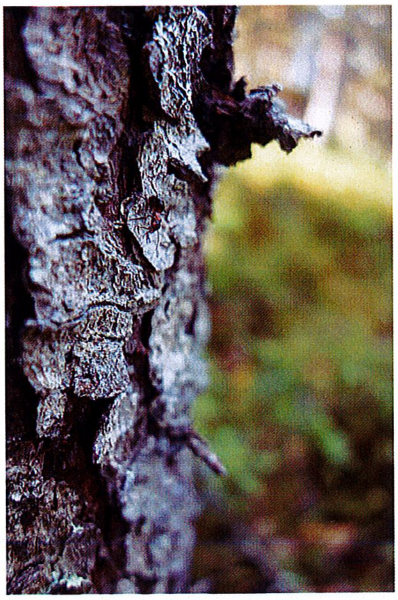
# Stand Structure in a Heterogeneous Old-growth Norway Spruce (Picea abies (L.) Karst.) Forest in Northern Sweden



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Degree of Master of Science (120 credits)
with a major in Earth Sciences
60 hec

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**ISSN 1400-3821**

**B1116**
**Master of Science (120 credits) thesis**
**Göteborg 2020**

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## Abstract

This study investigate the growth trend in an unmanaged Norway spruce forest in Västerbotten Country, Sweden. The result indicate that relationship between the diameter at breast height (1.3 m) and height follow a statistical significant trendline, where taller trees also represent wider tree diamater. The diameter hade a lower correlation to tree age, indicating that some trees in this area can have been suppressed for a time or have experience periods of high competition. Climate data (temperature, precipitation and North Atlantic oscillation) seem to have had only a partial (<50%) effect on the tree growth during two 40-years period. North Atlantic Oscillation showed no correlation with any tree chronology (standard and residual) during the past 160 years. A principle component analysis (PCA) were conducted, where the two strongest components corresponded to a cumulative variance equal to 55.5%. No chronology based on the two strongest components could fully explain the interaction between past climate and the tree ring growth detected in the study area.



## Sammanfattning

Denna uppsats kollar på tillväxttrenden i en orörd granskog I Västerbottenslän, Sverige. Resultatet påvisar att det finns en statistisk signifikant linjärtrend mellan stamdiametern mätt ifrån brösthöjd (1.3 m) och höjd. Desto högre träd, desto bredare stambredd. Ett svagare samband återfanns mellan ålder och stamdiametern. En orsak till detta kan förklaras med att vissa träd eventuellt har upplevt ett stadie av undertryckelse under en del av sin levnadstid, eller att området är konkurrens rikt. Klimatdata (temperatur, nederbörd och den Nordatlantiska oscillationen) visade sig bara till viss del (<50%) ha haft en inverkan på tillväxten under två 40-årsperioder. Under en 160års period indikerade Nordatlantiska oscillationen ingen korrelation med någon skapad trädkronologi (standard och residual). En principal komponents analys (PCA) utfördes, och visade att de två starkaste komponenterna tillsammans motsvarade en kumulativ varians motsvarande 55.5%. Två kronologier skapades baserade på den tillväxt ifrån trädproverna som korresponderade till respektive komponent. Ingen av dessa korologier kunde fullt ut förklara sambanden mellan klimatvariablernas inverkan på tillväxten i en orörd granskog.

## Contents

# Introduction

Fennoscandia contain a lot of forest, whereas the wood material historically have been used for multiple purposes such as; house engineering, silviculture, fire fuel, and building material (Skogsstyrelsen, 2015). It has late been suggested that forest become an important tool in tackling the increased climate concern regarding an enhanced climate change due to human activities. The climate impact have been taken up on different agendas, where trends of increased values of atmospheric carbon dioxide ($CO_2$), have resulted in local and global changes. Some of these changes have been detected in temperature deviations, as well as in water storage and soil properties, just to mention a few (IPCC, 2014). These changes have had various effect on vegetation growth, where some areas have benefited from these climate changes, whereas others have exhibited a decreasing vegetation growth during a longer timescale (Ols, Kålås, Drobyshev, Söderström & Hofgaard, 2019).

How and to what extent forest management have been practiced and should be practiced in the future have been highlighted in terms of what future consequences we may face in addition to climate mitigation (Lundmark et al., 2014). Fennoscandia is characterized by a long history of even-aged forest management, the majority of productive forestland having been actively managed for wood production for at least a century. Today this is the dominating silvicultural system with the aim to have an even age class distribution on the landscape level to allow a steady flow of timber from the forest.

An alternative to even-aged forest management is continuous cover forestry (CCF), a silvicultural system without a clearcut phase. CCF typically has uneven-aged heterogeneous stand structure and a continuously maintained forest cover, which does not follow a cyclic harvest-and-regeneration pattern on the stand level as it occurs in even-aged forest management (Zucchini, Schmidt & Gadow, 2001).

Instead, multiple selective cuttings over regular time intervals characterize the CCF system. In the classical CCF silvicultural practice single-tree selection, individual trees are harvested throughout the stand to maintain an uneven-aged (and uneven-sized) stand, achieve a desired diameter distribution, and to allow establishment and ingrowth of new naturally established seedlings (Ahlström & Lundqvist 2015). CCF assumes that harvested trees are replaced by ingrowth of smaller trees, which are trees that managed to survive and grow large enough to be qualified as samplings. The younger trees will then supplant the ones that have been harvested, and by that be able to maintain a more or less constant distribution over time, between the total number of trees and diameter distribution. The ingrowth of new trees depend on seed production, germination and plant establishment as well as growth and mortality of the young trees (Laar, Akça, Gadow, Pukkala, & Tomé, 2007).

The regulators controlling the fertility and density rate of a site are influenced by topography (which to a big extent regulates the temperature and water availability at a site), mechanical movement (soil and wind movement), geology (what type of soil type the vegetation are growing on and the soils nutrient supply) and sun exposure. The climatic interactions that occur within the different spheres have therefore a daily to annual growth effect on the forest (Fritts, 1976).

In the present study, are the dynamics of ingrowth in naturally heterogeneous Norway spruce dominated stands (*Picea abies* (L.) *Karst.)* in Västerbotten County, which has never been subjected to clear felling.

## Aim and hypothesis

The aim of this study is threefold: (1) to improve the understanding of growth trends in a boreal CCF or un-managed forest, (2) to investigate to what extent climate have influenced the forest growth (3) to look if any of the climate variables (air temperature, precipitation, North Atlantic Oscillation) can explain the growth trend seen in the study area.

These are the questions that have been asked to reach the aim:

- Is there a clear relationship between radial growth and age, or height?
- What is the average growth rate for Norway spruce to extend from 20 cm to 130 cm above ground?
- To what extent is the growth controlled by the different climate variables?
- Did the impact from any potential growth-controlling factor change over time?

# Background

## The Utilization of Swedish Forestry

The Swedish forest and the way it has been utilized have went through four major paradigm shifts over time according to Kardell (1992).

As hunter and gatherers the forest was used for survival and a source for firewood and tool material. This view became slightly more negative during the time-epoch consisting of farming practices. At that time had forest turned into an obstacle in terms of practicing ploughing and sowing. The forest decreased in relation to the increasing population, during the 1650's. But the soil erosion lead subsequently to lack of food and people dying, which gave the forest some time to naturally regenerate. It later became of economic interest during the industrial period, and exploitation of natural resources occurred on a bigger scale than before. During this period, a concern about the forest and its future provision was raised, follow-on a more sustainable way of using the forest and its resources. The last shift occurred during the 20$^{th}$ century and focus on forest conservation, when the forest gained a purpose of enjoyment and well-being for ourselves as well as other ecosystem (ibid, Skogsstyrelsen, 2015).

The economic importance of exporting timber and timber product, have made Sweden the World's 3$^{rd}$ largest exporter (2018), with and export value of SEK 145 billion and employing 70 000 people within the forestry sector (Forestindustries.se, nd). There is a big competition of the Swedish forestry, due to the versatility of the forest products (Brännlund, Lundmark & Söderholm, 2010). The forest is of many operators interest, it can e.g. be used as a tool to reach the country's climate goals and act as an carbon sink, it is also however of interest within the energy and transport sector, in terms of a source of renewable energy and for production of renewable fuel (IPCC, 2014; Skogsstyrelsen, 2015).

There are problematic climate goals to be addressed however, where some of them can't coexist without failing the other. Brännlund et al. (2010) gives an example, where '*restrict the effect from climate*', can't be reached if one want to '*preserve living forests'* (Sverige, 2008) (see *Differentiation un-managed and managed forest; Climatic value*).

## Differentiation within managed and un-managed forest

The characteristics of a managed and un-managed forest contain both pros and cons, and the definition of the different forest types may differ in literature.

One definition given by the *Lexicon Dictionary* (2020), of an un-managed, or primeval forest is "a very old or ancient forest, especially one in a natural state, untouched by agriculture or industry" and originate from the late 18$^{th}$ century. Another definition, "a forest area which have to a large extent been unregulated after the year 1900 […]" (Own translation, Kardell, 1992) does take into account that a lot of pollen and seedlings regenerating in old Swedish forest, originate from nearby countries, e.g. Germany. In contrast to un-managed, a managed forest is a forest with stands where the trees originate about the same time, either through anthropogenic acts like planting, or naturally through seeding from surrounded trees (Buongiorno & Gilles, 1987).

### Age

The age in old boreal forest in Fennoscandia, is described by Sirén (1995) to follow a 240 year life cycle, where forest excluded from fire events display an even aged stand structure class distribution. Forest going through fire event or wind activity show a bigger age distribution, a so called un-even aged distribution, when new regeneration occur in relation to these events in un-managed forest (Lilja, Wallenius & Kuuluvainen, 2006). An uneven-aged forest contain great age and size distribution, "where areas of homogeneous age classes cannot be distinguished" (Buongiorno & Gilles, 1987). There are however some types of smaller stands, where trees within similar class and age distribution are grouped together. These groups are in contrast to the compartments in the even-aged forest, much smaller and are not managed.

Trees within a managed stand have a termination date, where they are harvested at a certain age, often referred to as rotation age. Selective cuttings, referred to as thinning, are usually made to increase the growth of selected trees before the stand reaches their rotation age. The forest as a whole may be un-even aged, where trees differ in size inconclusively from one and another. These differences are not seen within the same stand, and are therefore portrayed as a mosaic landscape where the different stand are referred to as compartments (Buongiorno & Gilles, 1987).

### Stand structure and economic value

It is suggested that it takes up to 300 years to turn a forest back into a stand structure found in uneven-aged forest. That includes a stand-replacing disturbances, where the regeneration is determined by external event, self-thinning and competition (Čada, Svoboda & Janda, 2013). It is suggested that the forest first become deciduous dominated with pioneer species like Birch (*Betula)*, while conifers being suppressed during the first decades. In a later stage, 110 – 130 y later, in older age class have conifer species like Norway spruce instead become more dominant, and the amount of mixed species decreases (Lilja et al., 2006). A forest in different sized and age classes usually show marks of damage from trees growing nearby bumping into each other, leaving branches and tree tops randomly placed on the ground. The high amount of competition between individual trees gives the vegetation somewhat a deformed look with twisted and bent features, when the trees are trying to adapt and grow in a specific way to survive. Wind-thrown trees due to storm event usually result in a temporary even-aged forest which after 100-200 years starts to develop vegetation in multiple substrate (Kardell, 1992). Coarse woody debris (CWD), refers to dead wood in different stages of decay, is greater in a non-managed or so called natural forest compared to a managed forest. More snags, standing dead trees, have not been anthropogenically removed (Gibb et al., 2005).

Troup (1928) and Gadow (2001) implies that a natural grown forest without any or only little thinning, have a wide aged class distribution and a broader height and diameter interval. This type of forestry is referred to as continuous cover forestry (CCF). To perform selective cutting as an alternative to clearcutting, makes it possible for seedling to establish and grown on a naturally way. The ingrowth of new trees are thereby controlled by a forest physiology in terms of seed production, germination and plant establishment. This is in addition controlled by growth and mortality of the trees (Laar et al., 2007; Gadow, Pukkala, & Tomé, 2012). The economic benefit from un-managed and CCF forest is that they don't have any expiring date, and regeneration occur naturally as new samplings are replenishing the older harvested trees. Shade tolerant trees are a superior choice for this type of a more natural forest management (Lilja et al., 2006). Un-managed forest tend to be more open, with more space in-between trees or stands due to water-fluctuations and grazing (Niklasson & Nilsson, 2005).

