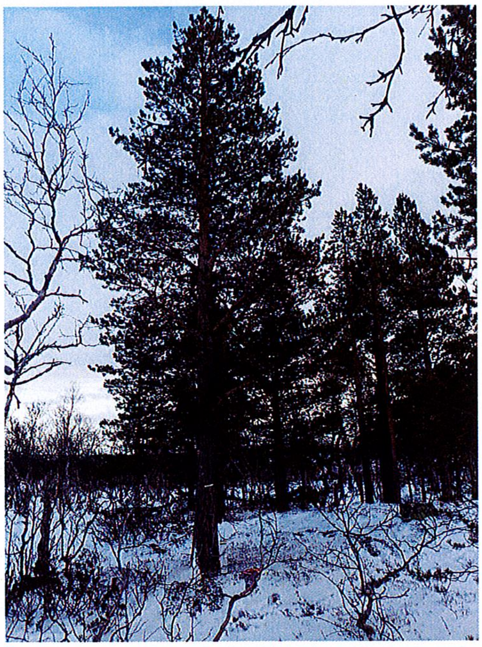
Faculty of Science

Response of trees to regional climate – a sensitivity study in Jämtland



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Abstract

Global warming is a key topic of present-day research, with the effects projected to be enlarged in Sweden. The county of Jämtland lies in the central Scandinavian mountains and is highly affected by changes in temperature and precipitation. Vegetation and ecotones depend on the climate and this connection creates the possibility of studying past vegetation growth in relation to climatic variables. Because of the location of Jämtland, it is affected by two different airmasses, the maritime from the west and the continental from the east, making it a suitable locality for studying differences in trees and their responses to climate. Not only will this gain an increased knowledge of the relationship between them but will also add validation to future projections. Tree rings are useful proxies in climate studies, and the aim of this study is to analyze and correlate tree ring width (TRW) against the climatic variables of temperature and precipitation. The chronologies span 207 years for Storlien, 1814-2020, respectively 402 years for Snasahögarna, 1619-2020, although this study focus on the past 101 years. During this period, each study site shows a similar pattern in TRW. Both chronologies are statistically significant against temperature, but not precipitation. This study implicates that regional climate is the main driving factor of radial growth in trees, which improves the possibilities to analyze climatic changes and expected growth responses. Our conclusions:

- Our results reveal that the trees, chosen for this study, show a large sensitivity to climate, specifically regional temperature. This relationship has mostly been sustained during the last 101 years.
- The maritime climate influences the growth of trees in this region, but indications suggest that the trees at Snasahögarna are more influenced by the continental airmasses than the trees at Storlien. Although the two sites display an overall agreement during the studied time period, small differences were detected, especially during the 1970s.
- A tree line movement to higher altitude has occurred between 1957 and 2020, most likely due to a changing climate. At some locations, the tree line movement are limited by steep slopes.

Keywords: Tree rings, tree ring width, Pinus sylvestris, climate change, tree line, tree line movement, Jämtland, Storlien, Snasahögarna, temperature, precipitation, maritime climate, continental climate

Sammanfattning

Global uppvärmning är ett aktuellt ämne inom nutida forskning, där effekterna förväntas bli stora i Sverige. Jämtlands län ligger i den centrala skandinaviska fjällkedjan och påverkas av temperatur- och nederbördsförändringar. Vegetation och ekotoner influeras av klimatet, och dess samband skapar möjlighet att studera tidigare vegetationstillväxt i förhållande till klimatvariabler. Jämtlands geografiska läge påverkas av två olika luftmassor, det maritima från väst och det kontinentala från öst, vilket därför utgör en lämplig plats för att studera skillnader i träd och deras respons på klimatet. Detta kommer inte bara öka kunskapen om förhållandet mellan dem, utan även ge validering åt framtida prognoser. Trädens årsringar som proxydata är användbara i klimatstudier, och syftet med den här studien är att analysera och korrelera årsringsbredd (TRW) mot klimatvariablerna temperatur och nederbörd. Kronologierna omfattar 207 år för Storlien, 1814-2020, respektive 402 år för Snasahögarna, 1619-2020, där den här studien fokuserar på de 101 senaste åren. Båda kronologierna är statistiskt signifikanta med temperatur, men ej med nederbörd. Den här studien implicerar att regionalt klimat är den främsta drivande faktorn för radiell tillväxt i träd, vilket förbättrar möjligheterna att analysera klimatförändringar och förväntad tillväxtrespons. Våra slutsatser:

- Våra resultat visar att träden, i den här studien, har en hög känslighet för klimat, särskilt för regional temperatur. Detta förhållande har mestadels bibehållits under de senaste 101 åren.
- Det maritima klimatet påverkar trädtillväxten i den här regionen, även om indikationer tyder på att träden vid Snasahögarna påverkas mer av kontinentala luftmassor än vad träden vid Storlien gör. Trots att de två studieplatserna uppvisar en övergripande likhet, upptäcktes skillnader, och särskilt under 1970-talet.
- Trädgränsen har förflyttats till högre altituder, mellan åren 1957 och 2020, troligen på grund av ett förändrat klimat. På vissa platser begränsas trädgränsens förflyttning av branta sluttningar.

Nyckelord: Årsringar, årsringsbredd, Pinus sylvestris, klimatförändringar, trädgräns, trädgränsförflyttning, Jämtland, Storlien, Snasahögarna, temperatur, nederbörd, maritimt klimat, kontinentalt klimat

Preface

We live in a changing world, a world where the climate and changes in regional weather systems increasingly threatens the livelihood of all living species. The field of dendrochronology is defending its place in the scientific arena with its reliability of extracting information of past and present climatic variables, improving the possibility to calculate and project future scenarios.

This study in climatology would not have been possible without the support of our supervisor, Professor Hans Linderholm. Not only because he provided us with the tree samples upon which this study is based, but also for the hours spent in lab with us when needed as well as giving valuable feedback. We also would like to thank our co-students for excellent feedback during writing, especially Jakob Gunnarsson for his cooperation with software challenges. Finally, thank you to the course leader Mark Johnson, for giving us the tools to excel in writing as well as gently steering us to the finish line.

Writing a Bachelor Thesis amidst a global pandemic is not the easiest task, but one which we now can add to our knowledge. The support from our family and each other has been invaluable in creating stability in the progress of this thesis.

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1. Introduction

1.1 Background

Global warming is a key topic of present-day research, and the Intergovernmental Panel of Climate Change (IPCC) concludes that temperature has risen with approximately 1℃ above pre-industrial levels. Additionally, another 0.5℃ is to be expected by 2030 (IPCC, 2018). Future air temperature in Sweden is anticipated to be warmer in the whole country, and precipitation is also expected to increase (Eklund et al., 2015; Länsstyrelsen, 2014). It is projected that by the end of this century, the temperature in Sweden will have risen 1℃ above global average, reaching as high as 3-4℃ above todays yearly average temperature. The winter temperature is expected to increase markedly, affecting northern Sweden significantly and with higher temperatures the period of snow cover will be shortened (Bernes & Sverige. Naturvårdsverket, 2016). Vegetation and ecotones depend on the climate (Bernes & Sverige. Naturvårdsverket, 2016), and this connection creates the possibility of studying past vegetation growth in relation to climatic variables. Not only will this gain an increased knowledge of the relationship between them but will also add validation to future projections.

Tree rings are one of the widely known proxies used to study changes in climate, naturally recording climate variability in the radial growth of their annual rings (Fritts, 1977; Linderholm et al., 2015). The high validity of tree ring data for analyzing climatic variabilities is emphasized by Pearl et al., (2020), as well as its usefulness for detecting present trends (Esper & Gaertner, 2001). By studying annual tree ring widths (TRW) as a response to specific climatic variables, this study aims to investigate the sensitivity of TRW in relation to climate change and the insights it might provide. Holtmeier & Broll (2005) says in their study that growth of trees is positively affected by regional warming. However, they also found that maritime and continental climate may differentiate growth of trees on a local scale and conclude by saying the further investigations are needed to understand the effect present conditions might have on trees. In Sweden, the county of Jämtland is a suitable locality for studying such effects. It lies in the central Scandinavian mountains and is highly affected by the changes in temperature and precipitation while simultaneously being affected by two different airmasses. The maritime airmasses from the west contains more moisture than the continental airmasses coming from the east, and as the moist airmasses move inland over the mountains, it results in heavy precipitation over the western parts of Jämtland (Länsstyrelsen, 2014). Not only will this study investigate sensitivity towards climate but also aim to answer which airmass has the strongest influence.

Several studies have been made on the Scots pine population in Jämtland in the past and the warming in the last couple of decades have favored the growth of pine, enabling new establishment (Kjällgren & Kullman, 2002; Kullman, 2007; Öberg, 2008; Kullman & Öberg, 2009; Linderholm et al., 2010a; Gunnarson et al., 2011; Seftigen et al., 2015; Linderholm et al., 2015). Scots pine (*Pinus sylvestris*) is one of the most studied tree species in Fennoscandia owing to its growth as a reliable parameter influenced by different climatic variables (Pearl et al., 2020). During the late 1990s and the early 2000s, sampling and collection of tree rings were made in this area (Linderholm & Gunnarson, 2005; Linderholm et al., 2010b). Updated chronologies in this region are of large interest, to study recent growth conditions in trees located in the tree line environment on higher latitudes. Additionally, tree lines are anticipated to move northward, as well as to higher altitudes, causing a shift in the vegetation zones in higher latitudes (ACIA, 2004). The tree line is defined as trees of a specific species with a minimum height of two meters in a specific locality. Previous research has revealed an expansion of Scots pine in Snasahögarna (Kullman, 2014). It is a helpful tool for detecting changes in the landscape, and to understand how climatic changes impact ecological processes, important for the biodiversity (Öberg, 2008) and will be a contributing complement to this study.

