the potential evapotranspiration, where negative values mean dry conditions, and positive wet (Vicente-Serrano, Beguería & López-Moreno, 2010). The SPEI-index was calibrated with the tree-ring width in a similar way as the meteorological data, to investigate which months correlated with the ring width.

Lastly, to identify the thinnest and widest years of the tree-ring width, a simple sorting in Excel was conducted over the years covered by the meteorological data (1860–1998). Twenty of the thinnest and widest were extracted and examined.

5. Results

Out of a total of 42 samples, 18 could be dated ranging from the year 1403 to 1928 from the sample sites Gårdberget (GA) and Vårdkallberget (VB) as shown in Table 1. No samples from Fanön (FA) could be dated. The new series had almost all completely overlapping years with the swed324 samples. Two of the series did partly overlap: GAP00329 which overlapped 189 years out of 226, and GAP00611 which overlapped 206 out of 251 years. All the dated samples had correlation values with the master chronology that exceeded the COFECHA recommendation minimum of 0.328 (Speer, 2010, p. 128). The remaining 24 undated samples did not correlate well enough to the master chronology and were therefore excluded from the results.

Table 1. The 18 dated samples from the two sample sites Gårdberget (GA) and Vårdkallberget (VB) with their timespan, total years, and correlation with the master chronology (swed324).

Tabell 1. De daterade proverna från de två provtagningsplatserna Gårdberget (GA) och Vårdkallberget (VB) med dess årsspann, totala antal år och dess korrelation med masterkronologin (swed324).

Sample ID	**Timespan**	**Years**	**Corr. with master (swed324)**
GAP00109	1450–1537	88	0.42
GAP00316	1487–1595	109	0.70
GAP00317	1554–1744	191	0.70
GAP0321B	1600–1737	138	0.49
GAP00329	1411–1636	226	0.55
GAP00330	1646–1812	167	0.49
GAP00350	1535–1689	155	0.66
GAP0361C	1520–1684	165	0.58
GAP00611	1403–1653	251	0.50
GAP00655	1480–1712	233	0.61
VBP00004	1722–1907	186	0.48
VBP00010	1733–1928	196	0.61
VBP10012	1654–1738	85	0.50
VBP20012	1741–1871	131	0.60
VBP00126	1735–1881	147	0.46
VBP10140	1570–1676	107	0.44
VBP20140	1678–1750	73	0.40
VBP00217	1789–1879	91	0.37

5.1 The SWED2023 chronology.

The dated 18 samples were added to the swed324 chronology consisting of 36 samples resulting in an updated chronology consisting of 54 samples. The updated chronology had a series intercorrelation of 0.585 and will hereafter in this report be referred to as SWED2023. The updated chronology was expanded 45 years back in time from 1448 to 1403, making the total chronology reach 595 years back in time (Fig. 7). The swed324 samples are labelled as "SBHT" in Fig 7. They show a high sample depth from ~1700 to 1998 but show a low sample depth in the earlier years, having only two samples dating back to 1589, and 1 to 1448. The SWED2023 chronology therefore expands the sample depth in the years with low depth by up to 12 samples.