Managed forest is of economic advantages, as they are controlled by artificial regeneration and therefore controlled in quality of the product, with similar height and trunk sizes. This is favorable for commercial specie preferring to grow in full-light conditions (Buongiorno & Gilles 1987). Competition is also somewhat regulated by thinning, which increases the radial growth and result in a more even quality of the forest (Valinger, Lundqvist & Sundberg, 1994; Karlsson 2013). An increase in radial growth have been detected in conifers close to strip roads, where the competition decreased as trees were removed, and was instead given a higher light, moisture and nutrient supply (Eriksson, Johansson & Karlsson, 1994; Mäkinen, Isomäki & Hongisto, 2006).

Using a clear-cut method during harvest, generates lower logging costs per unit of timber removed, as machinery doesn't have to take into consideration which trees are to be extracted and which are to be left in the stand, compared to a selective harvest. The vegetation that is left after a clear-cut is favorable as food for some animals like deer (Buongiorno & Gilles 1987). CWD in a managed forest located in Fennoscandia is somewhat between 2% - 30% less, compared to a free growing forest (Gibb et al., 2005), and around 90% or even more within Swedish forestry (Niklasson & Nilsson, 2005). The variation of CWD is regulated by standing volume and the uniformity of stands, which tend to lower the number of dead trees as a consequence. In addition, CWD is typically removed during the use of forest machinery, which often have an effect on reshaping the landscape (Ibid.). The natural stand structure found in old-growth stand is argued by Spies (1998) hard to be reconstructed in forest where traditional forest management is practiced. This will especially be seen in young stands, where a higher amount of dead wood will have been removed in the managed stands.

### Biodiversity

Spruce are commonly dominant in an un-managed forest, with exception of very dry or very wet lands. The amount of dead wood is beneficial for insects, animals that are in need of protection and different species of woodpeckers (*Picidae*). Old forest are low in nutrition compared to other type of woodlands, and contain a lower number of producing insect and therefore less breeding birds. Similar can be said for mammals, who's low population numbers are correlated with the low amount of edible material. The type of animals one can expect to see are the European pine marten (*Martes martes*) and the Red squirrel (*Sciurus vulgaris*). Other birds than woodpeckers that have been spotted are Grey-headed chickadee (*Poecile cinctus*) and Great grey owl (*Strix nebulosa*) (Kardell, 1992). Reptile and frogs are rare in this environments but it is never the less the home for a lot multiple red-listed invertebrates.

Dead wood is vigorous for many fungi species and an important resource for plant and animals. Roughly 90% of red-listed invertebrates that can be found in the Swedish coniferous forest are in need of CWD. Fungi, lichens, mosses and hepatics prefer larger-diamter CWD which has been under a longer state of decay, compare to some beetle species prefer snags (Gibb et al., 2005). In any type of managed forest, and especially in these practicing intensive management, species are close to extinction unless foresters are trying to rehabilitate the managed forests. The woodland can be restored from e.g. a clear-cut, or a semi-managed forest can be conserved and mimic the characteristics found in old forest habitats and by that improving the habitat quality in more regulated forest types (Lilja et al., 2006; Čada et al., 2013). Studies have shown that the removal of high quantities of dead wood in standard forestry practice have had a negative impact on the biodiversity (The European Forest Sector Outlook Study II (EFSOS II), 2011). Even an open clear-cut area might be a suitable forest type for red-listed or threatened species, as long as they are from a landscape close by and that CWD are left on the open area (Niklasson & Nilsson, 2005).

### Climatic value

The forest can be used as a strategy to mitigate climate change (EFSSOS II, 2011; IPCC, 2014). High and stable growth is important from a climatic point of view. High growth yield increase the ability to sequestrate a greater volume of atmospheric carbon dioxide ($CO_2$) through photosynthesis, and increase the possibility of an even wood supply (Brännlund et al., 2010). By increasing forest productivity and limit harvest or change silvicultural approach, a greater amount of carbon will be stored in the biomass and soil through sequestration (ESOS II, 2011).

Another strategy is to focus on renewable wood products. The carbon fixed in wood products, e.g. furniture or woodchips, are not released into the atmosphere until they decay or are destroyed. The time the carbon is bound in the product varies depending on their in-service lifespan (Brännlund et al., 2010; ESOS II, 2011). These products can be made from wood originating from sustainable managed forests and replace non-renewable materials. This is a few examples given to reduce carbon emission (ESOS II, 2011).

### Other values

There forest have historically and today have a hunting and outdoor activity value. Hunting has not only a value in terms of food or cultural heritage, it has also a value in terms of grazing impact and road kill accidents, which put economic pressure on the society. Picking berries and mushroom is only possible if silviculture have been applied as an act to decrease clear-cutting and increase well-being (Brännlund et al., 2010). An un-managed forest or managed forest to a small extent, have a recreation value and is a more attractive environment to visit compared to a clear-cut area (Lilja et al., 2006). Export of tourism services in Swedish forests where according to the Swedish Agency for Economics and Regional Growth (2008) the biggest practiced service.

Another study made by the Swedish Educational Broadcasting Company (Sveriges utbildningsradio, 2019), show that it has an important value regarding people's well-being. It has a recreation and landscape value and can be used to promote public health (Savill, Evans, Auclair & Falck, 1997).

## How to Detect Forest Growth

It is important to measure the growth within a forest to investigate the quality and any potential changes in growing patterns. This is very helpful for decision makers when the future of the Swedish forest are planned for (The Swedish National Forest Inventory, 2019).

Spruce trees have been used in previous studies to look at the radial and height growth in boreal forests and how the climate regulate such growth (Suvanto et al., 2016; Ols et al., 2019). These studies were made to estimate future growth responses in term of climate change. The result implies that the length:diameter distribution in an uneven-aged forest followed a negative exponential function, with a few peaks representing establishment events and/ or disturbance history (Smith, 1986; Spies, 1998; Čada *et al.*, 2013), and that samples taken at higher elevation were managed to preserve low-frequency temperature signals better than on lower altitudes (Treml, Ponocná,King, & Büntgen, 2015).

## History of dendrochronology

Another way of detecting growth is by using the information within the trees. Dendrochronology, or tree ring research is by today a familiar concept in Europe since it was first introduce in the early 15th century, when Leonardo da Vinci (1452-1519) acknowledge that there is a relationship between the thickness of annual tree rings and a trees growing condition (da Vinci, Guglielmo & Giovanni Gherardo, 1817). Another discovery was later made by two French analysts, du Hamel (1700-1782) & de Buffon (1707-1788), who find that severe winter caused a distinctly darker ring (Académie des sciences, 1737). In Fennoscandia during the same time period, Carl Fredric Broocman (1709-1761) and Carl von Linné (1707-1778) individually found that there was a response in tree growth to seasonally temperatures (Linné, 1745; Broocman, 1760). By comparing the differences and similarities among pine trees in northern and southern Finland, Ulric Rudenschöld (1704-1765) concluded growth is affected by a locations regional climate and soil condition (Rudenschöld, 1899).

It wasn't until the beginning of the 20$^{th}$ century that Andrew Ellicott Douglass (1867-1962), after he had studied environmental and meteorological time series impact on growth trends, managed to statistically validate the hypothesis that there is a relationship between climate and annual tree ring width (Fritz, 1976; Schweingruber, 1988; Linderholm et al., 2010). Douglass later became the director of the modern science of dendrochronology at *The Laboratory of Tree Ring Research*, University of Arizona, Tucson. The laboratory made it possible to continue the important work of dendrochronology not only in the USA, but rather around the world (University of Arizona Laboratory of Tree-Rings Research, 2017).

## Understanding tree ring physiology

The development and improved invention of the microscope in 17$^{th}$ century made it possible for scientists to get a better understanding of plant anatomy, and by the mid-18$^{th}$ century it was possible to deliver a clear interpretation of tree ring development (Schweingruber, 1988).

Trees usually form one annual ring each growing season. It is therefore possible to look at past annual differentiations and growth rates in various forest stands by counting the number of rings and measure the tree ring widths (TRX) in each sample (Schweingruber, 1988). An annual ring is typically split into two different wood density sections, lighter porous wood known as early wood in comparison with darker more dense wood referred to as late wood. Early wood is produced during the growing season starting in spring and continue to early summer, and is followed by a section of latewood, which is produced in late summer and the beginning of autumn, when the growing process decelerate before a tree enters a state of dormancy (Wilson, 1979; Speer, 2010).

## The use of dendrochronology

Dating tree rings and measure the TRX gives an opportunity for climatologist to gather historical climate data from the past, so called proxy data. There are other natural archives similar to tree rings, e.g. sediment cores and ice cores, which after being analyzed can be used to represent historical climate variations such as temperature or precipitation changes, forest fires, vegetation changes and volcanic eruptions (IPCC, 2001).

By measuring the TRW one is measuring the yearly increment (Douglass, 1909; 1914). Another way of gathering climatic information is by x-raying a tree sample, and compare the Maximum latewood density (MXD), which represent the density of the cell walls that have been created during a specific growing season. Compared to TRW which represent an annual trend, does

MXD represent a smaller climatic window improving the summer temperature representations by being less influenced by the previous year's temperature (Schweingruber, 1998; Luckman, 2007; Helama & Sutinen, 2016).

Depending on species and its location the TRX is suggested to be used in areas where the growth only is determined by either the temperature or water availability. The ring growth in temperate region depend mainly on temperature (Wodzicki, 1971), while the growth trend in trees located in the tropics is highly controlled by precipitation (Wils, Robertson, Eshetu, Sass-Klaassen & Koprowski, 2009; Koprowski & Duncker, 2012). In Fennoscandia TRX is highly used as a temperature proxy, and have provided several chronologies dated back e.g. 7.5 ka (Helama, Seppä, Bjune & Birks, 2012). Linderholm et al. (2010) and Seftigen, Björklund, Cook & Linderholm (2015) suggest however that trees from boreal forest may represent both temperature and precipitation, where the representation is determined by the vegetation's latitudinal location; temperature at higher latitudes and precipitation at lower latitudes.

Tree rings have been used to reconstruct temperature and water conditions in terms of precipitation and moisture from a local to global spatial scale. Trees ability and level of accuracy have made it possible to reconstruct temperature on a millennial (Jones, Osborn & Briffa, 2001; Moberg, Mohammed & Mauritzen, 2008; Schneider *et al.*, 2015; Wilson *et al.*, 2016; Anchukaitis *et al.*, 2017) and multi-millennial time scale (Grudd *et al.*, 2002; Helama, Linderholm, Timonen, Meriläinen & Eronen, 2002; Linderholm & Gunnarson, 2005; Pages 2k Consortium, 2013).

In a study made by Mikola (1956), conducted upon Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea Abies* (L.) *Karst*) samples from Finland, it was concluded that the growth diameter of Pine trees were dependent on July temperatures, while Spruce correlated to June temperatures. None of the species growth trend did correlate with precipitation, however, the diameter growth from trees located at dry sites was not favorable during very dry summers. Similar findings were reached by Helama & Sutinen (2016), where they in addition specified that the growth was dependent on late June temperature (with a threshold temperature below 13.6°C) and mid-July temperature. Neither did they find any statistic correlation between growth and precipitation. Older literature implies that a big difference between the two conifer species is how quick they seem to react to climatic changes. Pine seems to be more dependent on previous year's growth, compared to spruce who seems to lack this dependency (Ording, 1941; Hutisch & Elfving, 1944; Eklund, 1954; Jonsson, 1969). Additionally, historically temperature and precipitation sequences in terms of atmospheric circulation patterns, such as Southern Annular Mode (SAM) and North Atlantic Oscillation (NAO) have been studied through the use of tree ring data (Linderholm, Folland & Walther, 2009; Trouet, Panayotov, Ivanova & Frank, 2012; Villalba *et al.*, 2012; Abram *et al.*, 2014).