1.2 Dendrochronology

The study of tree rings is called dendrochronology and is the process of establishing calendar years to specific tree rings. There are several concepts and principles within this field. *The uniformitarian principle* states that there is a stability in the response of tree ring growth towards different processes through time. The principle of *limiting factors* states that a tree can only grow as much as the limiting factor permits. Limiting factors can change over time, as conditions changes (Fritts, 1977). The concept of *ecological amplitude* refers to the ability of vegetation to grow in certain habitats. It implies that near the boundary of its natural habitat, climate is often found to be a limiting factor for growth. *Site selection* is an important aspect considering type of investigation. It may be restricted to type of tree as well as to trees located in sites where the signal of a limiting factor may be high. *Cross-dating*, one of the most important principles, is the process of identifying tree ring patterns both internally as well as between trees, with the aim of establishing the year of each ring width. Equally important is *replication.* The more tree rings sampled and included in a dataset, the better. A chronology with many samples becomes more reliable and robust. Averaging several samples into one minimizes the signal of non-climatic factors affecting tree ring growth. S*tandardization* is the process of detrending TRW. Tree rings are known to show an age trend, which is desirable to exclude from the data to increase the environmentally affected signal in the widths (Fritts, 1977).

Lastly, the concept of *sensitivity*, referring to the variability in the widths of the rings. Variability in TRW is directly linked to variability in environmental factors (Fritts, 1977). While Taeger et al. (2013) claims the current year's climate has the largest influence on TRW, Semeniuc & Popa (2018) argues that climatic conditions influence during both the current and the previous year. Determining the sensitivity of trees to climate variables increases the possibilities to reconstruct past climatic conditions as well as project future ecological changes dependent on climate change estimates. When using tree ring data for estimating climatic conditions it is vital to determine which variable a specific chronology is sensitive to (Seftigen et al., 2015). Determining the sensitivity of trees towards climate conditions, and which variable they respond to most, projections of future changes can be made and contributions towards adapting for changes in ecotones can be improved.

1.3 Aim and hypothesis

The aim of this study is to investigate the climate sensitivity in Scots pine *(Pinus sylvestris)*, growing close to its tree line limit in Storlien and Snasahögarna in Jämtland. To analyze the TRW for the two chronologies, created in this study, TRW will be correlated with the climatic variables of temperature and precipitation, both on a longer timescale of 101 years as well as on a shorter timescale, dividing the time into three smaller subperiods of 40 years each. Investigating which variable affecting the growth of trees the most in these two areas, potential differences can be obtained and discussed, contributing to the discussion of global warming on a regional scale. Additionally, identifying the most influencing airmass can contribute to the understanding of local effects on trees. Finally, a change detection analysis of the tree line in

Snasahögarna will be complementing the statistical analyses. Doing this, our study aims to answer the following questions:

- Are the trees at the two sites sensitive to climate and which factor influence the most?
- Which airmass influence the trees in this region and is there any differences between the two sites?
- Has an upward tree line shift occurred in the area of Snasahögarna?

2. Method and Material

2.1 Study sites: Storlien and Snasahögarna

The study sites for this project are situated in the county of Jämtland, located in the central Scandinavian Mountains (Figure 1). Snasahögarna (N 63°13′43″, E 12°20′38″) is a minor mountain range, with one of the study sites located on the east side of the slopes roughly 675 m a.s.l, nearby the small village of Handöl. Snasahögarna shows a topography of even slopes up to a height of approximately 1400 m a.s.l (Öberg, 2008). Storlien (N 63°19′5″, E 12°5′42″) is located approximately 24 km west of Snasahögarna, close to the Norwegian border and around 600 m a.s.l.

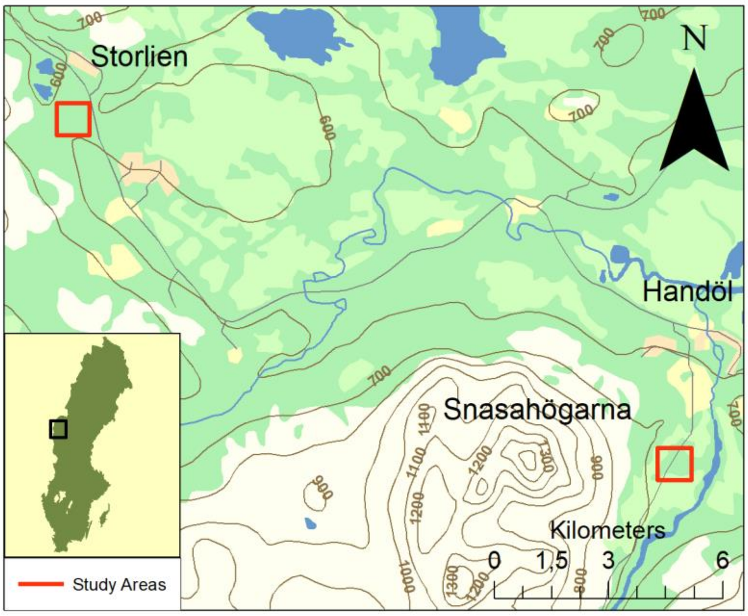

Figure 1. Location of the two study areas. (GSD-Översiktskartan, 1:100 000 - 1:500 000 © Lantmäteriet, 2021a)

According to the Swedish meteorological and hydrological institute (SMHI), the climate in Jämtland is characterized by cold temperate seasons with a marine climate (SMHI, 2021a, 2021b). Unlike most of Sweden's inner areas, the western parts of Jämtland are affected by the Atlantic Ocean (Öberg, 2008), with large amounts of precipitation in the western parts while some of the eastern parts are in rain shadow, creating differences in the amount of precipitation throughout the county (SMHI, 2021a). Most of the precipitation falls during the summer season, displayed by the climographs in Figure 2a-b and Figure 3a-b. Differences in precipitation based on location and influence of regional climate are visible in the same climographs, showing larger amounts of precipitation in Storlien compared to Duved/Mörsil throughout all months of the year. At the same time, precipitation has decreased in Storlien during the millennial shift compared to the middle of the 1900s. Storlien is subject to the moist westerly winds while the study site located east of Snasahögarna receives protection from the westerlies, with a possible contribution of a more continental climate. The temperature for both meteorological stations also display a shift of temperature to a warmer climate the last 100 years.

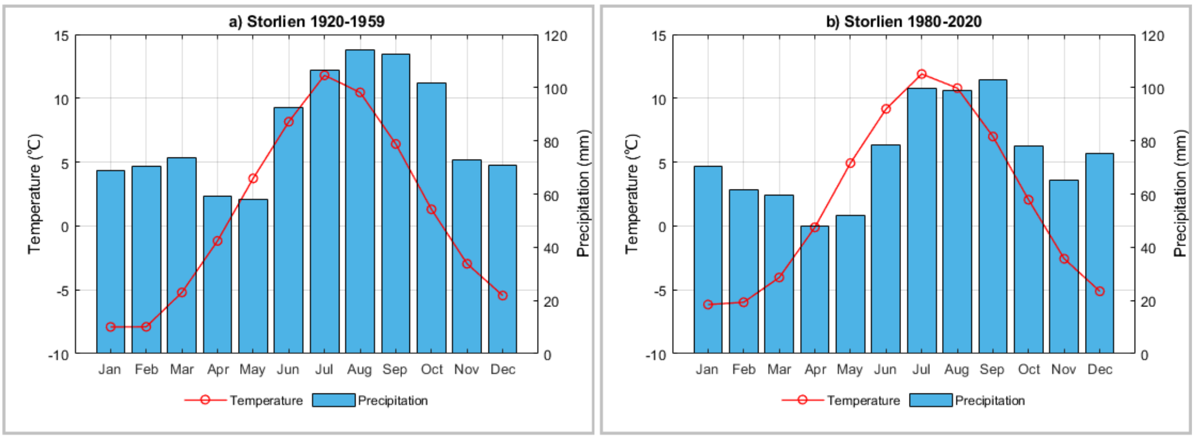

Figure 2. *Climographs of averaged temperature and precipitation in Storlien.* ***a)*** *Period 1920-1959. Large amounts of precipitation.* ***b)*** *Period 1980-2020. Precipitation has decreased compared to the first period and winter temperature is milder. (SMHI, 2021c, 2021d)*