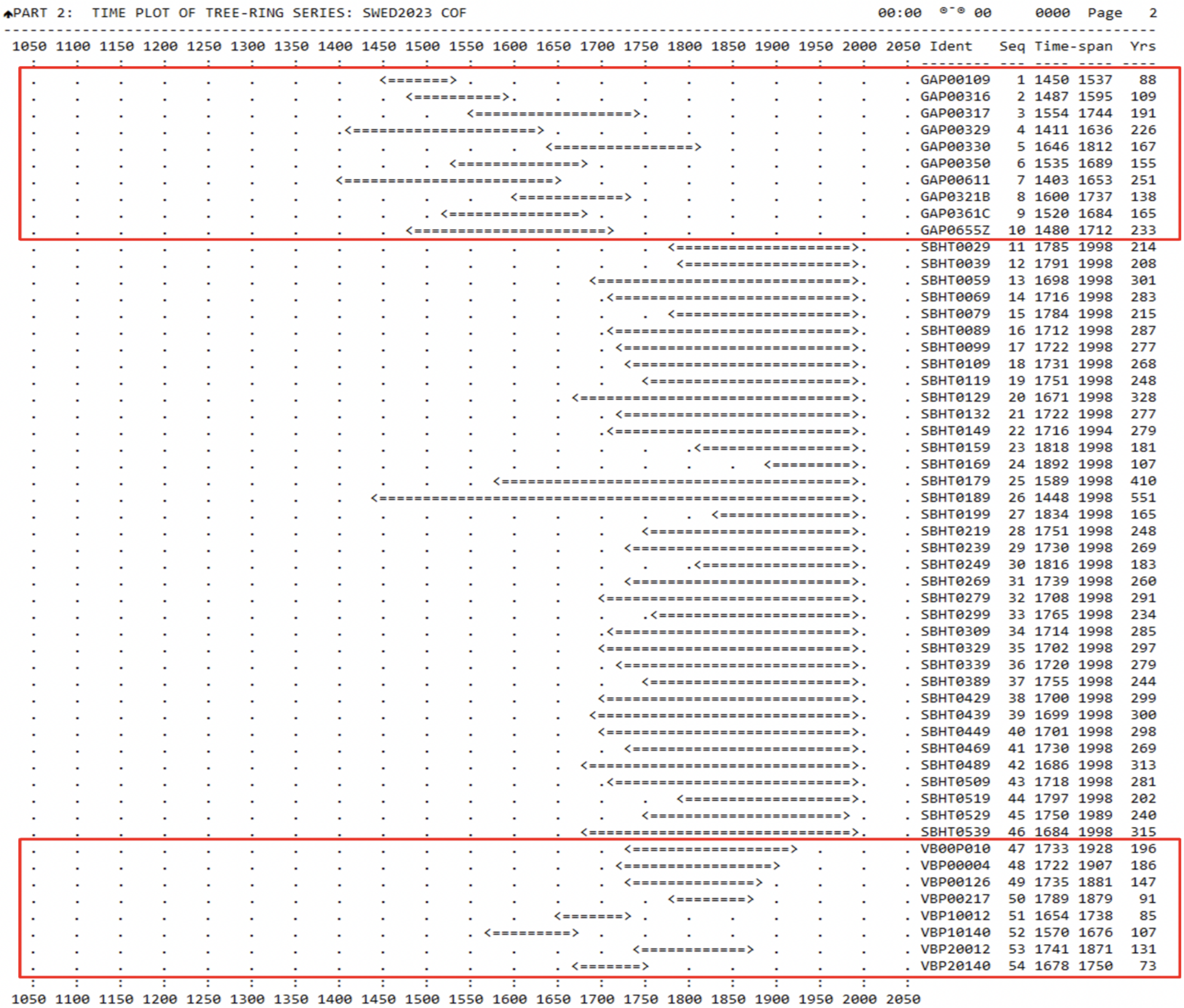

Figure 7. The SWED2023 chronology output from COFECHA with time-span and total years of each sample. New samples highlighted in the red frames. The total number of samples can be seen in the column "seq".

Figur 7. SWED2023 kronologin från COFECHA som visar tidsspann och totala år för varje prov. Nya prover är markerade i de röda ramarna. Det totala antalet prover kan ses i kolumnen "seq".

In Fig. 8, the SWED2023 chronology is firstly shown before the standardisation in ARSTAN (A), where fluctuations in tree ring-width are visualised throughout the chronology. Fluctuations can be seen in the early years where the sample depth is low (C), but also from the years 1700 to 1800, which most likely is related to the young trees from swed324 entering the chronology. The standardised chronology can be seen in B) where long-term variations in tree growth not related to climate (e.g., age trend) have been removed to isolate climate forcings in the trees for the latter climate analysis. The sample depth of the SWED2023 chronology is visualised in plot C) where the sample depth remains at a lower level around 10 trees before it increases in the 1700s.