Dendroclimatology research continued to develop and did during the 20th century try to explain the association between tree growth and other local climate factors such as insect outbreaks (Koprowski & Duncker, 2012), forest fires (Laitakari, 1920; Eide, 1926; Erlandsson, 1936), past water discharge fluctuations (Singh & Yadav, 2013) and radiocarbon concentration connected to sunspot activity in the past (Solanki, Usoskin, Kromer, Schüssler & Beer, 2004; Buntgen et al., 2018). Some have even combined multiple proxy data (Steinhilber et al., 2012); data from ice cores and trees, to investigate past solar radiation and cosmic activity.

## What controls tree growth

There are three factors influencing interdependently a forest sites growth productivity; climate, topography and soil (Deyoung & Sutton, 2016). Trees are able to register long-term and short-term influences, which are converted into physiological processes which affect the growth and is a response of both internal and external influences (Schweingruber, 1988).

## Tree ring signal

The formation of a tree ring is according to Hughes et al. (1982) a function of several variables mostly explained as signals (Equation 1). It is therefore of importance to detect and thereby be able to control one or multiple signals when one is investigating for example growth trends with the climatic signal at its maximum (Hughes et al. 1982).

$$R(t) = C + B + D + E$$

$R(t)$ = The measured tree ring width in year $t$
C = Macroclimatic signal common to trees at a site
B = Biological growth curve as a function of increasing tree age
D = Any disturbance signal for either; a random event affecting a single individual tree's growth, or which is common to most or all specimens at a site
E = Random growth signal, unique to each specimen.

(Equation 1)

## Climate variables controlling growth

### *Precipitation and moisture*

Regions exposed to a high amount of precipitation show low variation in tree ring widths, however variations in the amount of maximum latewood can easily be detected. Regions with low precipitation show a different annual ring structure with higher variation in ring widths and with pronounced indicator years (Schweingruber, 1993). Especially in a forest stand with high competition which is exposed to high amounts of radiation, where the competition for moisture limits growth (Nicklen et al., 2019).

Snow may have a positive and negative effect on the ring width as they can supply with water storage and shield young buds located below a snow cover from frost temperature. In that case, the tree continues to grow without any external influences. Locations experiencing avalanches or snow creeping are more likely to display a thinner tree ring which will be displayed as a sudden change in rings widths. This is due to damage related to this type of event when damage have occurred on the tree top or branches. This is especially seen in mountainous areas (Schweingruber, 1993; Martz et al., 2017).

In tropical regions with low differentiation in temperature between seasons, the state of dormancy or rest is entered during dry seasons and moved out during wet seasons (Breitsprecher & Bethel, 1990).

### *Radiation and temperature*

Incoming solar radiation is essential for trees ability to grow as the leaves primarily practice photosynthesis and respiration. The absorbed solar energy are being transformed into chemical energy which powers carbon fixation (Gregory & Nortcliff, 2013). The amount of irradiation will together with topography, altitude, and established vegetation at a site determine the temperature (Schweingruber, 1988; Gregory & Nortcliff, 2013).

Temperature affect the seasonal and the daily growing patterns. Years with summer temperature lower than average or with restricted amount of soil moisture will in relation to a good growth year - representing a wide ring – be presented as a thinner ring with less early wood within the annual ring (Schweingruber, 1988).

### Wind exposure

The wind velocity and the direction of such, highly affect the potential deformation of the whole tree trunk and can create potential compression wood, a new direction of growing wood (Schweingruber, 1993; 1988). It have also an effect on topography in terms of changing land masses and the regularity of storm events, where older trees have a tendency to fall onto younger trees and pushing them sideways. Fewer trees in a forest stand result in less competition and will increase the amount of available nutrients for the remaining stand, as well as it will leave the reminding standing threes more exposed to future wind events (Ibid.). Wind exposure upon vegetation may have a negative (Behrenfeldt, 2018) impact in terms of radial and height growth rate, as well as increase wind sway in a stand may result in a diameter growth as the trees are put under stress (Karlsson, 2013).

### North Atlantic Oscillation (NAO)

The pressure difference between Iceland and the Azores, commonly named the North Atlantic Oscillation (NAO) (Walker & Bliss, 1932), has an annual effect (Folland et al., 2009) on the westerly winds blowing across the North Atlantic Ocean, and is proven to be linked to temperature and precipitation patterns on regional levels. The effect of the NAO is more dominant during winter and early spring (Rogers, 1990), when greater temperature differences are found between north-south locations, and therefore greater pressure differences (Hurrell, 1995; Slonosky, Jones & Daves, 2001; Visbeck, Hurrell, Polvani & Cullen, 2001). During winters with high pressure differences (a positive NAO), the westerlies are stronger than normal and are transporting mild air from the Atlantic. This will be experienced as a warm and wet winter. When the pressure gradient is smaller (negative NAO), the westerlies are weakened and enhances cold air masses from the east to move westward. This type of circulation pattern occur during summer time as well, but at a smaller geographical scale reaching from North West Europe to Greenland, referred to as summer NAO (SNAO) (Fuentes, 2017) and has a significant impact on the climate over Fennoscandia (Hurrell, Kushnir, Ottersen & Visbeck, 2003; Folland et al., 2009). A positive SNAO is characteristic with dry, warm and cloud-free conditions over northern Europe, while southern Europe experience the opposite, but to a limited effect, with wet, cool and cloudy conditions (Linderholm *et al.*, 2009, Rydval *et al.*, 2017).

### Topography

Elevation, slope and aspect (the direction which the slope of a hill faces) are important elements for forest site productivity as well as for geomorphological processes (Deyoung & Sutton, 2016; Leonelli, Masseroli, & Pelfini, 2016). The topography is an important variable in terms of the exposure rate to various events e.g. fire event or wind activity (Čada *et al.*, 2013).

### Soil

Other natural parameters that affect the growth diameter of trees are the soil type and its ability to drainage water and supply nutrients. Trees with deep roots standing in nutrient rich subsoil will produce wider tree rings in contrast to a shallow rooted species growing in a rocky dry subsoil (Schweingruber, 1993).

## Site Description

### Location and local history

The study area for this project, is located around the forest of Hemnäs, which is located 39 km from Storuman [65°5′27″N 17°6′27″E] and 25 km from Sorsele, [65°32′N 17°32′E], between the two towns in Västerbotten county (Figure 1). The population of the municipalities (2018) have been estimated to be around 5900 and 2500 inhabitants for Storuman and Sorsele, respectively (Statistiska Centralbyrån, 2018).

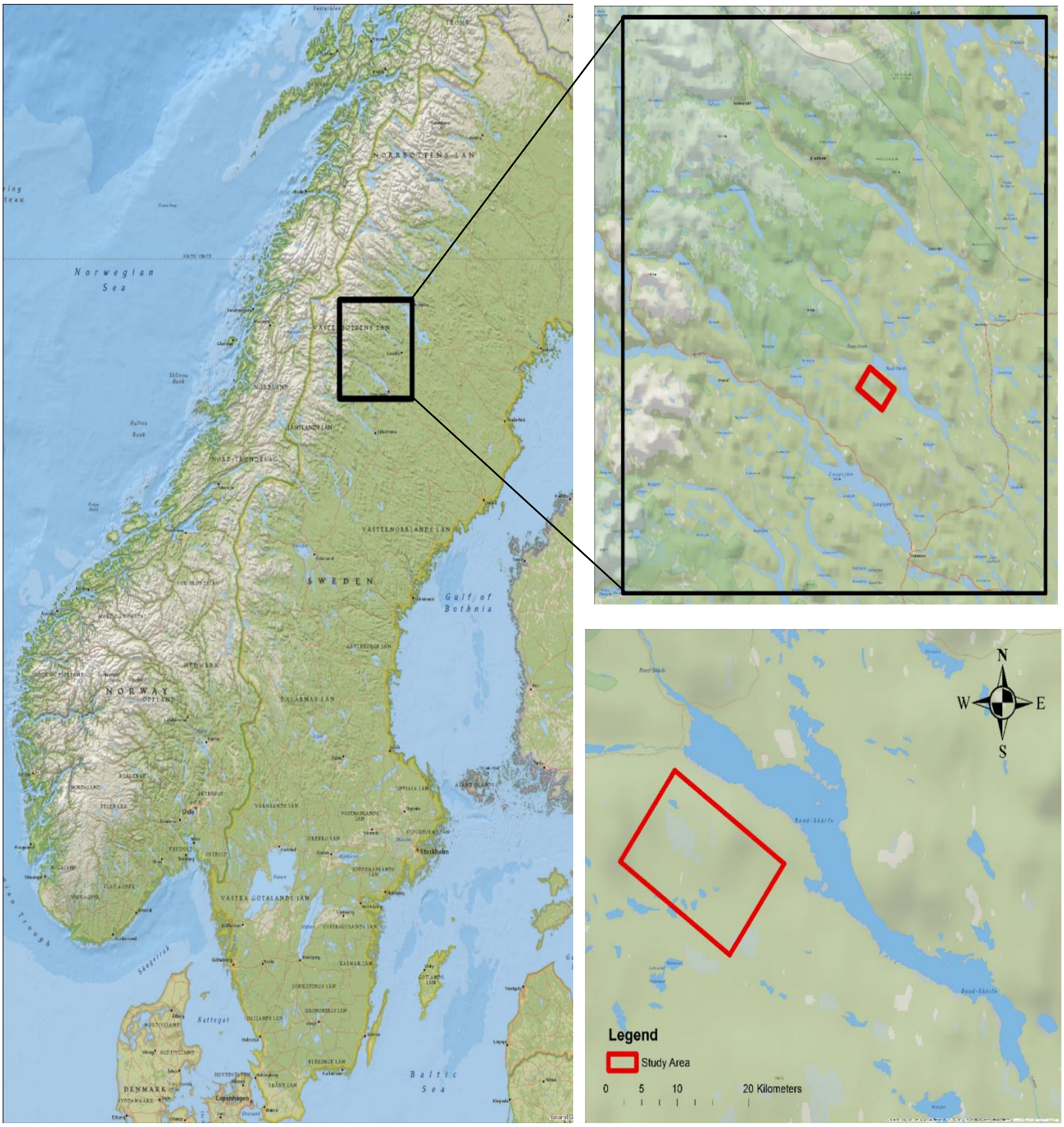


*Figure 1*. Overview map over the forest of Hemnäs. Red rektangual indicate study site. Data collected from GIS Base maps.

An inventory made by Swedens largest forest owner, Sveaskog during the autumn of 2018, came to the conclusion that the average age of the forest is 130 y – 150 years old. One spruce have however been age-determined to an age of 330 years (Daniella Andersson, personal communication, October 11, 2019). A small proportion of known thinning has been done within the forest around Hemnäs, which by the year 2017 became categorized as high value forest by the The County Administrative Board, in Västerbotten (Länsstyrelsen, 2017).

Historically have the locals used the forest around Hemnäs as a source of income, as the trees were sold as timber. Extraction of the resin was done after harvest, and before the logs were transported towards the nearby waterbody. The timber was rolled down the slopes and directly into the lake Storjuktan during summer time. During wintertime were the logs stacked upon each other on the ice of the lake, while one were waiting for thawing temperatures. The final destination of the logs were Östersjön (Valter Linder, personal communication, October 9, 2019). The forest is now owned by Sveaskog and have been through a management shift to un-managed forestry since the late 1950's (Ibid., Daniella Andersson, personal communication, October 11, 2019). The forest of Hemnäs seems to be in a transition period, where it historically have been a slightly thinned forest, a CCF, which is now becoming according to the definition by Kardell (1992), an un-managed forest.

The study area is established along the lake Storjuktan and is estimated to be dominated by 85% spruce vegetation, 10% birch (*Betula*) and 5% pine (*Pinus*). Goat willow (*Salix caprea*) can also be frequently found together with blueberry shrubs and mosses (the authors own observation).

## Climate

Both Storuman and Sorsele are characterized by a Dfb climate according to Köppens-classification system. This implies that it is generally cold and humid with average annual temperature of 0.2°C, with relatively high amount of precipitations throughout the year, with average annual rainfall of 549 mm in Storuman and 565 mm in Sorsele (Swedish Meteorological and Hydrological Institute, open source). The highest air temperature and amount of precipitation occurs in July (Figure 2).