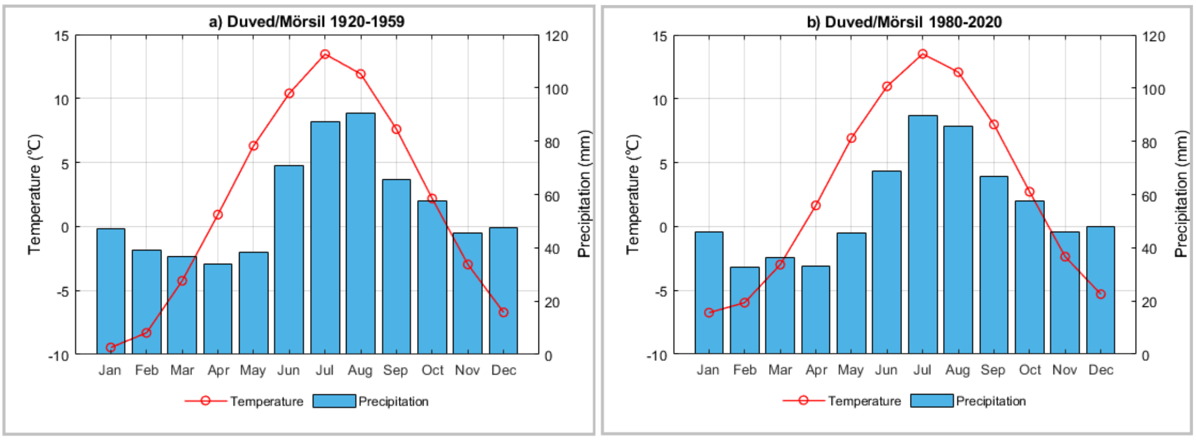

Figure 3*. Climographs of averaged temperature and precipitation in Duved/Mörsil.* ***a)*** *Period 1920-1959. Large variation in temperature.* ***b)*** *Period 1980-2020. Temperature has increased during the winter. (SMHI, 2021c, 2021d)*

The winter landscape of the study sites is visualized in Figure 4. Apart from large areas of bare rock, the soil mostly consists of mires and till, with streaks of glacial depositions (SGU, 2021). The dominating species of trees are birch (*Betula pubescens* ssp. *tortuosa*), fir (*Picea abies*) and pine (*Pinus sylvestris*). The vegetation consists mostly of heaths with dwarf birch (*Betula nana*), blueberry (*Vaccinium myrtillus*) and crowberry (*Empetrum hermaphroditum*) as well as grass (Öberg, 2008).

Figure 4. *The landscape of the study sites. Storlien to the left and Snasahögarna to the right. (Photographer: Hans Linderholm, 29th-31st December 2020)*

2.2 Tree ring datasets

All tree samples used in this study were provided by Professor Hans Linderholm. The most recent samples were collected the 29th and 31st of December 2020. We were also provided with 24 previously collected and assessed radii from Snasahögarna, taken in 1998/2002. For the new samples, Snasahögarna consists of 30 radii from 15 trees, where two radii have been taken from one tree in different angles, hence called a and b cores. The new samples taken in Storlien consists of 40 radii (a and b cores) from 20 trees. All tree samples are from Scots pine (*Pinus sylvestris*). Boring from the bark to the pith of a tree will yield a cross section of the stem. The assembled samples were prepared for analysis by exposing the tree rings with a razorblade, followed by adding chalk to enhance the contrasts. The ability to determine annual rings is because of the biological formation of trees. When a new growing season starts, conifer trees respond by creating wide cells which are light in color, called earlywood. During the growing season, the cell structure becomes flatter, the cell size becomes denser and darker in color; these cells are called latewood. This transition from earlywood to latewood is what comprises an annual ring (Fritts, 1977; Cuny et al., 2014). Because of the difference in cell structure between the wider earlywood cells and the narrow latewood cells, it is possible to detect the start and end of each ring, enabling counting of tree rings (Fritts, 1977). Measurement of the TRW was made using the software TSAP-Win™ which, in combination with the measuring tool LinTab™, creates a time series of each sample. The software is manually operated with the user deciding the widths of the tree rings. The unit of resolution is 1/1000 mm.

Cross-dating is the process of identifying tree ring patterns both internally as well as between trees, with the aim of establishing the year of each ring width (Fritts, 1977). Cross-dating was made in TSAP-Win™. For Snasahögarna, cross-dating of new samples with older ones, a robustness could be built into the new chronology. A chronology is an averaged time series with yearly values derived from all qualitatively assessed samples from a specific study site. By combining several samples into one, the effects of non-climatic impacts are reduced, and the climatic signal provided by the tree rings is enhanced (Fritts, 1977). Based on the output from TSAP-Win™, a total number of 41 radii from Snasahögarna was determined to be included in the final chronology, called SnasaMaster. The same procedure was applied to Storlien and gave a total of 26 radii to a final chronology, called StorlienMaster. Three radii were omitted from the cross-dating because of damages or disturbance in the radial growth from twigs. One from Snasahögarna as it was not possible to count the rings. Both cores from one tree from Storlien was cut as the middle growth of the tree's radius could not be measured. Upon finalization of the cross-dating process, another 13 radii from Snasahögarna, and 23 from Storlien were excluded. The removal of inappropriate samples with low correlation is an important aspect in creating chronologies with high certainty (Fritts, 1977). The cross-dating procedure was validated by using another software called COFECHA™ to control the quality of the ring-count. It assesses the accuracy of the measurements and detects outliers, listing them as potential problems for further investigation (Grissino-Mayer, 2001). All corrections were checked visually in the physical samples.

Trees are also known to display an age-trend, with the width of the tree rings declining as the radial size increases for every year (Linderholm et al., 2010a; Young et al., 2011). According to Fritts (1977), there are two reasons mainly contributing to this. Firstly, young trees grow more strongly while older trees grow less strongly. Secondly, young trees have a longer growing season than old trees. Running the chronologies in the software ARSTAN™, the age trend is removed by curve fitting of an exponential curve (Holmes et al., 1986). Removing the low-frequency signal related to age, allows the climatic signal to emerge. This standardization process creates a time series of average yearly standardized indices (Fritts, 1977). The standard output was used for this study.

2.3 Climate datasets

Datasets for temperature (SMHI, 2021c) and precipitation (SMHI, 2021d) representing maritime and continental conditions was downloaded from the databank supplied by SMHI. They consist of monthly averaged values and were derived from a total of five meteorological stations: three stations represent Storlien (Storlien-Storvallen A: 132170, Storlien-Visjövalen: 132180, Storlien: 132620) and two represent Duved/Mörsil (Duved: 132240, Mörsil: 133190) with a combined time series ranging from 1919 until 2020 (Figure 5). Since none of the meteorological stations have a continuous recording for the years 1919 to 2020, a combination of the time series had to be done. The maritime conditions are indicated by the stations centered in Storlien. Storlien station represents the years 1919-1962, followed by the Storlien-Storvallen A station for the years 1963-2009 and lastly the Storlien-Visjövalen station for the years 2010-2020. The continental conditions are indicated by Duved station, representing the years 1919-1971, followed by the Mörsil station for the years 1972-2020. All stations are thought to represent the regional climate well as they display the variance in climatic conditions in this area.

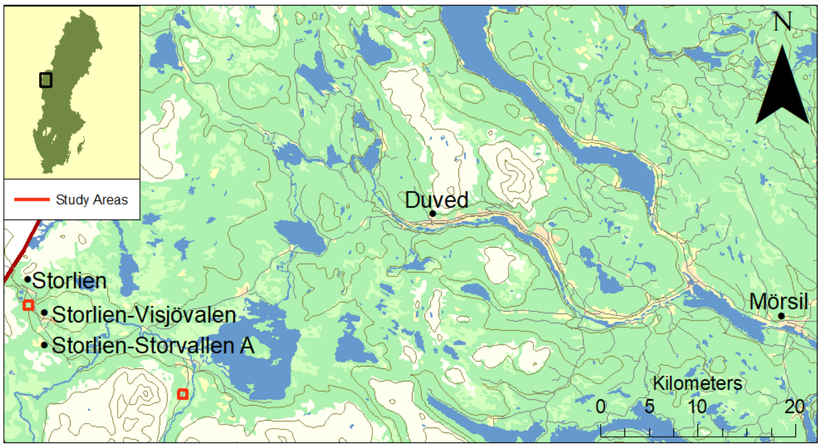

***Figure 5**. Location of the five meteorological stations. (GSD-Översiktskartan, 1:100 000 - 1:500 000 © Lantmäteriet, 2021a)*

2.4 Statistical methods

A period starting 1920 lasting until 2020 was used for this study. It was determined as sufficiently long to show a variety of trends during analysis. Additionally, this time period was divided into three subperiods of 40 years, with overlapping years to the surrounding subperiods, to allow emergence of short-term signals. To explore any potential differences as well as similarities between the study sites, the chronologies was plotted and correlated against each other. To investigate any relationship of the tree rings to the climatic variables, a correlation analysis was made towards single months as well as an averaged value for June-August, using the corrcoef function in Matlab™. Finally, the function linear fit was used to fit trendlines to the climatic variables through time.

2.5 Tree line change analysis using remote sensing

Tree line studies are suitable as an indicator for a changing climate since possible shifts of the tree line are easy to visualize. Trees has a fast response of new conditions in an environment (Öberg, 2008). For this study, a tree line position change analysis for the years 1957 and 2020 was performed in the software ArcMap™ version 10.7.1, to analyze the tree line changes in Snasahögarna, which is one of the highest mountains nearby where the tree ring datasets were collected. Further, a broader perspective of how trees respond to a changing climate can be provided. In this change detection analysis, no specific tree species are chosen, and it is the visual tree line that is in focus.

This change detection technique is often used for historical images taken in black-and-white, where the availability and quality of imagery is limited (Webb et al., 2010). For this study, a historical analogue aerial photograph from the year 1957 was compared to a satellite image from the year 2020. The two images, with different image type (Table 1) were georeferenced to enable a comparative analysis. A line that marks the tree line was manually drawn in the photographs for 1957 respectively 2020 and was visually analyzed to provide an answer if the tree line has changed during the 63-year long time span. Using an elevation data grid 2+ (Lantmäteriet, 2021c) and the 3D Analyst tool in ArcMap™, topographic profiles were added perpendicular to the tree line at four different locations to get information about the slopes and how much the tree line has moved in altitude.