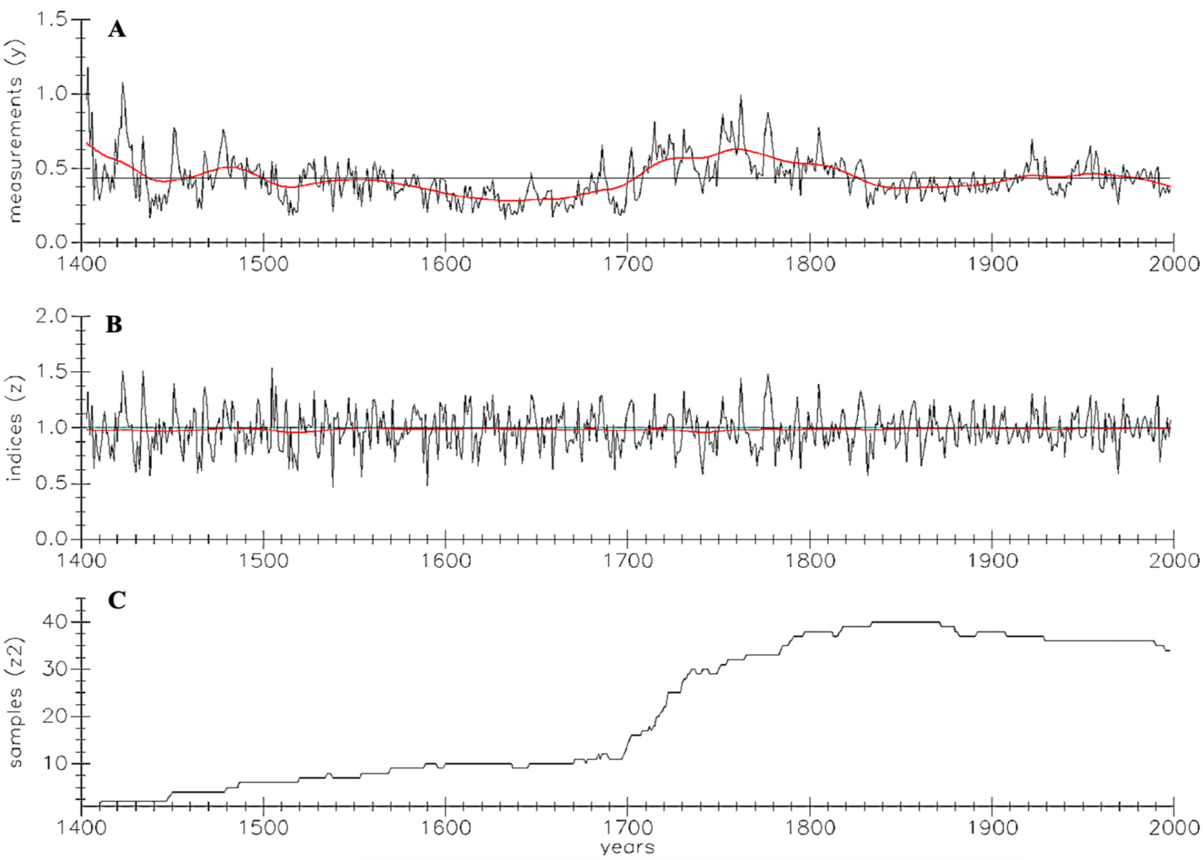

Figure 8. SWED2023 chronology extracted from ARSTAN. Plot A) shows the raw tree-ring width chronology before the standardisation. Plot B) represents the tree-ring width chronology after standardisation in ARSTAN. Plot C) shows the sample depth through time.

Figur 8. SWED2023 kronologin extraherad från ARSTAN. Diagram A) visar kronologin över trädringsbredd innan standardiseringen. Diagram B) representerar kronologin över trädringsbredd efter standardisering i ARSTAN. Diagram C) visar provdjupet genom tiden.

To confirm that the result was representative for the whole population ARSTAN calculated the rbar and EPS statistics for the standardised samples (Fig. 9). The rbar (A) shows the mean correlation between the series when detrended from yearly growth (Zafar, Ahmed, Farooq, et al. 2010). Plot B shows the EPS strength of the population through the chronology. The EPS was stable until fluctuating and dropping below the adopted 0.85 EPS value in 1690, then reaching above the same value 1650–1610. Thereafter it remains just around 0.85 until 1550 when it is steadily dropping. The rbar follows the EPS (B) as it drops in the same time periods (1550, 1590, 1675). Apart from adding to the already sufficient sample depth for the 20th, 19th and 18th century the new samples expanded the depth in the 17th, 16th and 15th century. Despite this, more samples are needed in the two latter eras to reach the acceptable EPS threshold for the detrended tree ring-width data.