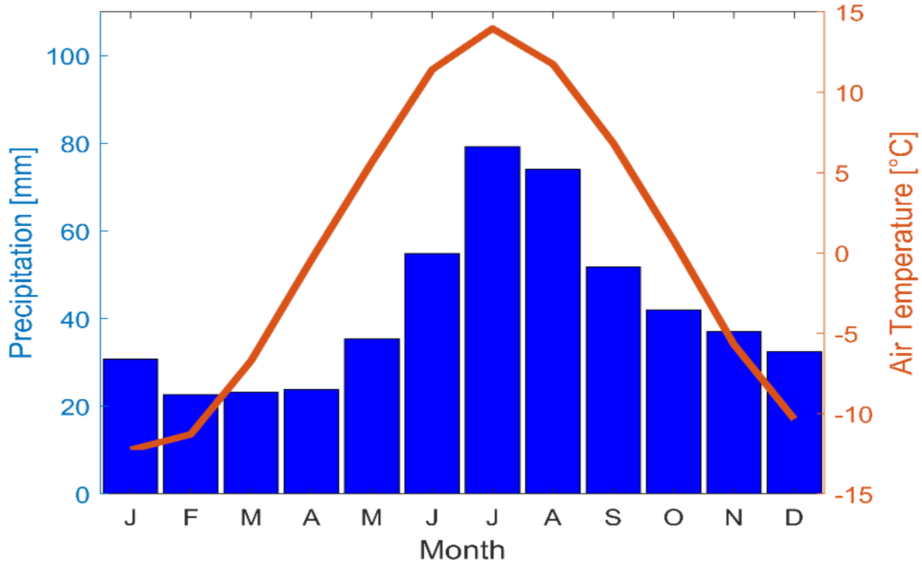


*Figure 2*. Monthly average air temperature and precipitation values for the study area based on the period 1860-2018. Source: SMHI, 2019.

# Method

## Field Work

### Field site

There is a forest road connecting the west and east part of the study area. A part of the field site have during the autumn of 2019 been divided into eight different areas. Four of the areas are at a size of 2.25ha, located on the west side of the road, in contribution to four areas of 1ha located on the east side. Each area holds a number of stands within its area (Figure 3). The different areas are part of an ongoing project and for more information contact Fredrik Sjödin, SLU Umeå. Samples were taken from all of the eight areas.

*Figure 3*. Overview map over the sample areas. Smaller boxer represent areas of 1ha located on the east side of the road. Bigger boxes represent areas of 2.25ha located on the west side of the road. For color explanation, contact Fredrik Sjödin. Source: Fredrik Sjödin, SLU, 2019.

### Sample distribution

Between the 23$^{rd}$ and 26$^{th}$ of September, 2019 51 trees were randomly sampled and used to collect height data, which was estimated by the Haga Hypsometer method. The hypsometer uses trigonometry to calculate the height of a standing tree from the base to the top of the crown (Equation 2, Figure 4).

D = Distance from object in eye height.
A = Tan (a) x D
B = Tan (b) x D

Tree Height = A + B

(Equation 2)

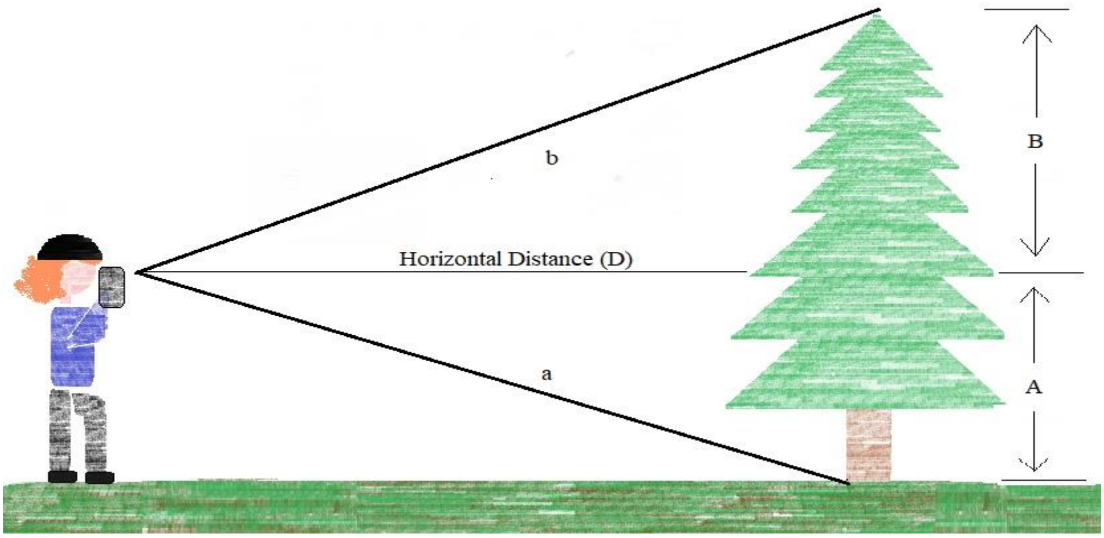


*Figure 4.* Visualization of a hypsometer reading. Painted by the author.

The same trees were used to take measurements of the diameter at breast height (dbh), which is equal to a height of 130 cm above ground. In addition were two core samples from each tree extracted. To eliminate any possible biased diameter data from potential wind exposure, a mean diameter was created from two measurements at dbh made by a non-digital caliper. Two core samples from each tree; 20 cm above ground and 130 above ground, were in additional collected by an 8mm increment borer. Height, dbh, coordinates and a short site description of the plots in each respective stand were written down and summarized in a Microsoft Excel spreadsheet directly in the field.

Of the original 102 tree cores collected did three of the samples break during the laboratory-preparation stage. Another four computerized samples were removed before the chronology and statistical analyzes were made, due to unreliable quality in digital resolution when only parts of the pith were hit during the collecting process. Seven tree core samples collected from the forest of Hemnäs have therefore been removed from the original sample population (Table 1).

*Table 1.* Sample distribution table, collected in September 2019 by the author.

| **Data Set** | *Sample Size* |
|---|---|
| ***Height and Diameter*** | 51 |
| ***Tree Cores:*** | |
| 20 cm above ground | 47 |
| 130 cm above ground | 48 |

## Lab work

### Sample preparation

The preparation of the cores were made at the *Gothenburg University Laboratory for Dendrochronology* (GULD), where samples were glued onto wooden mounts and grinded with multiple grades of sandpaper (240, 400, 800 and 1200) to be able to clearly visualize the annual rings with a stereomicroscope.

## Statistical analysis and data handling

### Age determination and standardization

All samples were measured, age determined and digitalized by the TSAPWin$^{TM}$ software program with a precission of 1(10$^{-3}$) mm, and counting the rings from the bark (representing the calender year 2019) towards the pith. The quality of the datasets where checked by the help from the software COFECHA (Holmes et al., 1986), which also gave a correlation between different samples. This statistically software program, was very helpful in terms of finding any potential human errors, such as missing or count a year twice, and any potential false or additional rings where removed from the digitalized sample. To be able to conduct long historical chronologies, all samples were cross-dated. This was done by identifying ring width anomalies in local samples, see if one can match these ring boundary patterns and overlap with a sample that is longer. This technique referred to as cross-dating (Fritz, 1988) is used to create a longer historical timeline visualizing past climate variability and growth trends.

The software ARSTAN was used to create chronologies representing each area in addition to build a main chronology. All the chronologies were age-detrended with the purpose of eliminating the natural age-trend, which is shown within samples as a gradual decline in ring width. Due to the purpose of this project and its question of interest all dataset were standardized, a statistical function which makes it possible to compare the observed value in a sample and compare it to the population mean. This simplifies the comparison of growth-trends between different samples. Other statistical information was also provided by this software program.

The new dataset were correlated with the three chronology outputs given by ARSTAN (*Standard, Residual and Arstan*). The differences between the three chronologies are that the *Standard chronology* is detrended and standardized, the *Residual chronology* have in addition taken into consideration autoregression (predicting future growth from previous values), and *Arstan chronology* consider all of the above, as well as autoregression from climate. The Arstan chronology were later not used, because one wanted to exclude the 'climatic memory' it takes into consideration.

### Radial growth and height

The average radial growth was calculated from the two measurements taken from the same sample tree. The number representing the diameter at breast height was converted from mm to cm in Microsoft Excel spreadsheet. Each sample tree was height estimated three times by the Haga Hypsomether, to eliminate any potential biased result from wind movements swinging the trees or any type of miss readings. The average from the three reading was written down in Excel spreadsheet and was later converted from dm to m.

## Climatic data

Precipitation (mm) and temperature (°C) data from two different weather station around the study area; Stensele [65°3'39.6"N 17°11'37.32"E] and Sorsele [65°32′N 17°32′E], were collected from SMHI's open data webpage. The temperature and precipitation data from Stensele contained monthly average values from 1860 - 2004. The Sorsele station contained monthly average values from year 1931 – 2019, with a few values missing. The two temperature (precipitation) data sets were later used to create a temperature (precipitation) dataset for the whole period 1860 – 2019, and are from here on referred to as 'temperature data' ('precipitation data'). The average monthly NAO data is collected from National Oceanic and Atmospheric Administration's open climate webpage (www.noaa.gov). The climatic variables were correlated within the SPSS software program, where Pearson correlation test (two-tailed) were conducted, and the result later shown in a table or displayed as a plot created in MatLab. The winter NAO were chosen to indicate wind anomalies because this type of data were not to be found from the stations close to the study area. The $r^2$– value indicate the relationship among the two variables being correlated. A p-value <0.05, or marked as '*' respond to a significance level equal to 95% certainty. P-value <0.01, marked as '**' is equal to a significance level of 99% certainty or higher.

## Principle Component Analysis

To investigate if any of the climate variables have a bigger growth impact on the *P .abies* growing around the Hemnäs forest, a Principle component analysis (PCA) was conducted based on all of the samples. The purpose of PCA is to get an overview between observations and potential variables, and to recognize which variable is the most valuable for clustering the data. Here, the number of components affecting the tree ring growth were of interest. The PCA was conducted in the SPSS software program, and based on the tree core samples collected at a height at 130 cm above ground.

# Result

## Diameter and Height Relationship

The relationship between the dbh (cm) data and the estimated height (m) from the study area are represented by data from 51 trees (Figure 5, orange diamonds). The majority of samples are spread out at a height between 10 m and 20 m, which correspond to a dbh between 10 cm to 30 cm. The dataset displays to 81% a statistical significant increasing trend with a p-value <0.01 (**), where an increase in height of 0.7m correspond to an increase in dbh of 1 cm.

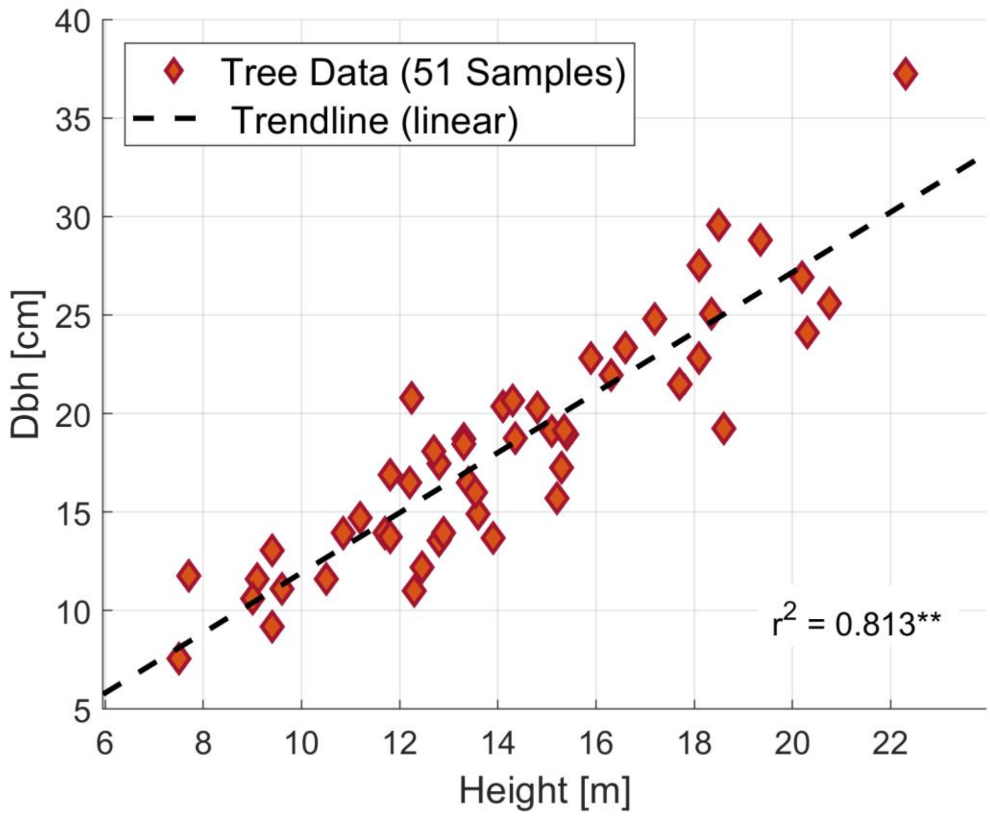


*Figure 5*. Height and diameter growth relationship displayed in a scatter plot. Source: Fieldwork data from Hemnäs, 2019.