Table 1. *Metadata about the aerial photography and the satellite imagery. (Analogue aerial photography in greyscale 1957 © Lantmäteriet, 2021b. Copernicus Sentinel data 2020 © processed by ESA, 2021)*

Year	ID	Imagery technique	Image type	Camera type	Pixel size	Source
1957	Z_57_20_02a_05	Aerial photography	Analogue photograph	Analogue	15	Lantmäteriet
2020	Sentinel-2 L2A 2020-08-10	Satellite Imagery	Optical imagery, true color	Multi-spectral instrument	10	Copernicus Sentinel data processed by ESA

3. Results

The final chronologies vary in length. StorlienMaster spans 207 years between 1814-2020, while SnasaMaster consists of a total of 402 years, from 1619-2020. For this study only the last 101 years is selected for investigation. A summary from the process of standardization is shown in Table 2. The results shows that StorlienMaster better represents the study site population than the equivalent for Snasahögarna, as well as to a larger extent being influenced by a single factor of its variance. The signal strength (SS) indicates how many trees is needed for the climatic signal to emerge, where the value of 0.85 is a commonly used limit (Buras, 2017).

Table 2. *Results of standardization. Considerable differences exist between the two study sites.*

Location	Variance due to autoregression (%)	Mean correlation	Variance in PC1 (%)	Signal-to-noise ratio	Signal Strength (SS) of 0.85 (nr of trees needed)
SnasaMaster	57.3	0.462	50.08	4.297	7
StorlienMaster	45.8	0.660	69.57	19.419	3

3.1 StorlienMaster and SnasaMaster comparison

The chronologies for each study site show a similar pattern in TRW throughout the study period, visualized in Figure 6, with a correlation coefficient of 0.74. StorlienMaster does not include as many young trees as SnasaMaster (Figure 7a, 7b). In Figure 8, SnasaMaster varies within a range of 0.53-1.50, while the equivalent for StorlienMaster is 0.46-1.53. Both chronologies display the lowest peak in 1928, while the second to lowest values are around 0.68, found during different years for the two sites. Figure 8 also illustrate that the largest difference between the chronologies occurs around the 1970s, with StorlienMaster having a high amplitude while SnasaMaster shows a low. Even though the amplitude differs for the two chronologies, the pointer years are the same.

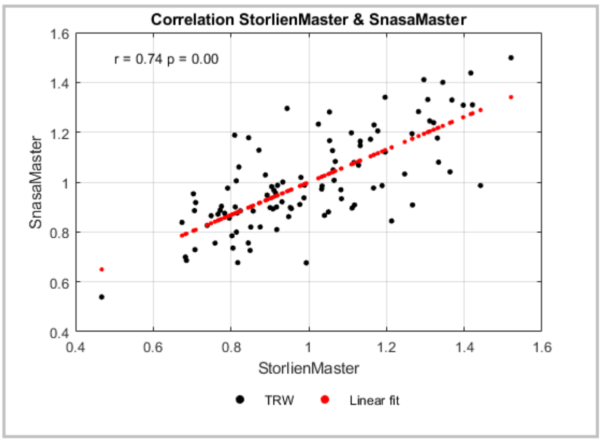

***Figure 6**. Scatterplot of TRW. Correlation coefficient is 0.74 with a p-value of 0.00. To a large extent, the trees in this region seem to follow a similar growth curve.*

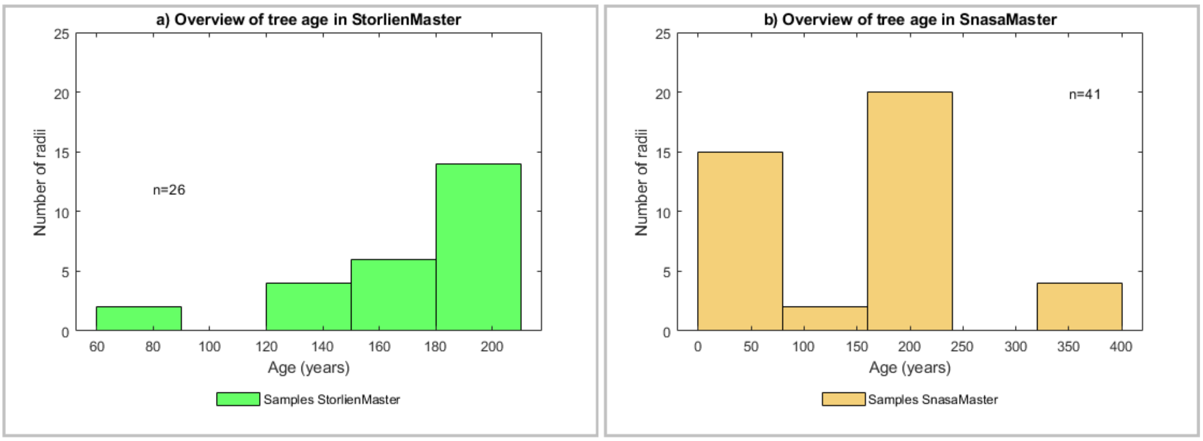

***Figure 7**. **a**) Overview of age of the trees in StorlienMaster. **b)** Overview of age of the trees in SnasaMaster. The trees in SnasaMaster are younger than StorlienMaster.*

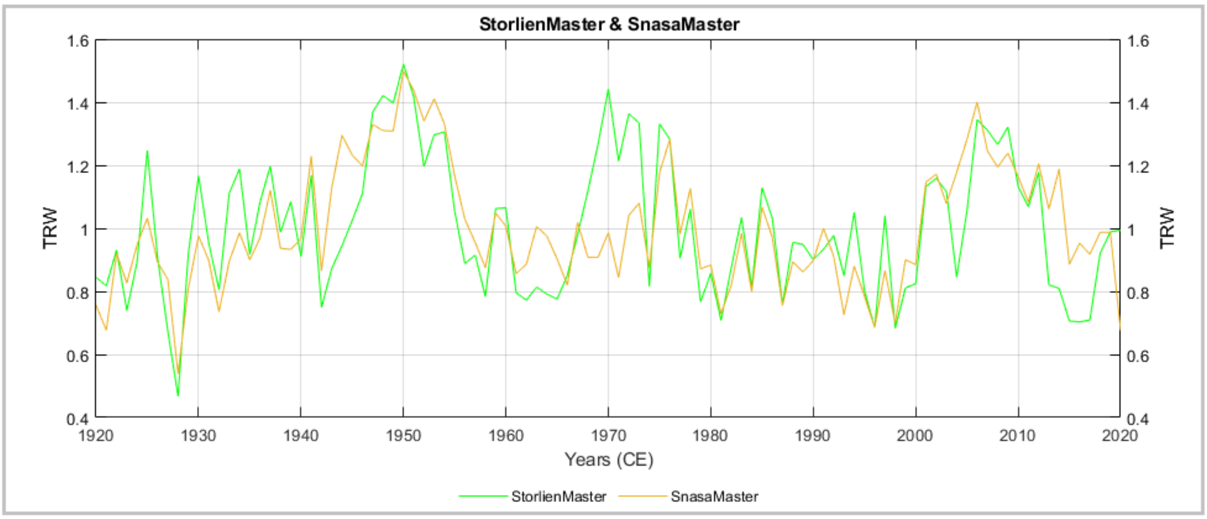

***Figure 8.** StorlienMaster vs SnasaMaster. Both chronologies display growth within approximately the same range. Largest difference in the 1970s.*

3.2 Climate analysis

Figure 9a-d and Figure 10a-d shows the correlation coefficients for each site, respectively. The best correlation for both sites is against temperature with no apparent connection to precipitation. StorlienMaster (Figure 9a and Figure 9c) shows highest correlation with the summer months June to August, and the combined average called JJA from both stations. It also shows that the trees at Storlien better responds to the maritime climate represented by Storlien station data than the continental climate represented by Duved/Mörsil. StorlienMaster also display significant correlation against October and December the previous year. In similarity with StorlienMaster, SnasaMaster is best correlated against the summer months, as well as the combined averaged temperature from both stations. Also, these trees display higher influence from the maritime climate. Additionally, growth is connected to the fall months of the previous year, as far back as September. Dissimilar to StorlienMaster, SnasaMaster correlates well with the more continental climate of the previous year. Although StorlienMaster shows statistically significant values for one month during the previous year for precipitation (Figure 9b, 9d), it is evident that growth of trees at Storlien is influenced by temperature.