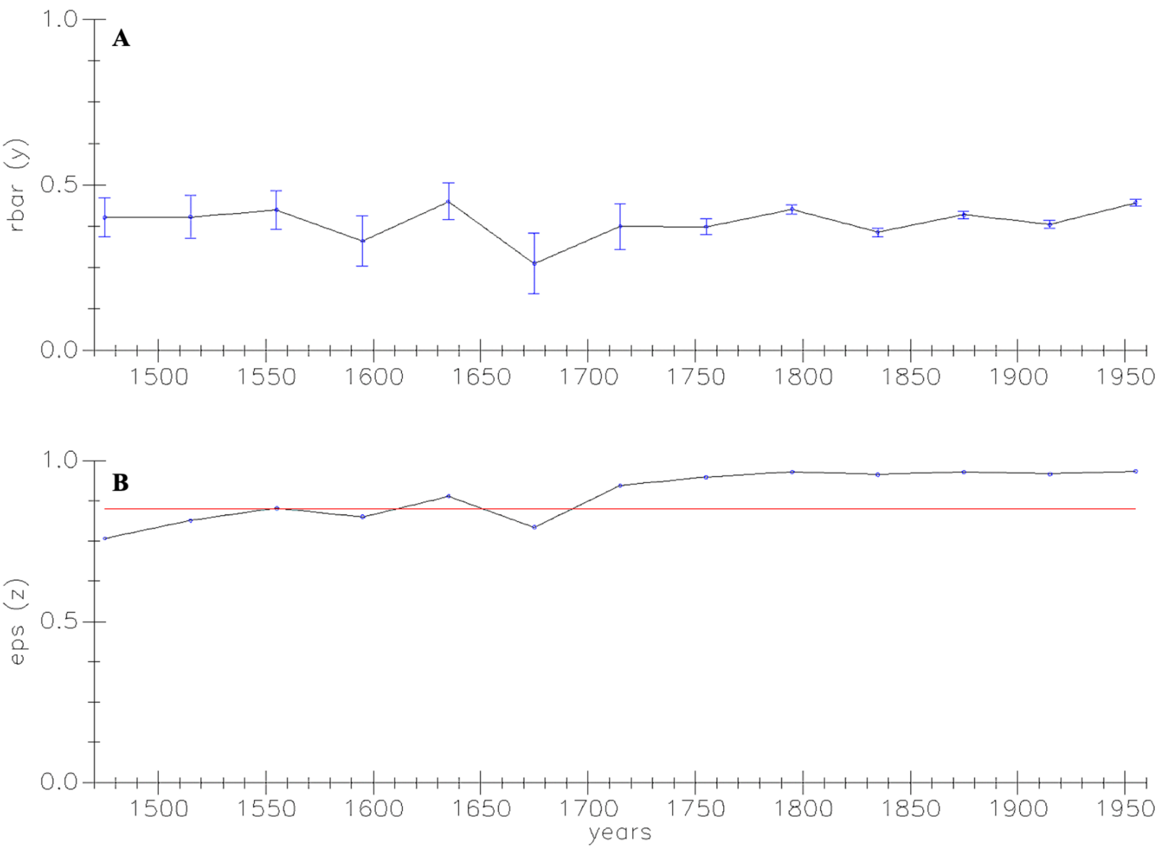

Figure 9. The rbar in A) represent the average correlation between all detrended tree-ring width time series. The EPS statistics in B) shows that the credibility of the chronology is dropping and fluctuating from 1670 and back.
Figur 9. Linjediagram A) representerar den genomsnittliga korrelationen mellan alla standardiserade träringsviddserier. EPS diagrammet B) att kredibiliteten av kronologin faller och fluktuerar från 1670 och bakåt.

5.2 Tree-ring width and climate

5.2.1 Calibration against Härnösand meteorological data

When standardised through ARSTAN the samples tree-ring width growth were calibrated with the Härnösand monthly temperature and precipitation data over the period 1860–1998. As seen in Fig. 10 there was a positive correlation with precipitation in June, with a correlation coefficient at 0.33, indicating a rather weak, although significant climate signal.

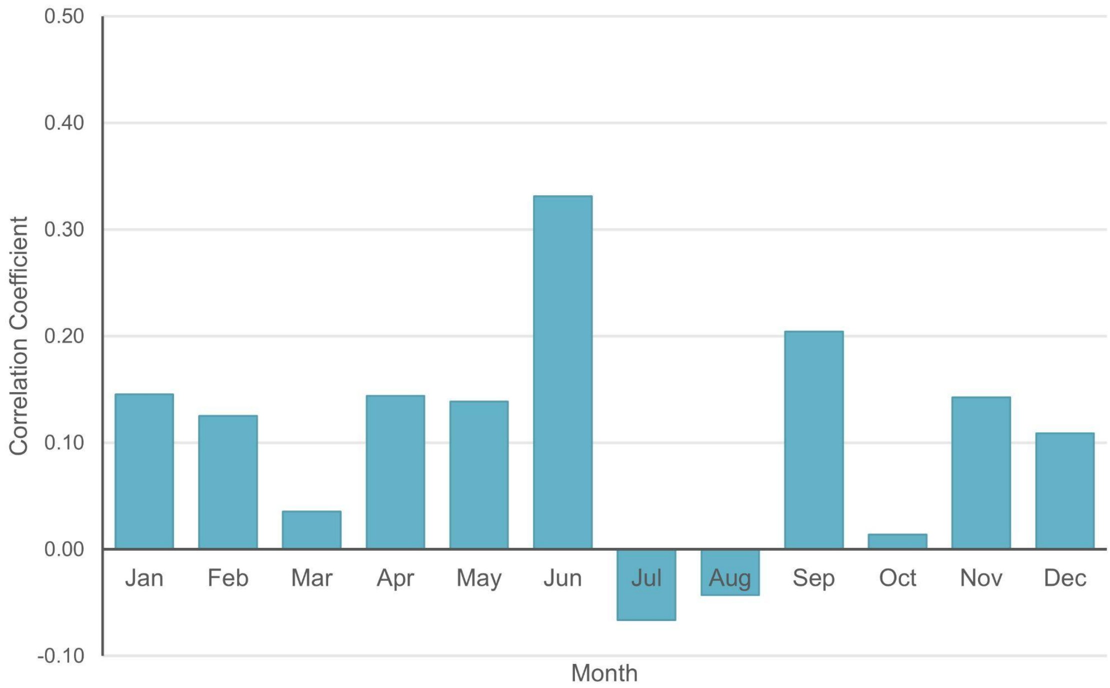

Figure 10. Correlation between monthly precipitation from Härnösand meteorological station and the standardisation tree-ring width chronology for the period 1860–1998.

Figur 10. Korrelationen mellan månadsvis nederbörd från Härnösands meteorologiska station och den standardiserade trädringsvidd-kronologin för perioden 1860–1998.