## Diameter and Age Relationship

Correlating tree age, determined from cores sampled from a height of 130 cm above ground, together with dbh (cm) show a relatively clustered result (green dots). The majority of data points can be found between the tree age of 75 years to 150 years, which correspond to a diameter from 10 cm to 30 cm (Figure 6). A few outliers can be observed, which are representing the youngest and the oldest tree core samples. Running all the 48 samples as one data reveal a statistical significant increasing growth trend of 0.06 cm in diameter per growing year, with a p-value <0.01 (**) and correspond to a $r^2$-value of 16%.

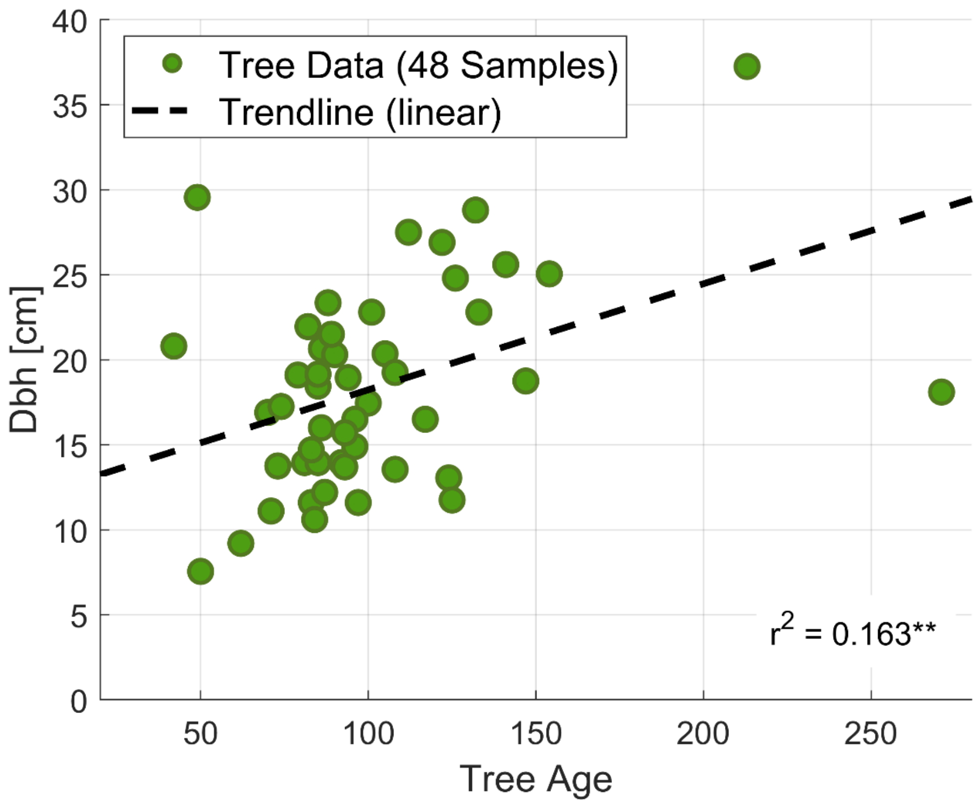


*Figure 6*. The relationship between tree age, given by tree samples extracted at dbh (130 cm height), and diameter growth displayed in a scatterplot. Source: Fieldwork data from Hemnäs, 2019.

## Growth Rate

The average age given from 47 cores collected at a height of 20 cm and 48 cores at a height of 130 cm above ground are dated back to the calendar year 1911 and 1918 respectively (Figure 7A). Data from samples at 20 cm above ground have a standard error of mean (SEM) equal to 4.3 years and samples at 130 cm height have a SEM equal to 5.5 year. The growth rate calculated from the samples collected at a height of 20 subtracted the growth rate calculated from the samples extracted from a height of 130 cm, show an average growth rate of 6.88 years, and with SEM equal to 3.04 years (Figure 7B).

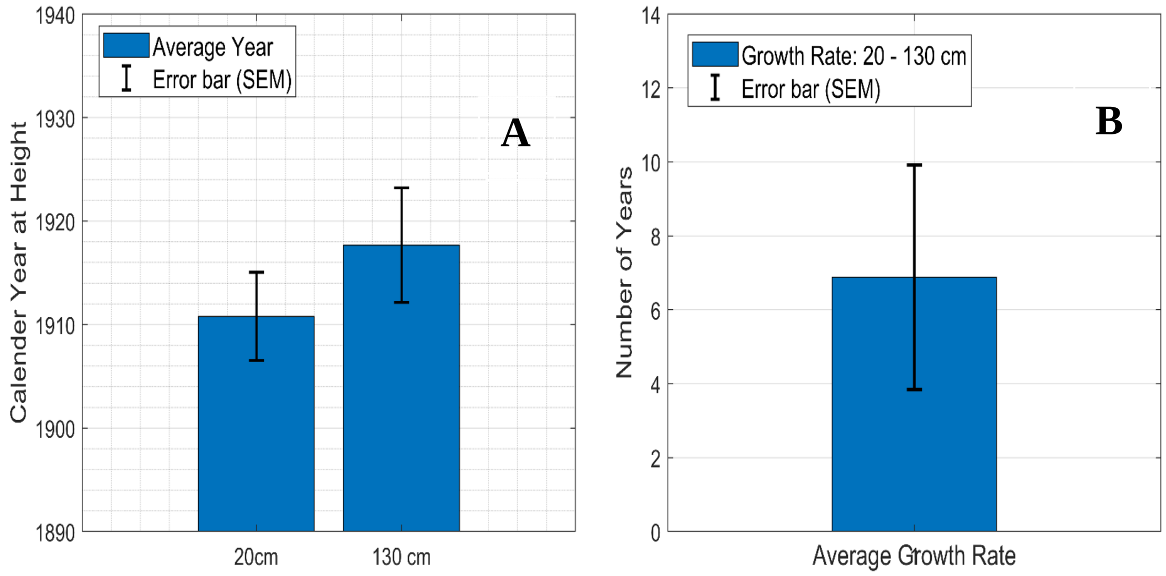


*Figure 7*. Average growth rate displayed as bars. A) Samples at 20 cm = #47, SEM 4.3y. Samples at 130 cm = #48, SEM 5.5y. B) Sample size = #95,SEM 3.0y.

## Ring Width Chronologies

Plotting all the tree rings together (Figure 8A, grey line) show a broad tree ring distribution from all of the 95 samples. Two chronologies represent the annual radial growth from 1748 to 2019 with an average tree age of 107 year (Table 2). The Standard chronology (Figure 8 A, dotted line) display two greater growth peaks with a duration of 15 years between the two periods 1830-1835 and 1860-1875. The lowest growth rate are displayed in between these peaks, around 1840-1860. The Residual chronology (solid line) follow a similar overall trend found in the first chronology, but with less fluctuation and fewer peaks from year 1790 throughout the year 1915. Its lowest and greatest growth peak occur during year 1835 and 1860 respectively.

The sample depth (Figure 8B) display low values with a sample size below 50 samples until 1920's. The oldest and the youngest samples are dated to year 1748 and year 1977 respetively. All 95 samples represent the chronology from 1940 throughout 2019.

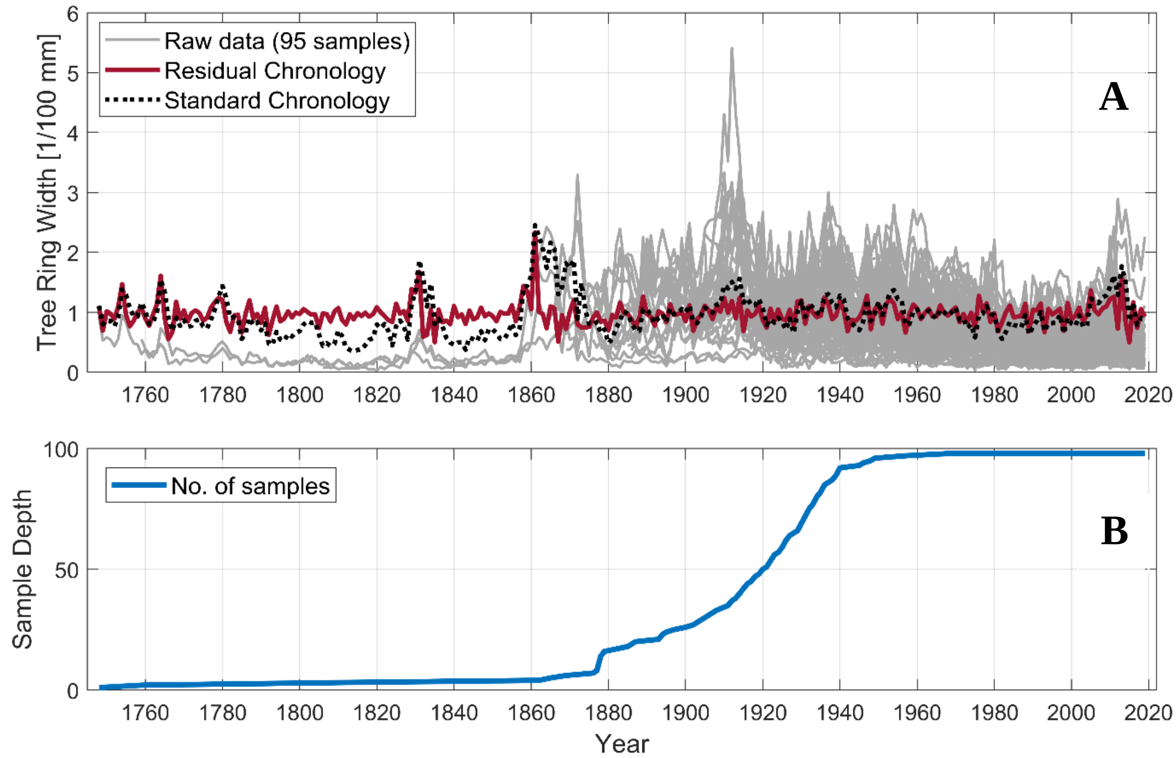


*Figure 8*. A) Raw data displayed with the two chronologies used throughout this report. B) Sample size overview.

The two chronologies, the *Standardised* and *Residual* show slightly different values in mean sensitivity and standard deviation (Table 2).

*Table 2*. Chronology statistics for tree ring chronologies, created by the ARSTAN software program.

| **Chronology** | |
|---|---|
| Time Span | *1748 - 2019* |
| Average Tree Age | *107 y* |
| No. of Samples | *95* |
| Average Ring width (mm/y) | *0.605* |
| ***Standardised Chronology:*** | |
| Mean sensitivity | *0.169* |
| Standard deviation | *0.343* |
| ***Residual Chronology:*** | |
| Mean sensitivity | *0.185* |
| Standard deviation | *0.202* |

## Climatic Growth Indicators

### *160 year trend*

Correlated monthly average values for temperature and precipitation between the growth period (May to August) for year 1860 – 2017, indicate that the temperature and standard chronology (precipitation and residual chronology) have the strongest correlation with June temperature (July precipitation) (Figure 9 – 10 and Appendix: Table 1). The growth trend can to 5% be explained by historical temperature fluctuations, with a p-value <0.01 (**). Precipitation anomalies show a lower correlation of 2.5% and with a p-value equal to <0.05 (*).