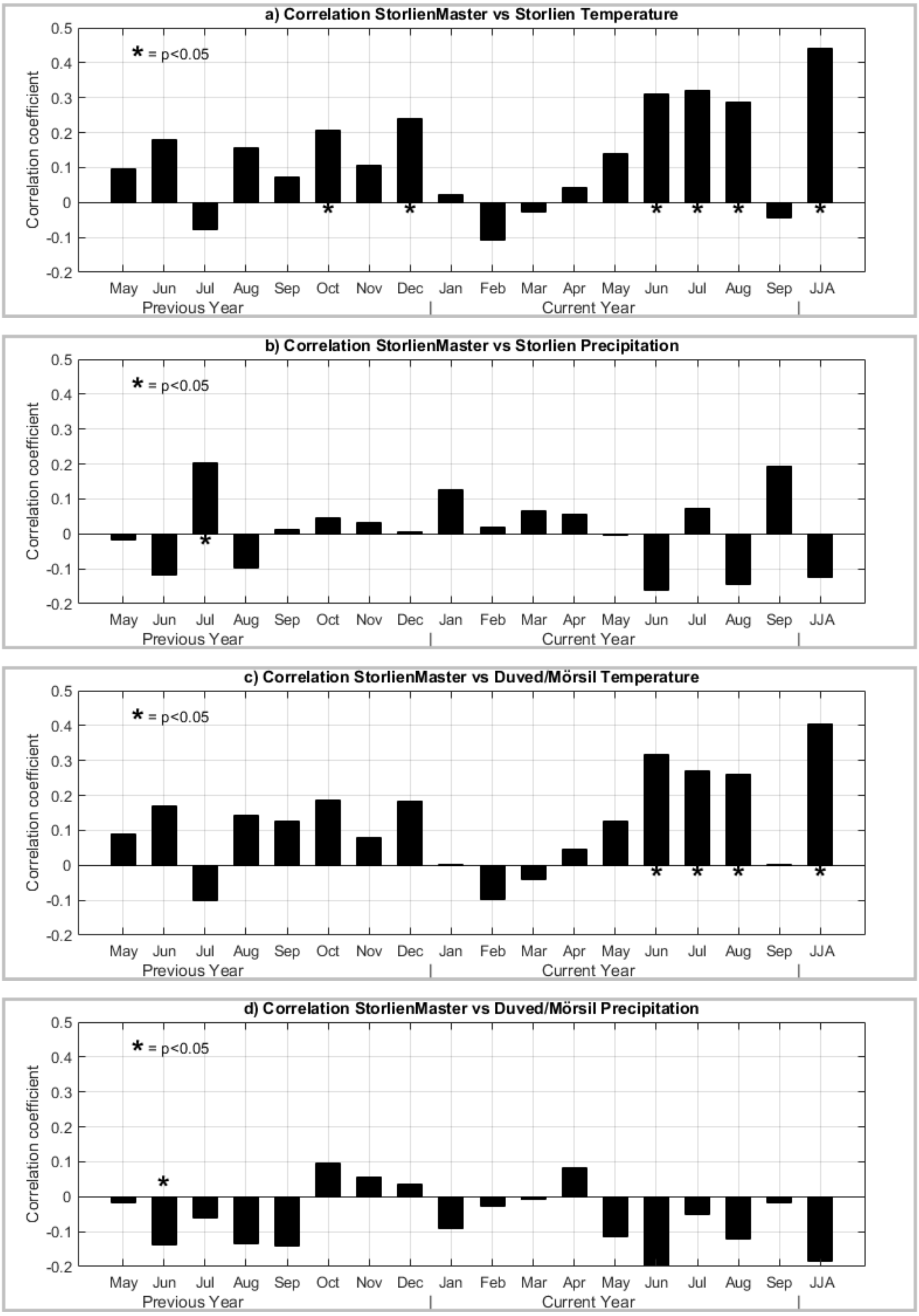

Figure 9. *Correlation coefficients StorlienMaster vs temperature and precipitation.* ***a)*** *Storlien temperature. Highest correlation during the summer months of June-August, also visible in the JJA average.* ***b)*** *Storlien precipitation. Although July of the previous year is statistically significant, precipitation is not affecting TRW in Storlien.* ***c)*** *Duved/Mörsil temperature. Similar patterns as with Storlien temperature, but the correlation is not as strong with lower coefficients.* ***d)*** *Duved/Mörsil precipitation. June, show a statistically significant value, however precipitation is not the most influencing factor for growth.*

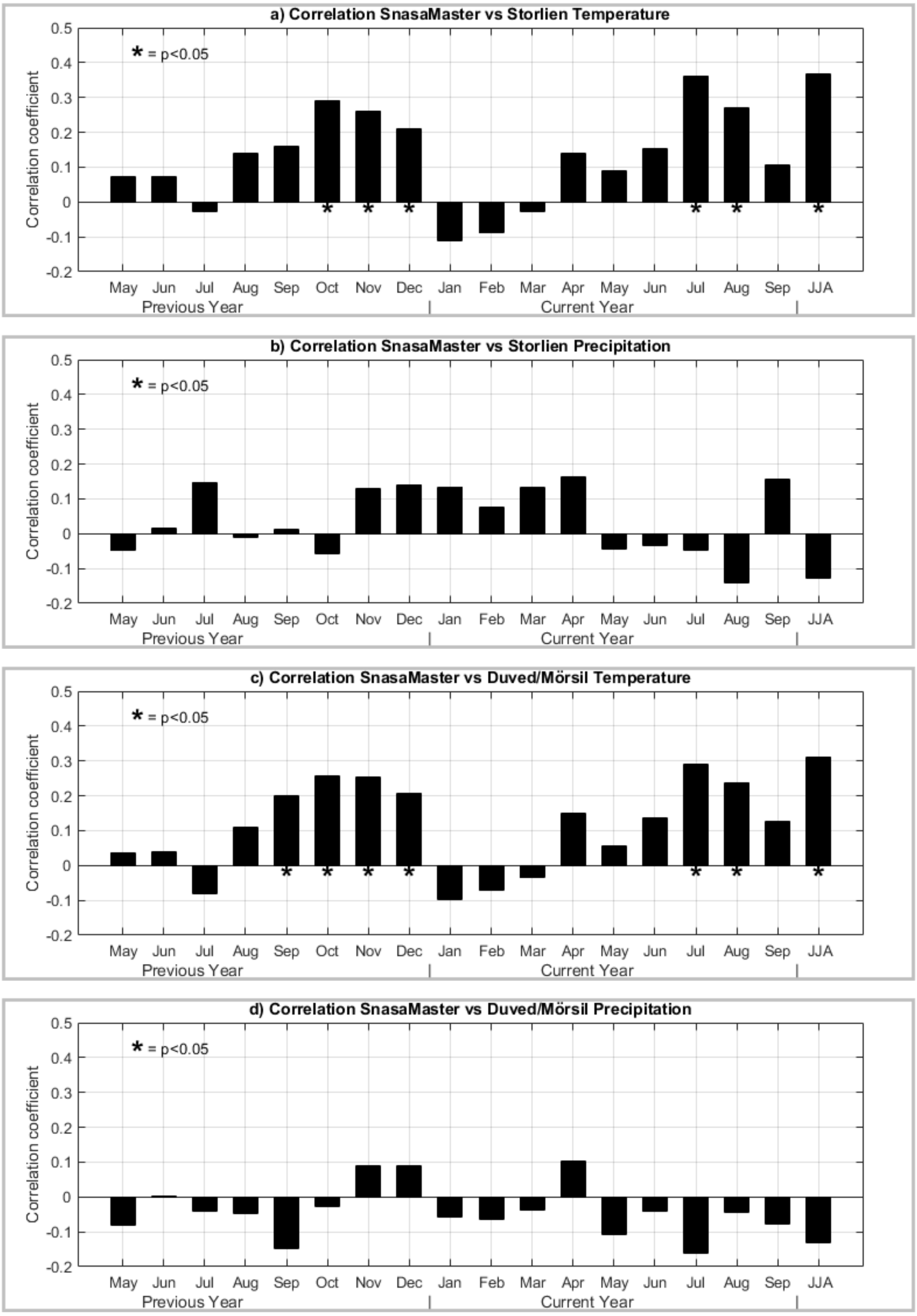

Figure 10*. Correlation coefficients SnasaMaster vs temperature and precipitation.* ***a)*** *Storlien temperature. Highest correlation during the summer months of June-August, also visible in the JJA average. Noticeable is the high correlation during October-December the previous year.* ***b)*** *Storlien precipitation. Low correlation, lack of statistical significance.* ***c)*** *Duved/Mörsil temperature. Similar patterns as with Storlien temperature, but the correlation is not as strong with lower coefficients.* ***d)*** *Duved/Mörsil precipitation. Again, low correlation and lack of statistical significance.*

Because of the strong connection between the two masterchronologies and the temperature data from Storlien meteorological station, both chronologies were plotted with the averaged June-August temperature from Storlien station, Figures 11 and 12. The largest difference against temperature for both chronologies are in the 1950s, a phenomenon also visible in the middle of the 1970s.