To find out how the June precipitation correlation has changed since 1860, the whole time period was divided into 30-year segments with a 10-year overlap (Table. 2). It showed that the correlation has been fluctuating around 0.3. However, in the segment of 1940–1970 the correlation with precipitation was much higher (0.54)

Table 2. Correlation for June precipitation in 30-year running segments with a 10-year overlap in the period 1860–1998. Last segment consists of 38 years.
Tabell 2. Korrelation för juninederbörd i löpande 30-års segment med 10 års överlapp i perioden 1860–1998. Det sista segmentet består av 38 år.

Running 30-year segment	**June correlation**
1860–1890	0.29
1880–1910	0.39
1900–1930	0.23
1920–1950	0.36
1940–1970	0.54
1960–1998	0.31

Total June precipitation correlation: 0.33

Temperature over the period 1860–1998 had the strongest correlation with tree-ring width in May with a correlation value of 0.37 (Fig. 11).

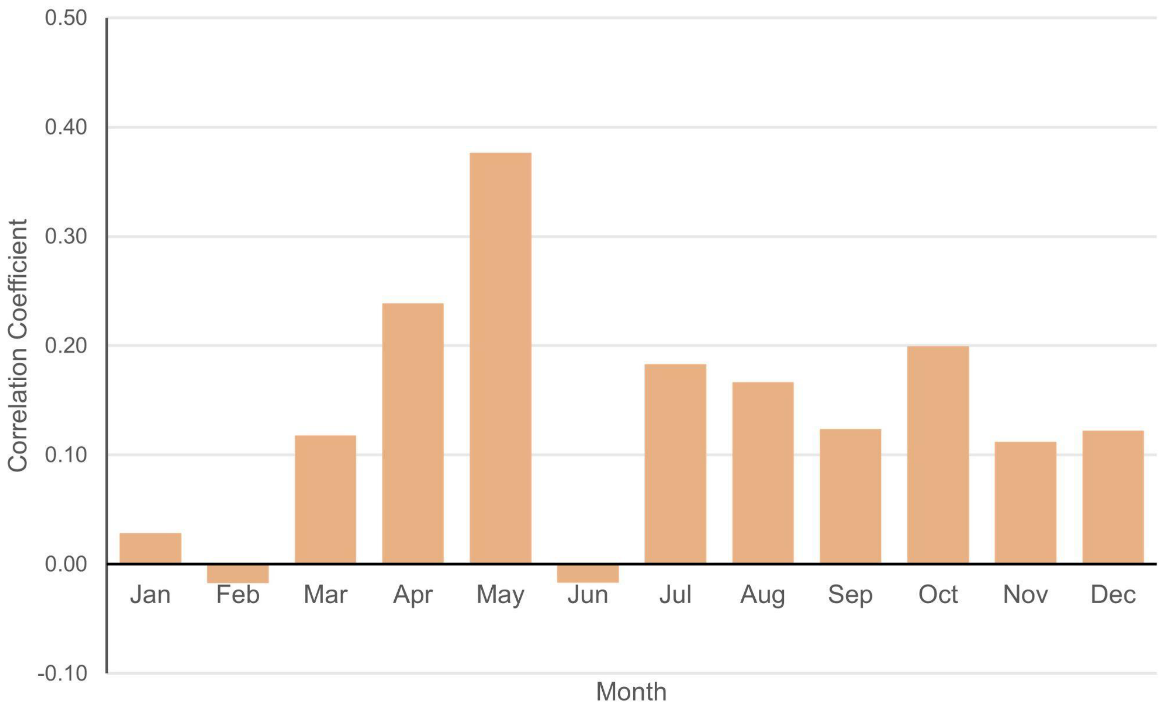

Figure 11. Correlation between monthly temperature from Härnösand meteorological station and the standardised tree-ring width chronology for the period 1860–1998.
Figur 11. Korrelationen mellan temperatur från Härnösands meteorologiska station och den standardiserade trädringsvidd-kronologin över perioden 1860–1998.

When dividing the whole May temperature period of 1860-1998 into 30-year segments with 10-year overlap it showed a much lower correlation than expected (Table. 3). None of the segments had equally high correlation as for the whole period and the segments 1920 - 1950 were negative.

Table 3. Correlation of May temperature with tree-ring width divided into 30-year segments with a 10-year overlap in the period of 1860–1998. Last segment consists of 38 years.
Tabell 3. Korrelation mellan maj temperatur och trädringsvidd uppdelad i 30 årssegment, med 10 års överlapp perioden 1860–1998. Sista segmentet består av 38 år.

Running 30-year segment	**May correlation**
1860–1890	0.22
1880–1910	0.31
1900–1930	0.32
1920–1950	-0.06
1940–1970	0.21
1960–1998	0.003

Total May temperature correlation: 0.37

5.2.2 Calibration against SPEI

The standardised tree-ring width from ARSTAN when calibrated against the drought index Standardised Precipitation-Evapotranspiration index (SPEI) showed the highest correlation in June at a correlation value of 0.40 over the period 1901-1998 (Fig. 12).