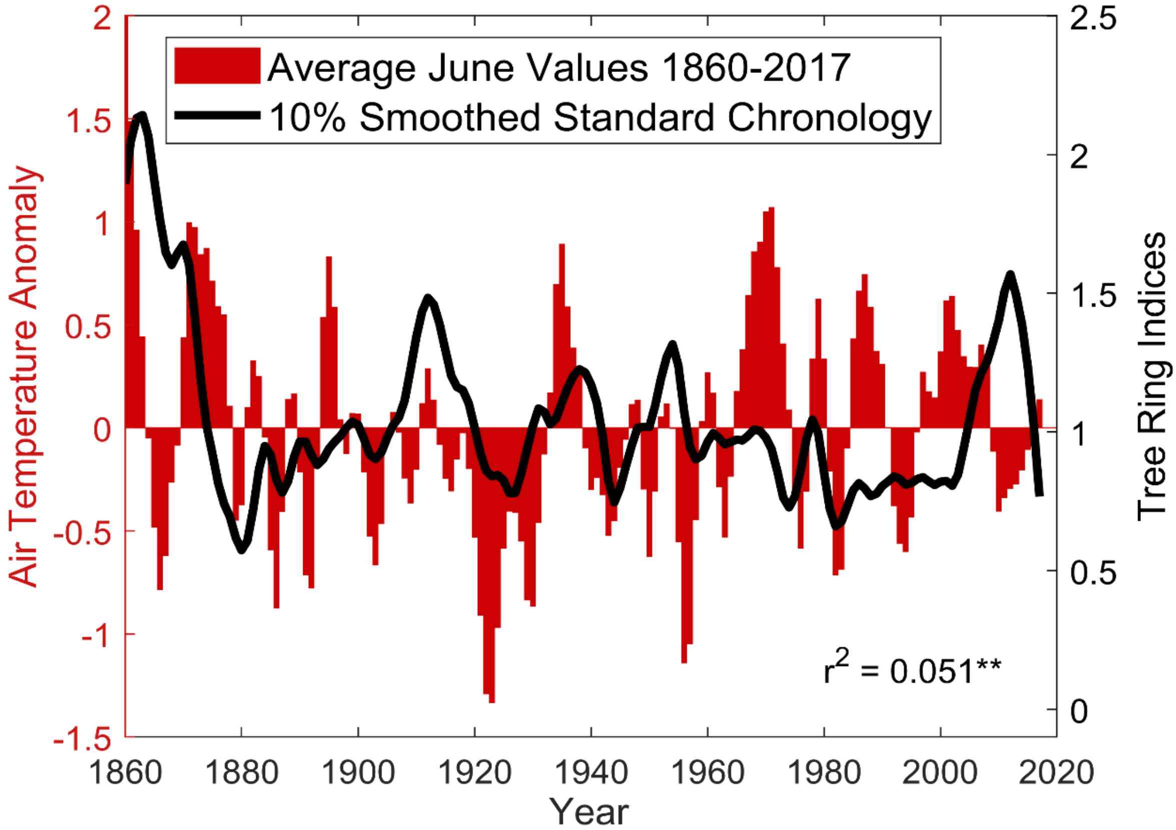


*Figure 9*. Air temperature data (July) plotted with the standard tree ring chronology.

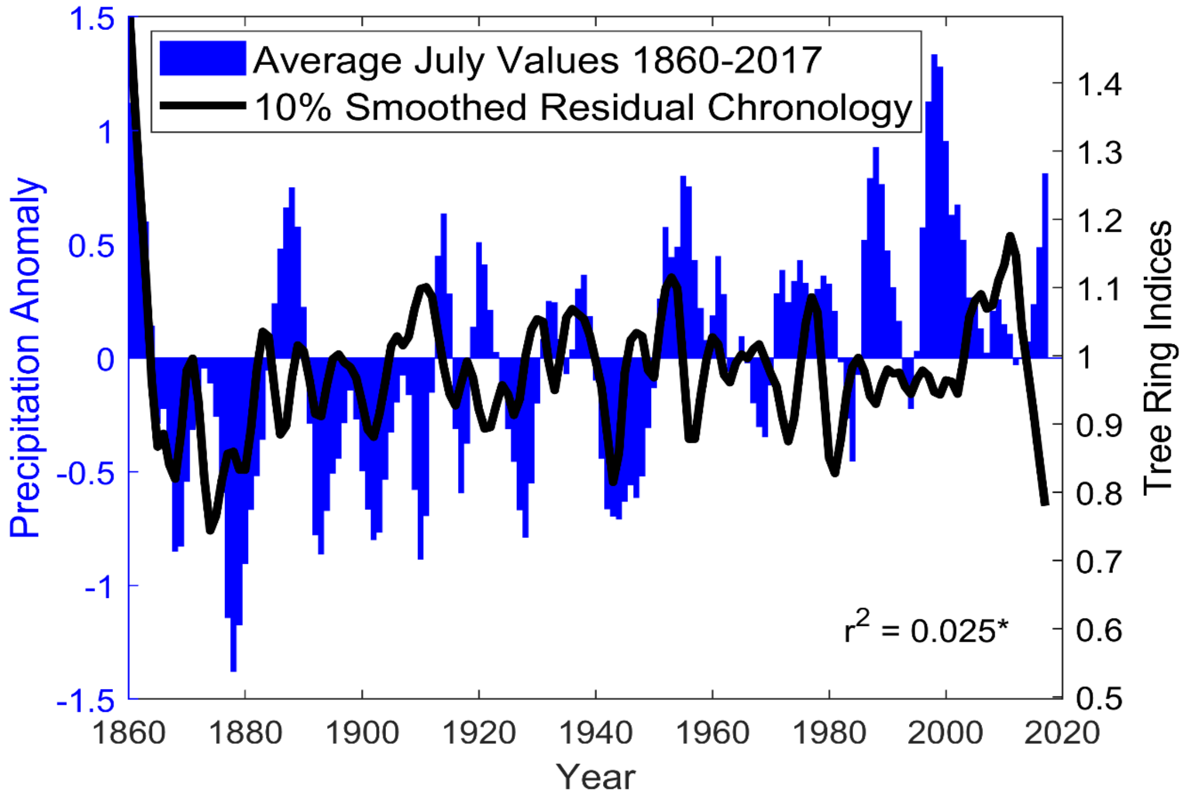


*Figure 10*. Precipitation data (July) plotted with the residual tree ring chronology.

The NAO winter index, which is represented by averaged values from December previous year throughout March for represented year (1860-2019), did not show any correlation with the standard chronology (Figure 11). The temperature and (precipitation) dataset lack June (July) data for the two previous years, 2018 and 2019.

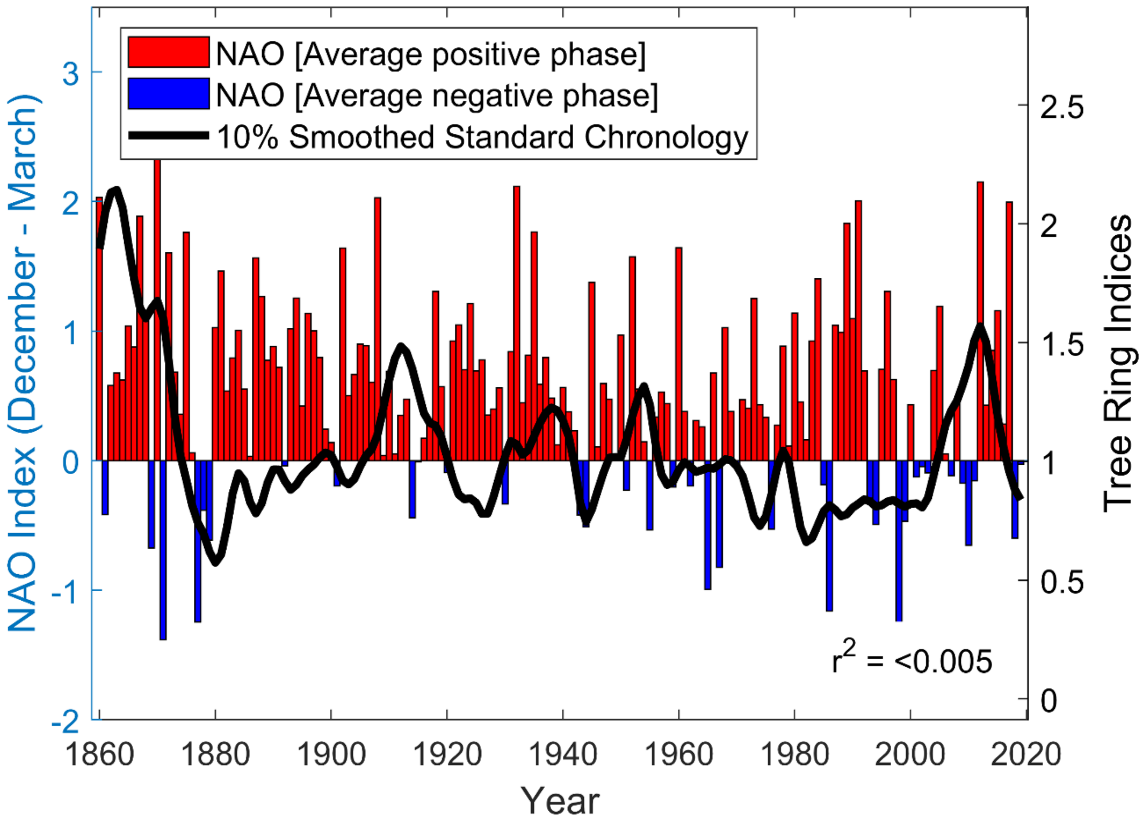


*Figure 11*. NAO data (December - March) plotted together with the standard tee ring chronology.

### *40 year trend*

The 160 year trend are divided into four periods to investigate if any of the climate variables have had an great growth impact during a shorter period of time. The periods represent á 40-year trends [1860 - 1899, 1900 - 1939, 1940 – 1979, 1980 – 2019], although temperature and precipitation have a slighter shorter last period, with 38 annual values compared to NAO with 40 values. The four decadal trends suggest with more than 99% certainties that increasing July precipitation of 115 mm to 39% can explain the increasing growth trends in $1(10^{-3})$ mm during the first period (Table 3), and that June temperature during the beginning of the 1900's until the 1940 had an 21% impact on the radial growth in the trees (p-value <0.01). A temperature increase of 3.69°C generate an average increase in $1(10^{-3})$ mm tree ring indices (Appendix: *Figure 1*). NAO did not show any significant impact on the growth during any of these four periods.

*Table 3*. Chronology statistics for meteorological data in Hemnäs, created by the ARSTAN software program.

| **Time interval** | *1860-1899* | *1900-1939* | *1940-1979* | *1980-2019* |
|---|---|---|---|---|
| ***Precipitation:*** | | | | |
| *(July)* | | | | |
| $R^2$ | 39.1% | 9.7% | 1.4% | 6.6% |
| P - value | <0.01 | >0.05 | >0.05 | >0.05 |
| ***Temperature:*** | | | | |
| *(June)* | | | | |
| $R^2$ | 2.8% | 21.3% | 7.1% | 7.1% |
| *P - value* | >0.05 | <0.01 | >0.05 | >0.05 |
| ***North Atlantic Oscillation:*** | | | | |
| *(December previous year to March)* | | | | |
| $R^2$ | 0.5% | 9.9% | 0.4% | 0.05% |
| *P - value* | >0.05 | >0.05 | >0.05 | >0.05 |

## Principle Component Analysis

The number of components affecting the tree ring growth to ≥10% in the samples taken at dbh, gave a result of two components. 33 of the samples were affected by component 1 which explains the variance by 38%, the reminding 15 samples were more affected by components 2, explaining 17% (Figure 12).