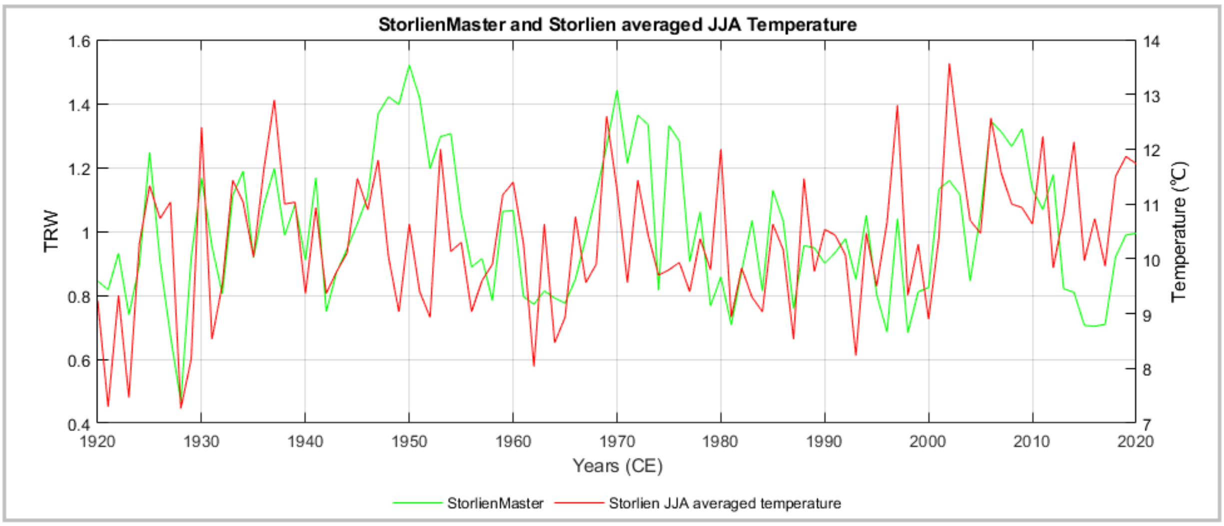

Figure 11. *StorlienMaster plotted against Storlien averaged June-August temperature. The largest deviation found in the 1950s.*

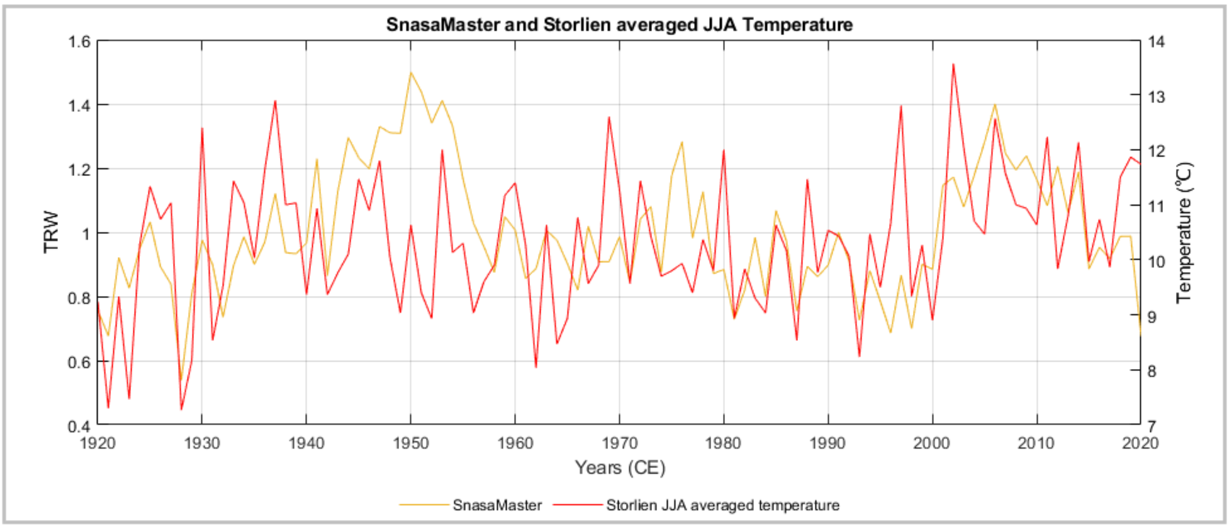

Figure 12. *SnasaMaster plotted against Storlien averaged June-August temperature. The largest deviation also found in the 1950s.*

By dividing the time period into three shorter subperiods of 40 years each (41 for the last period), a possible change of response towards climatic impacts can be investigated. Correlating each subperiod with the June-August averaged climatic data from each meteorological station yielded similar results, displayed in Table 3 and Table 4. Although it has been established that tree ring growth are most influenced by temperature, also precipitation was averaged over the summer months of June to August to detect a possible change of response during the past subperiods. StorlienMaster only shows statistically significant values against temperature, where periods 2 and 3 correlates equally with both meteorological stations, with only period 1 differing in advantage of temperature from Storlien meteorological station. Out of twelve correlations, SnasaMaster only have three statistically significant values, all with temperature.

Table 3. *StorlienMaster. Correlation values for the three subperiods TRW against averaged June-August climatic data. TRW is only statistically significant against temperature, with not statistically significant values marked in grey.*

STORLIENMASTER	**1920-1959** **Period 1**	**1950-1989** **Period 2**	**1980-2020** **Period 3**
Storlien Temperature (averaged JJA)	r = 0.49 p = 0.00	r = 0.43 p = 0.01	r = 0.48 p = 0.00
Storlien Precipitation (averaged JJA)	r = -0.10 p = 0.52	r = -0.13 p = 0.41	r = -0.06 p = 0.69
Duved/Mörsil Temperature (averaged JJA)	r = 0.38 p = 0.02	r = 0.43 p = 0.01	r = 0.48 p = 0.00
Duved/Mörsil Precipitation (averaged JJA)	r = -0.02 p = 0.89	r = -0.26 p = 0.11	r = -0.15 p = 0.36

Table 4. *SnasaMaster. Correlation values for the three subperiods TRW against averaged June-August climatic data. Only three correlations statistically significant. Not statistically significant values marked in grey.*

SNASAMASTER	**1920-1959** **Period 1**	**1950-1989** **Period 2**	**1980-2020** **Period 3**
Storlien Temperature (averaged JJA)	r = 0.40 p = 0.01	r = 0.18 p = 0.27	r = 0.49 p = 0.00
Storlien Precipitation (averaged JJA)	r = -0.30 p = 0.06	r = 0.06 p = 0.70	r = 0.01 p = 0.93
Duved/Mörsil Temperature (averaged JJA)	r = 0.26 p = 0.11	r = 0.20 p = 0.21	r = 0.45 p = 0.00
Duved/Mörsil Precipitation (averaged JJA)	r = -0.20 p = 0.21	r = -0.05 p = 0.75	r = -0.08 p = 0.63

3.3 Temperature trend analysis

A trend analysis was conducted for the averaged JJA temperature from both meteorological stations, Figure 13a and Figure 13b. For Storlien, the trend for the entire period is statistically significant within a 95% confidence interval with a positive trend. Also, period 3 (1980-2020) shows statistically significant values although displaying a steeper gradient then the long-term trend. For Duved/Mörsil, the long-term trend is not statistically significant. Similar to Storlien, period 3 (1980-2020) are however significant, displaying a steep positive trend.

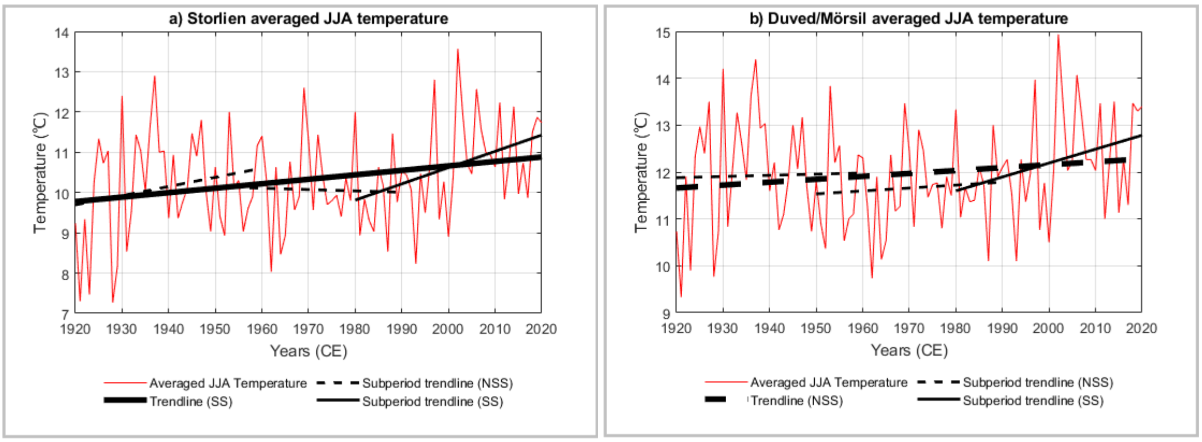

Figure 13. a) *Trend analysis of Storlien averaged June-August temperature for the time period 1920-2020, as well as the subperiods, although these are not statistically significant.* ***b)****. Trend analysis of Duved/Mörsil averaged June-August temperature for the time period 1920-2020, as well as the subperiods.*

3.4 Tree line change

The visual tree line analysis in Snasahögarna, for the years 1957 and 2020, indicates a movement of the tree line (Figure 14). During the 63-year long timespan used in this study, a tree line movement to higher altitudes has occurred.