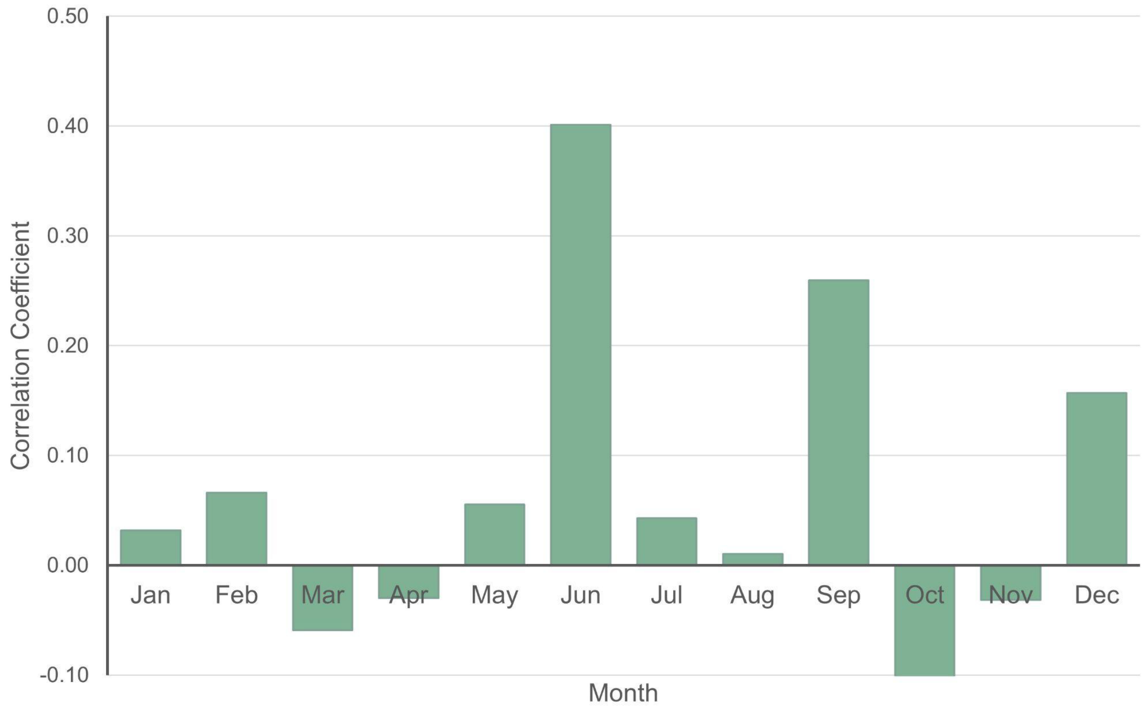

Figure 12. Correlation with monthly SPEI-index and the standardised tree-ring width chronology for the period 1901–1998.

Figur 12. Korrelationen mellan månadsvis SPEI-index och den standardiserade trädringsvidd-kronologin över perioden 1901–1998.

5.2.3 Marker years

The sorting of the years with the 20 thinnest and widest rings resulted in table 4 and 5, also showing June precipitation and May temperature of the year from the Härnösand meteorological station. Only years covered by the meteorological data were examined (1860–1998). The years with the widest rings all occurred in the 20th century (Table. 5). The majority of the years with the thinnest rings occurred in the 19th century, but 5 of them also in the 20th century. Clusters of consecutive years could in the thinnest sorting be found from 1861–1864 and from 1871–1874 highlighted in bold in table 4. In the sorting of the years with the widest rings, clusters of consecutive years could be found from 1923–1925 and from 1952–1954, highlighted in bold in table 5. The results reflect the tree-ring width growth-correlation to precipitation in June and temperature in May for the years with meteorological data. The years with wider rings have more precipitation in both May and June than the thinner years while temperature seems to be increasing mostly in May compared to the thinner years.

Table 4. Years with the thinnest rings extracted from the SWED2023 chronology, with June precipitation and May temperature.

Tabell 4. År med de tunnaste ringarna extraherat från SWED2023 kronologin med juni nederbörd och maj temperatur.

Year	**Standardised tree-ring width**	**June precipitation (mm)**	**May Temperature (°C)**
1861	**0.53**	**0**	**4.9**
1874	**0.54**	**8.9**	**5.5**
1862	**0.56**	**43**	**7.3**
1881	0.68	18	5.8
1863	**0.68**	**59.1**	**6**
1871	**0.69**	**13.4**	**4.5**
1872	**0.69**	**9,1**	**6.3**
1880	0.69	15.5	7.1
1873	**0.72**	**36.5**	**4**
1891	0.73	9	7.3
1940	0.74	16.1	7.8
1969	0.76	10.2	6.2
1888	0.76	3,2	5.3
1894	0.76	14.2	7.3
1867	0.76	89.5	1.2
1902	0.77	15.6	4.6
1903	0.77	21.2	6.1
1864	**0.78**	**44.9**	**4**
1936	0.78	11.8	8.7
1899	0.78	50.9	4.9

Table 5. Years with the widest rings extracted from the SWED2023 chronology, with June precipitation and May temperature from Härnösand meteorological station.