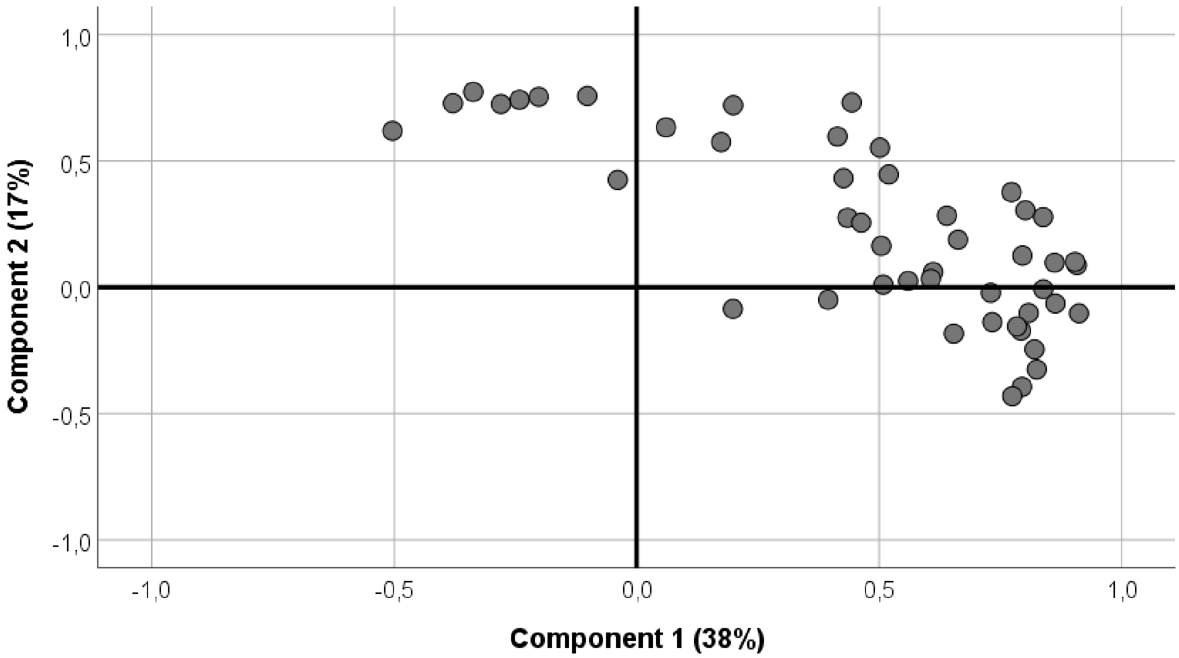


*Figure 12*. PCA output created in SPSS from 47 tree core samples at a height of 130 cm.

Two different chronologies based on the two different components (Table 4) were individually correlated with the climate variables (temperature, precipitation and NAO). This was done with the purpose to trying to determine if any of the two components could possibly represent any of the climate variables.

*Table 4*. Chronology statistics for tree ring chronologies, created by the ARSTAN software program.

| **Chronology** | *PC1* | *PC2* |
|---|---|---|
| Time Span | 1806 - 2019 | 1748 - 2019 |
| Average Tree Age | 103 y | 110 y |
| No. of Samples | 33 | 15 |
| Average Ring width (mm/y) | 0.758 | 0.465 |
| | | |
| ***Standardised Chronology:*** | | |
| Mean sensitivity | 0.200 | 0.237 |
| Standard deviation | 0.457 | 0.462 |
| | | |
| **Residual Chronology:** | | |
| Mean sensitivity | 0.174 | 0.294 |
| Standard deviation | 0.191 | 0.298 |

One component, component 1 (Figure 13, solid line) display a statistical significant correlation with average air temperature in June between year 1969 - 2017 (Figure 13). This relationship is representable to 13% on a significant level equal to 95% (*). Component 2 show no statistical significance.

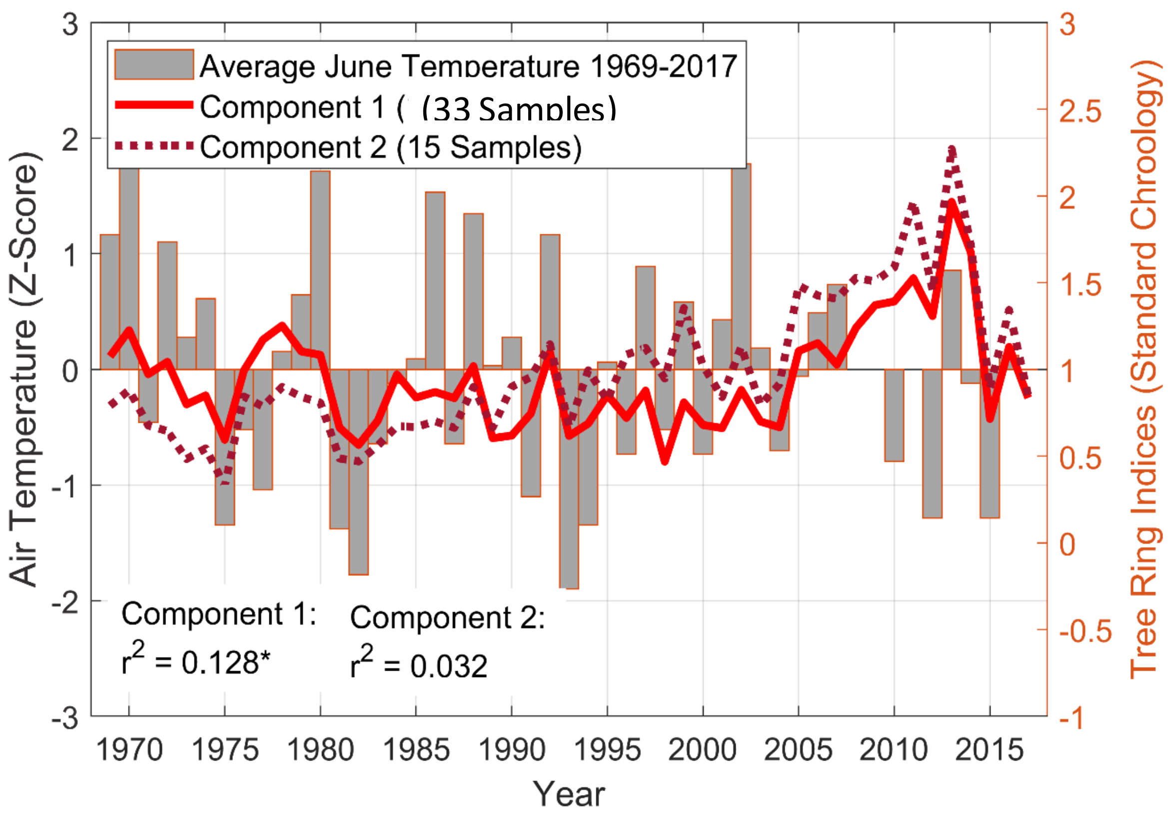


*Figure 13*. The significant relationship between component 1 and 2 are plotted together with average June temperatures. Component 1 show a statistical significant equal to 13%. Component 2 show no significance.

No other significant relationships were found in the other two climate variables, precipitation (Figure 14) or NAO (Figure 15).

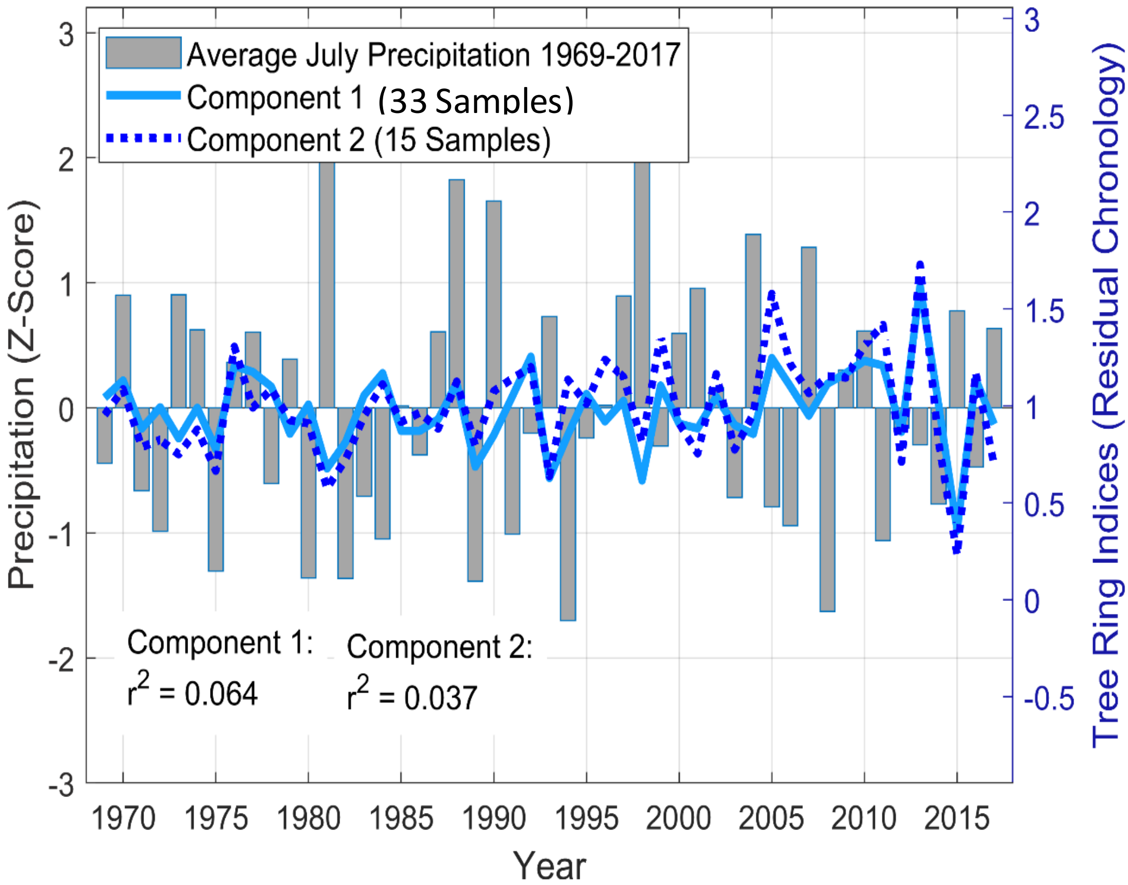


*Figure 14*. Correlation between component 1 respectively 2 together with average July precipitation. No statistical significance were found between any of the components.