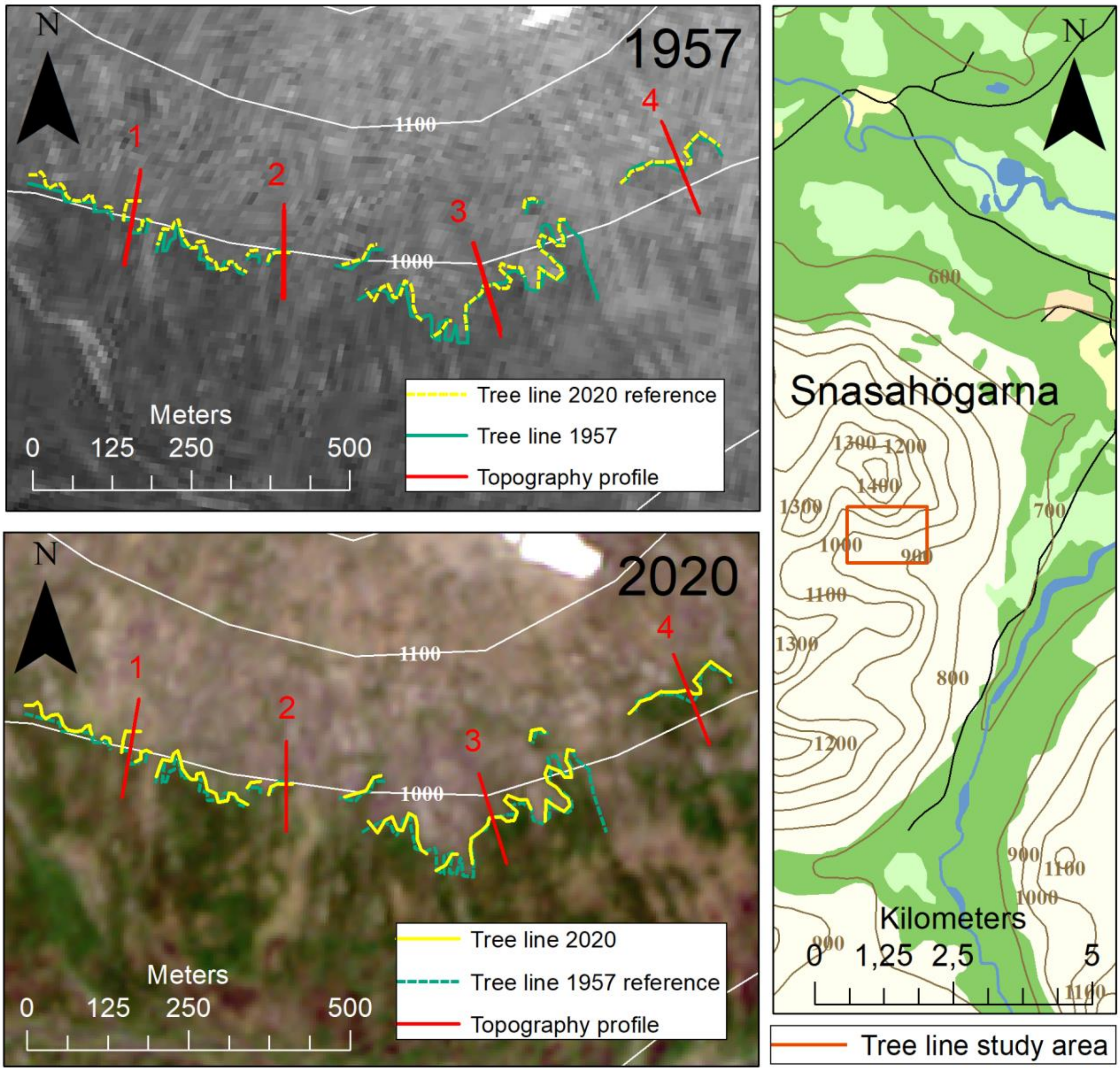

Figure 14. The tree line movement between 1957 (green) and 2020 (yellow) in Snasahögarna. The red lines, perpendicular to the contour line, show the topography profile at four different locations. (Analogue aerial photography in greyscale 1957 © Lantmäteriet, 2021b. Copernicus Sentinel data 2020 © processed by ESA, 2021)

The topography profile (TP) graphs show the slope and the tree line change for four different locations, perpendicular to the tree line (Figure 14). TP1, illustrated in Figure 15a, show that the tree line is located approximately 22 m higher in 2020 than in 1957. Between the green (1957) and the yellow (2020) dots, there is a section in the topography that is flat. In TP2, the tree line has not changed during the time period. Seen in Figure 15b the green and the yellow dots has the same location, just at the bottom of a steep slope. Visible in TP3, the tree line has stayed at the same altitude. Figure 15c show that the tree lines in both 1957 and 2020 are in a steep slope. Lastly in Figure 15d, TP4 show that the tree line is located about approximately 8 meters higher in 2020 than in 1957. Both the green dot and the yellow dot are in a slope with a lower angle than the slopes in TP2 and TP3.

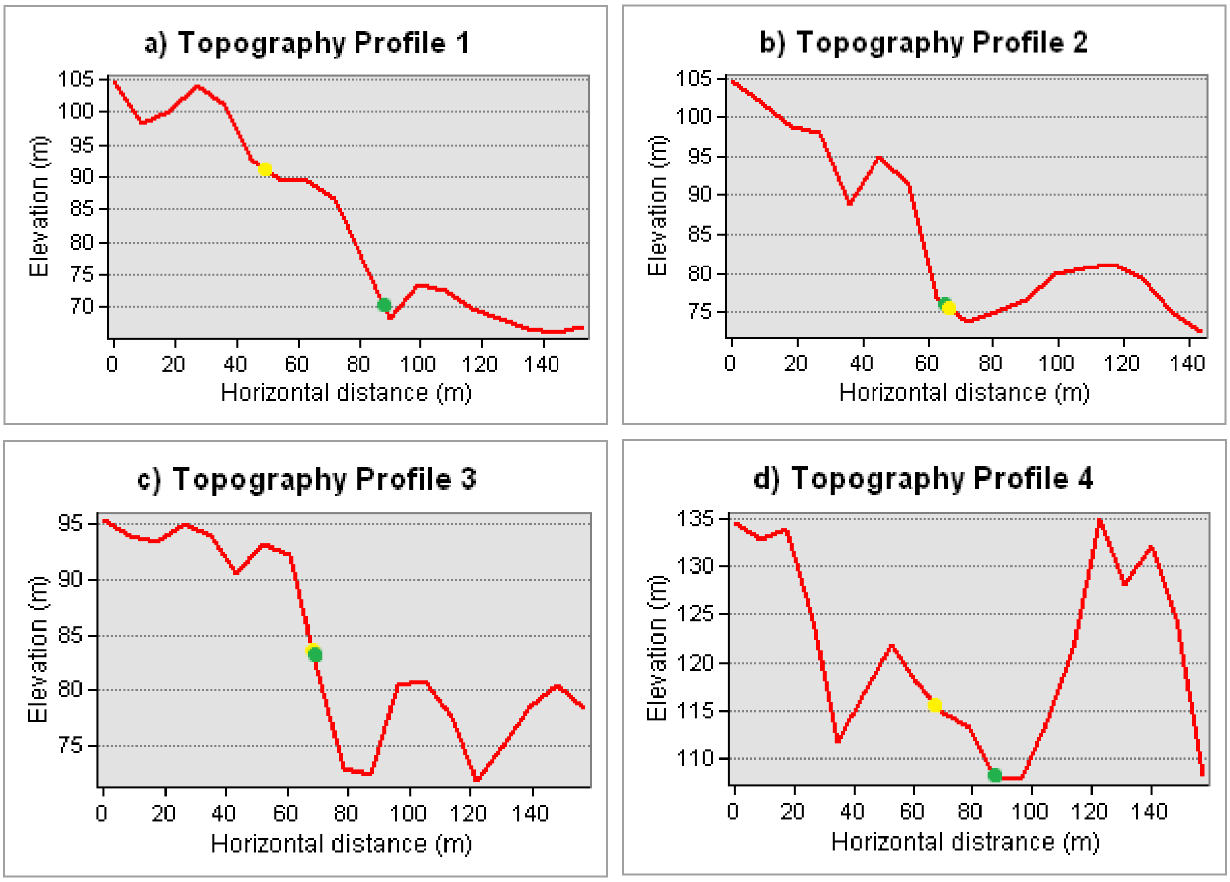

Figure 15**. The topography profiles for the four different locations perpendicular to the tree line. The green dot represents the tree line location in 1957 and the yellow dot represents the tree line location in 2020.* ***a) *TP1 show a slope with a flattened section, between the green and the yellow dots, with a difference in elevation of about 22 m.* ***b)*** *TP2 show that the green dot and the yellow dot at the same height. The tree line has not changed much.* ***c)*** *TP3 show that the green dot and the yellow dot are at the same height. The tree line has not changed much.* ***d)*** *TP4 show a difference in elevation between the green dot and the yellow dot of about 8 m.*

4. Discussion

Our results show that the limiting factor for growth of trees in this region is temperature. This finding is supported by previous studies saying that the climatic variable mostly influencing the growth of tree rings, for both study sites, is temperature (Kjällgren & Kullman, 2002; Linderholm & Gunnarson, 2005; Linderholm et al., 2015). Although the regional climate is strongly connected to the TRW, there is small seasonal differences to which type of airmass the two sites respond to. The most influencing months of the year is June, July and August, although the fall of the previous year also seem to have a contributing effect on TRW. The new tree ring data produced for this study extends the existing TRW chronologies up to the year 2020 in Jämtland and is a welcoming contribution to the common tree ring network. Additionally, a tree line expansion to higher altitudes was found. Our results combined, improves the possibilities of analyzing climatic changes and expected growth responses from trees, enhancing projections of changing ecotones and possible adaptation plans. Another indicative result for the future of this region is the long-term positive trend for the averaged June-August temperature in Storlien.

4.1 StorlienMaster and SnasaMaster comparison

The chronologies representing our two study sites display similarity in yearly tree ring growth, validated by the correlation analysis, showing a correlation coefficient of 0.74 ($p<0.00$). This confirms that they are affected by the same climatic conditions and follow a similar growth curve. However, some differences throughout the time series are visible in Figure 8, primarily around 1970, with StorlienMaster increasing growth rates which is not visible in SnasaMaster. This comparison of the chronologies shows there is a large regional influence of climate in this area. Differences in TRW between the sites are possibly the attribute of local conditions, due to microclimate. Our results also confirm the variability of growth within the studied population, where SnasaMaster displays a higher variance, indicating a more individual growth response to different environmental factors.