Tabell 5. År med de bredaste ringarna extraherat från SWED2023 kronologin, med juni nederbörd och maj temperatur från Härnösand meteorologiska station.

Year	**Standardised tree-ring width**	**June precipitation (mm)**	**May Temperature (°C)**
1980	1,31	83	7,3
1946	1,32	79,8	8,1
1921	1,33	60	9,2
1974	1,34	41,3	7,1
1987	1,36	98,3	6,1
1990	1,36	43,5	10,1
1923	**1,36**	**69,6**	**5,5**
1952	**1,36**	**52**	**7,5**
1983	1,37	31,4	8,5
1984	1,40	69,9	9,9
1947	1,41	43,7	9,4
1958	1,41	25	7,2
1972	1,41	28,4	6,7
1929	1,43	105,1	6,8
1924	**1,43**	**117,2**	**5,9**
1925	**1,44**	**32,4**	**7,8**
1953	**1,46**	**74,9**	**8,3**
1991	1,46	145,7	7,1
1957	1,52	99,2	7
1954	**1,55**	**61,4**	**9,1**

6. Discussion

The 18 dated samples expanded the master chronology (swed324) 45 years back in time, from 1448 to 1403. More importantly it has increased the sample depth significantly between the years 1480 to about 1700 (i.e., 220 years). The results showed that the period 1403 to 1480 contains too few samples to make up a reliable part of the chronology as it consists of less than the minimum number of 5 samples per segment (Esper, Cook, Krusic, Peters, & Schweingruber, 2003). The sample depth of swed324 was also expanded between about 1700 to 1998 although from a previous high level. Even though the chronology could be expanded by 50%, the EPS value shows that the chronology is fluctuating from 1560 to 1680 (Fig. 9). This EPS threshold (0.85) suggests that the climate signal confidence is uncertain in this time span. However, Buras (2017) argues that this is a misunderstanding within the dendrofield and that a lower number still would be statistically significant although not as strong. On that account, the result should not be considered unreliable, rather it should be handled with caution. Furthermore, the high correlation between the dated samples in this study and the master chronology (swed324) indicates that the samples have been correctly dated. Factors that might affect the correlation are the location of the different sampling sites. This should not be a problem at this sight though as all the samples come from the same region with high statistical correlation in COFECHA. However, it should be noted that it is a coastal area with variations in topography, slope and aspect that might affect microclimate (Ljungqvist et al., 2020; Speer, 2010 p. 20) and therefore distribution of precipitation. As on-site sampling was done by others, our understanding of the place has been limited. However, this did probably not affect the result with the method of choice, but a field study could be beneficial for further research. Furthermore, there are many more samples from these sites, and perhaps the key to further expand the sample depth can be found among them. For example, it is likely that samples from Fanön could be crossdated if more samples from this site were examined.

The correlation between the meteorological precipitation data and standardised tree-ring width shows the highest correlation in June (0.33) for the period 1860-1998, which indicates that the tree-ring width growth is most affected by precipitation in that month (Fig. 10). When divided into 30-year segments, the correlation value for June fluctuates with time, although the segment between 1940 and 1970 showed a higher correlation (Table 2). These correlations were expected to be higher, especially in comparison to Jönsson & Nilssons (2009) results from nearby Härnösand. Although they used a different method and correlated daily precipitation for both May and June together (1961-2001), it is possible that such an approach would have been beneficial in this study as well. For temperature, there was a higher correlation in May (0.37) for the period of 1860 - 1998 (Fig 11). However, when divided into 30-year segments the correlation values were rather low and decreasing (Table 3). The results in the climate correlation therefore suggest that the temperature signal is becoming weakened at the same time as the precipitation signal is increasing. However, as this study only investigated monthly precipitation it might miss details about daily, heavy rainfall. This in combination with the low water holding capacity in the ground and increased evapotranspiration due to higher temperatures might give misleading information about the correlation to precipitation (Jönsson & Nilsson, 2009). This might also explain why the tree-ring width correlates the best with SPEI-index (1901-1998) in June (0.4) and should therefore be further studied. However, it should be considered that the period for SPEI is shorter than for precipitation and temperature.