An interesting finding was the age of the new samples. In SnasaMaster a large number were of age between 40-70 years, indicating a shift in population taking place in the mid-twentieth century. This trend in age is not visible for the samples from StorlienMaster. This suggests a higher rate of new establishments taking place at Snasahögarna due to a favorable local condition. However, this should be regarded with caution as it could be an effect of sampling rather than a validation of tree age for the area.

4.2 Climate sensitivity

We have found that temperature is the influencing factor governing the growth of tree ring width in this region. The best correlation is found during the summer months of June-August in the growth year, as well as against a combined average of June-August temperature called JJA. Both chronologies indicate a better connection with the maritime climate of Storlien, although they also have a significant correlation with the continental climate but to a lesser extent. This was expected for StorlienMaster, and for SnasaMaster it shows that the close distance to Storlien is an important factor although located on the leeside of the mountain. Furthermore, TRW and precipitation show no statistically significant relationship, although StorlienMaster shows a statistically significant connection with Storlien precipitation in July of the previous year, and in June the previous year for Duved/Mörsil. Since no other values are statistically significant, and the relationship is the opposite, positive for Storlien precipitation, and negative for Duved/Mörsil, it is interpreted as an anomaly and possibly occurring by chance.

Displayed in Figures 11 and 12, it is evident that a wide tree ring corresponds with high averaged JJA temperature. For SnasaMaster, the variance between widest and narrowest tree ring is 0.97 during the period of this study. The equivalent for StorlienMaster is 1.07. The plotted lines for each chronology against the averaged June-August temperature for Storlien station corresponds when looking at the difference of highest and lowest temperature, validating temperature as the most influencing factor for TRW. There are however certain years with the opposite relation towards temperature, where we have wide tree rings and low temperature, for example in the 1950s. Interestingly, both chronologies peak during the same period, indicating that something has influenced, on a regional scale, the growth at both sites which cannot be attributed to temperature who shows the opposite. Another apparent difference is around 1970, as previously mentioned. While StorlienMaster peaks, SnasaMaster does not show any signs of the same. Looking at temperature for this period it can be stated that it peaks in 1969, and thereafter decreases. StorlienMaster looks to have a delayed effect while SnasaMaster does not respond in the same way. While the chronologies and temperature curves peak and dip the same, the amplitude differs. Shortly thereafter, in the middle of the 1970s, the same phenomenon as seen in the 1950s is displayed. Both chronologies peak even though temperature does not. The opposite conditions are visible in the late 1990s, early 2000s. While the temperature peaks, none of the chronologies respond accordingly in amplitude. Also, in this period we have the same variance between temperature and TRW, but not the same amplitude. Combining these differences, it is apparent other environmental factors have considerable influence, most likely attributable to local conditions.

While StorlienMaster correlates only to the temperature derived from Storlien meteorological station the previous year, and not at all against Duved/Mörsil, SnasaMaster shows a correlation towards temperature during the fall months in the previous year from both stations. This can be interpreted as SnasaMaster being more influenced by the continental airmasses during the fall than StorlienMaster. Additionally, the variance due to autoregression (Table 2), which indicates how much of previous years result influences the result of the growth year, indicates that SnasaMaster is more influenced by previous year's growth with a value of 57.3%. Different opinions exist as to whether it is only the current years climate or both previously and current years climate that influences the growth of tree rings (Taeger et al., 2013; Semeniuc & Popa, 2018). Although our study indicates the largest influence of TRW is the current year's summer climate as suggested by Taeger et al., (2013), it confirms the results of TRW being dependent on the fall/winter temperature of the previous year as well, as proposed by Semeniuc & Popa (2018). This result is also consistent with findings from Tuovinen (2005) indicating significant relationship of TRW with the fall/winter temperatures of the preceding year. His study suggests the formation of earlywood relies on energy reserves, conditioned by the fall/winter climate of the previous year. He also found that this relationship might be governed by the interaction of temperature and precipitation, a finding our study does not have the ability to determine. However, suggestions can be drawn as to the importance of precipitation. StorlienMaster has weaker relationship with the previous year than SnasaMaster. Storlien station data also shows higher precipitation values than Duved/Mörsil. It could therefore be argued that the lesser amount of precipitation in the continental climate seems to be a favorable condition, however more detailed studies must be done before any conclusions can be drawn.

For SnasaMaster, many trees included in the chronology were of an age between 40-70 years. A study by Kullman (2014) presented an overview of changes in the Scots pine population between 1973-2012. It registered an increase of pine populations of almost 30%, closely related to the regional temperature. Holtmeier & Broll (2005) describes how local conditions such as wind exposure and snow burial might protect seedlings. They also conclude that the existence of younger trees is a good sign on sensitivity towards environmental changes. Because of the location on the leeside of the mountain, the trees from Snasahögarna might experience favorable conditions regarding wind exposure as a possible explanation of the number of young trees compared to StorlienMaster. Additionally, a new forest conservation act was taken in place in 1920-1930 for the southern and middle parts of the northern Sweden where Jämtland is located, to improve the forest after the large timber exploitation on the 19th century (Sivertsson, 2004). This act, which could possibly explain the upswing of tree growth in the 1950s, regulated felling and established the new generations with small plants instead of seeds, and took care of the new plants with the goal to get a better and more flourished forest. The article by Sivertsson (2004) also mention that the area around Handöl provided charcoal felling in the 1930s-1950s, which was a requested product during the World War II. The upswing of tree growth might therefore be explained by a new forest conservation law, with safer establishment of new trees, in combination with a possible response to charcoal felling.

We also examined whether the trend and relationship between TRW and climate has shifted on a shorter timescale. The climate in general in this region displays increasing winter temperatures and decreasing precipitation since the beginning of our studied time period. The analysis confirms the relationship between TRW and temperature, and a conclusion can be drawn that no shift in response of TRW between temperature and precipitation has occurred during the last 101 years, although the relationship is not statistically significant for many periods for SnasaMaster. The difference between the chronologies and temperature in primarily the 1950s could not be explained by the correlation analysis on shorter timescale. StorlienMaster results still suggest a high influence of temperature, but the results for SnasaMaster is different. During period 2, the results indicate a loss of connection to temperature. Interestingly, it coincides with the possible high rate of new establishments of pine occurring simultaneously. A transfer of influence of precipitation was not noted, however the method for this study only included analysis of June-August average for comparison reasons. Tuovinen (2005) suggests that precipitation might influence more during the winter season, indicating a possible connection to the increased establishment of pines.

4.3 Tree line change

The study of the tree line at Snasahögarna in Figure 14, comparing images for the years 1957 and 2020, illustrates that the tree line has moved to higher altitudes. Since this analysis depend on the visual quality, the limited access of aerial imagery for the study area, both quantitively and qualitatively, might affect the accuracy of tree line movement measurement. However, the result is still sufficient to draw conclusions of possible changes. With the help of topographic profile graphs, indications of the tree line movement can be drawn and reasons for differences in changes.

Out of the four topography profiles (TP), TP1 illustrate the largest tree line movement of about 22 m and is the only one with a section of flat topography near the dots. TP2 and TP3 has no tree line movement but very steep slope angles. TP4 have had a tree line movement of approximately 8 m in a slope, but it was not as steep as the previously mentioned TP2 and TP3. Steeper slopes seem to inhibit the tree line movement to higher altitudes, while a flatter slope indicates a larger tree line movement. The reasons for differences in tree line movement at different locations can therefore be explained by local variation in topography, which also correspond with the study by Sjögersten & Wookey (2005).

The detected tree line in this study is most likely birch. Öberg (2008) mentions the tree line of birch (*Betula pubescens ssp. tortuosa),* being located at a higher altitude compared to the tree line of pine *(Pinus sylvestris)* and fir *(Picea abies)* for study sites in Jämtland. She also confirms that where a tree line movement has occurred, it was seen in all three species, towards a higher altitude. An increasing trend of temperature in this area means the length of the snow cover season will decrease, providing a longer growing season for yearly growth and more time to establish new trees (Öberg, 2008; Länsstyrelsen, 2014), a conclusion supported by our results. This information validates an expected tree line expansion of also Scots pine. The trees in this region grow close to its upper elevational limit. Combining the knowledge gained from our analyses, our study confirms the concept of ecological amplitude, saying that trees close to its natural boundaries are limited by climatic variables, in this case temperature. A changed tree line towards higher altitudes, together with a high correlation against regional temperature, support the general idea of changing ecotones in this area as a response to climate.

5. Conclusion

This project revealed that temperature and regional climate dominates the growth of tree rings. It contributed with two chronologies for Storlien and Snasahögarna, respectively. Future studies on global warming on a regional level should lead the research as different regions will experience different climate changes. Combining the results from this study, future tree line expansion is to be expected for this area. With a positive trend in temperature, trees are likely to grow more vigorously, establishing new stands on higher altitudes, altering existing ecotones boundaries.

- Our results reveal that the trees, chosen for this study, show a large sensitivity to climate, specifically regional temperature. This relationship has mostly been sustained during the last 101 years.
- The maritime climate influences the growth of trees in this region, but indications suggest that the trees at Snasahögarna are more influenced by the continental airmasses than the trees at Storlien. Although the two sites display an overall agreement of the chronologies during the studied time period, small differences were detected, especially during the 1970s.
- A tree line movement to higher altitude has occurred between 1957 and 2020, most likely due to a changing climate. At some locations, the tree line movement are limited by steep slopes.

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