Regarding the marker years when the thinnest and the thickest rings occurred, the thinnest ring widths are clustered around the 19th century, and the thickest around the 20th century (Table 4 & 5). The thinnest and the thickest ring widths in the whole time series coincides within these clusters. It also becomes evident that both precipitation and temperature is higher during the clusters of thicker ring width compared to the thinner ring-width clusters, which suggests that the increase of these climate factors also increases the tree-ring growth. This confirms the results from the correlation analysis that a warm and wet early growing season is beneficial for tree growth in this site. Although, as noted by Stokes & Smiley (1996, p. 3), ring width is not proportional to precipitation, and not by temperature either. This is most evident when comparing 1921 to 1954 (Table 5.) where both precipitation and temperature are about the same, although tree-ring width differs. Furthermore, the marker years from this thesis in comparison with marker years from Sandström et al. (2020) (also from the High Coast region) coincides. The majority of the thickest and thinnest years from this thesis corresponds to the thickest and thinnest of Sandström's marker years. This gives an indication that the dating of the samples was correct, and also strengthens the potential of using Scots pine from this region.

The sample's strong correlation to each other is supported by COFECHA. The expedition to the High Coast region collected many more samples than used in this thesis. Therefore, it is very likely that these will expand the chronology further back than the 1400s. Further measurement and dating are therefore needed to create a longer reference chronology. Although the hydroclimatic signals were weak this study has shown that it exists. Further research is therefore recommended as hydroclimatic changes are not properly understood, which is important as it holds information about complex climate systems (Jönsson & Nilsson, 2009; Ljungqvist et al. 2020). As hydroclimatic factors are of importance for e.g. energy production it would be valuable to understand how the hydroclimatic regimes work further north where much of Sweden's hydropower plants lie. This study offers an insight to the potential of this hydroclimatic research in this region. It also highlights the need to obtain more reliable data using other methods than ring width, such as density (Blue intensity) (Seftigen et al. 2020) and quantitative wood anatomy (Frank, Fang & Fonti, 2022).

6.1 Discussion of method

Why were only 18 out of the 42 samples dated? When dating cores from living trees, the calendar year can be assigned to the latest formed ring closest to the bark. This gives the sample an anchor in time from which the dendrochronologist can count and date back in time from (Speer, 2010, p. 96). However, when analysing discs from dead trees as in this thesis, an anchor in time is harder to find simply because the tree's time of death is not known. Due to the time frame of this thesis, the samples that initially got a reliable anchor in time in the first dating step, with a high correlation throughout the sample with the reference chronology were chosen. The samples that initially did not get an anchor in time and correlated to two or even three places in a span of 500 years would have required more time in for example visual controls for false or missing rings. Therefore, due to the limited time frame only the easily dated samples were selected for the analysis, also because any inaccurately dated samples would have caused an error source which would potentially affect the results.

Furthermore, the measuring of the rings in the program Coorecorder was a time-consuming method that required focus to place the coordinates right, and to not miss or double place any coordinates. Both auto-placement and manual placement of the coordinates was used, which could yield a difference in the position relative to the earlywood/latewood. To be placed as similarly as possible, the manually placed coordinates tried to replicate the autoplaced ones. A part of the quality control of the measurements and dating in COFECHA involved the program giving suggestions on moving segments several years back or forward based on its statistical analysis to give a better correlation. Some of these suggestions were considered not to be accurate after visually checking the regarded samples, and was thereby left as it was, given that the segment correlations before moving were over the minimum value (0.32). The segment length that was examined was set to default at 50 years, with a 25-year overlap which could have affected the results in relation to setting it to a smaller segment. In ARSTAN it is important to know what signals are being removed. Due to limited experience with ARSTAN climate signals of interest could have been removed, which could have affected the result. The cubic smoothing spline which was set to 25 years in consultation with the supervisor. From our gained experience of the area, being new to dendrochronology, both Coorecorder, COFECHA and ARSTAN could have been more examined if given more time, which could have produced different results.

The meteorological data from the Härnösand station were considered a good alternative in collecting monthly temperature and precipitation because of its good range of historical data back to 1860, with only one missing monthly value. When collecting meteorological data from one station it could contain local extremes, especially regarding precipitation amount. The Härnösand station is also at a distance of 50 km from the sampling sites. Precipitation is therefore likely to differ and not a perfect replication for the local stand. Gridded climate data (e.g., CRU TS) could therefore provide a more representative dataset for the region. It interpolates data from various stations which evens out extreme events and gives an average value of the temperature and precipitation in the measured region.

7. Conclusions

To conclude, the study has been able to date discs of Scots pine from the High Coast region back to 1403, and thereby expanded the sample depth in the existing swed324 chronology by 45 years. Furthermore, it has expanded the previous depth of 36 samples (1448-1998) with an additional 18 samples which provided a stronger sample depth between the years 1480-1700 (i.e., 220 years). Although the hydroclimatic signals in tree-ring width were weak, they showed a significance which indicates the potential of tree-ring based proxy data from Scots pine in the High Coast region. The correlation between tree-ring width and SPEI-index in June showed the highest correlation (0.4). The relationship to precipitation (0.33) and temperature (0.37) were somewhat weaker, although a signal could be found. The method used in this thesis explored the most conventional tree-ring proxy, the annual tree-ring width. Finally, other methods and tree-ring proxies are likely to boost the climate signal and should therefore be investigated.

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