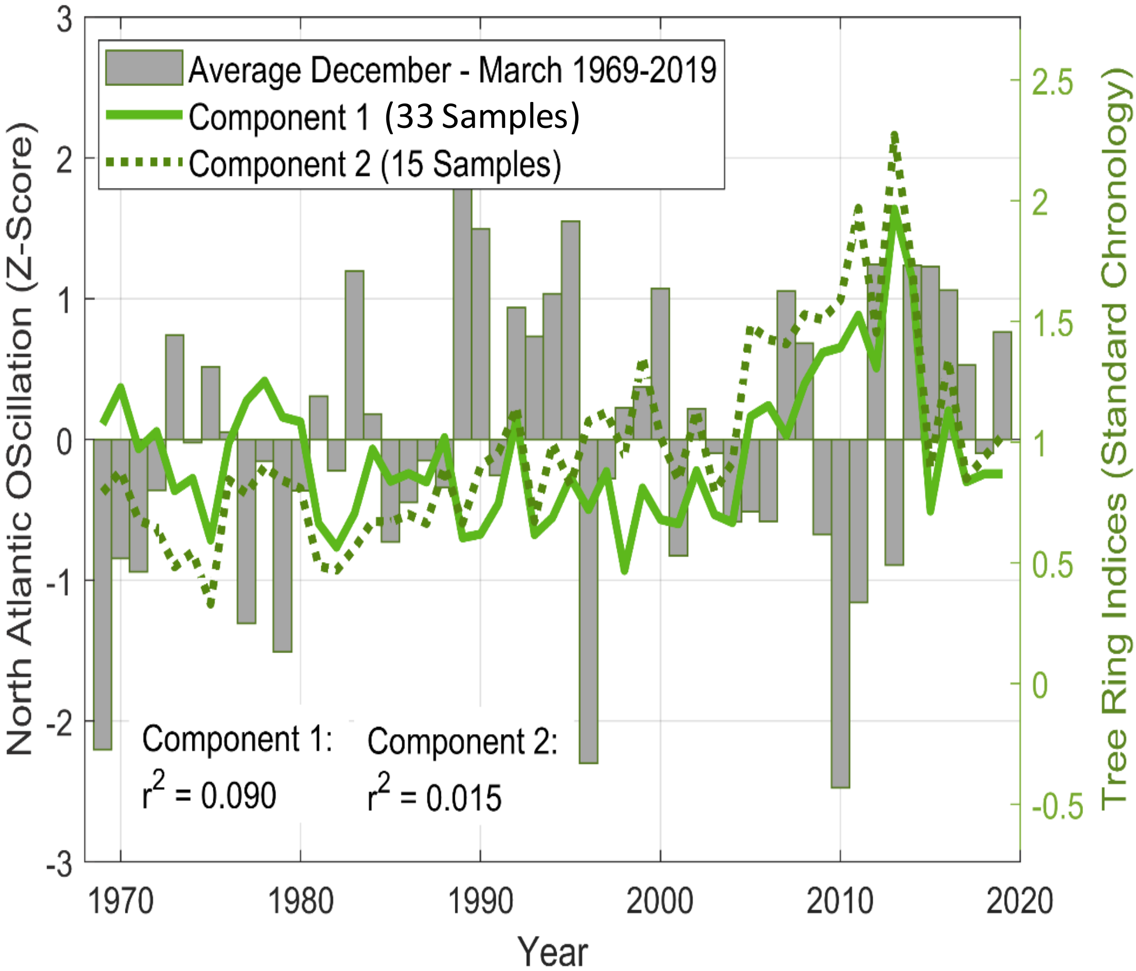


*Figure 15*. Correlation between component 1 respectively 2 together with average NAO winter mode. No statistical significance were found with any of the components.

# Discussion

## Growth trends in an un-managed forest

A relatively linear trend between height and diameter size, with only a few outliers, was found in this study. These outliers might indicate past event of disturbances where these outliers survived and benefited from lower competition, followed by a period of new establishments of ingrowth, which would be characteristics for this type of forest according to Lilja et al. (2006). A different results have however been found in a few previous studies, where the authors found that their un-managed forests displayed a diameter and height relationship that resembles a negative exponential function (Smith, 1986; Spies, 1998; Čada *et al.*, 2013). When the age and diameter data was plotted together did it display a less linear trendline compared to the one observed in the dimeter and height data. Instead it displayed a somewhat more clustered result. Most of the data is within the age interval of 50-150 years of age. The diameter within this age interval does fluctuate between a diameter intervals of 7cm – to 30 cm. A more scattered age distribution similar described by Ahlström & Lundqvist (2015) was expected, compared to the cluster of data seen in this report. This however agrees with precious studied that, not surprisingly, even thinner tree may be at the same age as trees with greater diameter. The result also suggest that the thinner trees with high age have grown during suppression. When the trees leaving a state of suppression, is it likely that it might correspond to an event of disturbances. That would result in lower competition from surrounding trees that are equal or hold an even greater distribution in size and age. But it might as well forcing lower vegetation to enter a state of suppression, at the time when ingrowth have established and starts to compete with vegetation nearby. This trend is likely not to be seen in a managed forest, where even flow of timber are favorable.

These event of disturbances can also be reflected when all the raw data are plotted together. There are great fluctuations among the samples, where only a few tree cores show a similar annual growing pattern. A few peaks from the whole data set can be indicated around calendar year 1915, 1940, 1950 and 1960. The peaks represent periods of favorable growing conditions.

Another interesting finding is the wide SEM represented in the average growth rate from 20-130 cm, illustrating that the growth within the study area is highly influenced by disturbance event instead of traditional rotation events. This can be seen more clearly when one compare the average calendar year at 20 cm and 130 cm height. The average growth from samples collected at dbh implies a bigger SEM, pointing to a nonlinear height trend within the forest with greater variation.

The tree age determination over the area differs from the age that was determined during a past inspection. There are only a few very old trees outrunning an age above 200 years. The average tree age in the sample population used in this study was 107 years, while the average population age determined by Sveaskog (2018) was 130 – 150. One possible explanation to this age diversity is that a smaller random sample population was used by the author compared to the one that was obtained by Sveaskog. Another explanation is that age fluctuations are connected to local geographical patterns. Looking at the local history of the Hemnäs forest, it is known that the trees was transported via water bodies. Therefore could the trees growing closer to the water body have been favorable, in terms of shorter distance between the location where the trees are growing and the transportation way. If this hypothesis is true should one be able to find older trees, similar in age to the ones obtained by Sveaskog, growing deeper in the forest at a longer distance away from the lake.

### Climate and its growth impact

One could have expected that temperature would be the most dominant climate determent factor after reading the result from similar studies made in the past. The annual growth data form the samples did only show relatively low climate correlations during the 160 year period that was investigated. Of all of the three climate variables, did the temperature representing the month June show an $r^2$-value equal to 5% while July precipitation values display an even lower correlation of 2.5%. This findings are similar to earlier result conducted in Scandinavia (Mikola, 1956; Helama & Sutinen 2016), where June temperature show a stronger correlation to growth trends compare to precipitation. One big difference between the result concluded from this study and previous studies (Mikola, 1956; Helama & Sutinen 2016), is that the data in this report actually found a significant relationship between growth and precipitation, even if the correlation was low. The NAO data used in this report did surprisingly not correspond to any correlation what so ever. One could have thought that some response, even a small one should have been obtain in the samples because NAO is more dominant during winter and because other studies have used tree rings to study this phenomena. When the longer meteorological dataset was investigated in shorter trends of 40-years intervals did precipitation have a higher $r^2$-value during the first period of 39%, compared to the temperature's $r^2$-value in the second period 21%. No significant relationship have been found between the annual growth and climatic impact after the year 1940 to date. The result suggest that the area during the two first 40-year periods have experienced a shift in climate dominated growth factors. Where the growth was dependent on precipitation at first, but later became dependent on temperature. The lack of any correlation between the growth trends and the NAO data, even during shorter periods of time, were once again not something the author of this report did expect. Especially when one had read how previous studies had found that the NAO have had an historical impact on the growth of their tree samples.

One possible explanation to the lack of relationship between NAO and growth is the NAO's 'lack of memory' from earlier seasons, which are to some extent confirmed by several authors (Ording, 1941; Hutisch & Elfving, 1944; Eklund, 1954; Jonsson, 1969), and is therefore not so dependent on growth from previous years.

The shift in climate dominated factor raises the questions why this shift occurred, what influenced this type of shifts and what is the dominating growth factor from the year 1940 to date. Fritts (1976) points out that the geology in terms of soil type and nutrients supply controls the fertility and density within the forest. This type of activities and exchanges below ground, in terms of controlling factors, were not investigated in this report. It would have been interesting to include soil data to get a better understanding of the interactions and feedbacks that occur between water availability, temperature changes and nutrient availability belowground. A better method for future studies, investigating similar topics is suggested to include the interaction between different variables.

The low correlation between the meteorological variables and the chronologies made from the component analysis was to some extent controversial. Most part of the samples, about two thirds, indicated that their growth trends to some extent had been highly influenced by component 1. But none of the chronologies could with a strong confidence explain what that component was related to.

Going through the notes which were taken out in the field, and comparing the description of the different growing conditions and local features found where the samples were taken was done in an attempt to get a clear picture why and which samples had a stronger to one of the components. No clarification was reached on that matter. Neither was any clear explanation brought to light why the two chronologies (component 1 and component 2) react differently to the climate data and to each other. One possibility could be that the variable which represented the component were not included and investigated in this study. For example, wind could be one of these parameters that might have been able to explain some of the registered growth trends in the forest of Hemnäs. To be able to retain the value of old history of an un-managed forest, one need to be able to understand which these growth controlling factors are and how they work. By understanding the feedbacks, one can understand and be prepared what kind of effect and to what extent future climate change will have on this type of forest.

### Future Forest

The value of a CCF or totally un-managed forest have several important values, in terms of history, habitat, well-being and from a climate perspective just to mention some. To turn more forest to something similar like CCF-forest seem to be suggested as a solution in terms of forest conservation and improve habitats. The characteristics in terms of amount of dead wood is clearly of a big importance for 90% of the red-listen invertebrates, which are today thriving in the Swedish CCF-forest. But a younger forest with regular rotations may be a better alternative in terms of lowering atmospheric $CO_2$ through carbon sequestration. Especially when not all of the carbon is directly released back into the atmosphere, but can instead contain a shorter in-service lifespan. Brännlund et al. (2010) points out that it is impossible to reach all the set climate goals by fully relying on the forest and forestry activities. By reaching one goal, we have failed to reach another. This is an important recognition for policy makers, that can't be overlooked. No matter which of the climate goals we decide to reach, or how we chose to use the forest, is it of high importance to understand what potential consequences one may face depending on what type of decision and plans we make for the forest. It is important to not fully rely on the forest alone in terms of deciding which of these goals are to be reached, in terms of postponing the responsibility of taking actions.

## Summery and Conclusions

This report investigate the relationship between radial growth and height from 51 trees, as well as radial growth and age from 48 trees growing in an un-managed Norway spruce forest. The correlation between the size of the diameter and height are relative linear, while the size of the tree diameter and age are clustered. The level of competition and suppressed trees make some of the trees to grow in a more spontaneously pattern compare to a linear pattern. It takes approximately 7 years +/- 3 years for *P. abies* to grow from a height of 20 cm to 130 cm. Climate variables such as precipitation and temperature have been a controlling factor in terms of growth in the past. But this report failed to point out which one of the climate variables (precipitation, temperature or North Atlantic Oscillation) that has the biggest impact on the radial growth to this date. It is suggested to include belowground data, for example soil data, to get a better understanding of today's regulating growth factors and any potential interactions. To understand the benefits of an un-managed or a CCF-forest, and the factors affecting its growth, is important in terms of preparing future consequences related to climate change. Especially since policy makers are relying on the forest in terms of lowering the effect of climate change by reaching climate goals. The biggest issue here is that all of the goals can't be reached without opposing another.

- There is a clearer relationship between the diameter size (diameter at breast height) and height, compared to the diameter and age.
- It took approximately 7 years for the sample trees to grow from a height of 20 cm to 130 cm.
- Precipitation and temperature have had a greater influenced on growth compared to the North Atlantic Oscillation.
- Their growth impact seem to have changed over time, from being determined by precipitation to temperature influenced.
- What controls the growth in the un-managed forest today, could not be determined by one factor alone.

## Acknowledgement

I would like to thank my supervisor Professor Hans W. Linderholm at University of Gothenburg, and co-supervisor Professor Thomas Lundmark at the Swedish University of Agricultural Sciences, for making this collaboration between universities possible. Thank you for your given time, expert advice and financial support throughout this thesis. I want to address a special thank you to Hans for all the feedback he have given me so quickly.

I want to thank everyone that somehow have been involved in this thesis in any kind of way.

There are however some people that I want to give a special thanks to. Thank you Fredrik Sjödin for letting me accompany out in the field, to Carl Vigren, Fredrik Hörnsten & Tinkara Bizjak for their company in the office and input of ideas. Last but not least, I thank Tzu Tung Chen (Sassa) for the software support and help at Gothenburg University Laboratory for Dendrochronology.

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# Appendix

## Appendix 1

*Table 5*. Correlation bewteen air temperature and standardized (precipitation and residual) chronology during the growing month, for period 1860-2017.

| | **Correlation Year 1860 - 2017** | |
|---|---|---|
| *$r^2$-value* | Temperature and Standard Chronology | Precipitation and Residual Chronology |
| *May* | -0.049 | -0.082 |
| *June* | 0.226 | -0.060 |
| *July* | 0.165 | 0.159 |
| *August* | 0.000 | -0.050 |

## Appendix 2

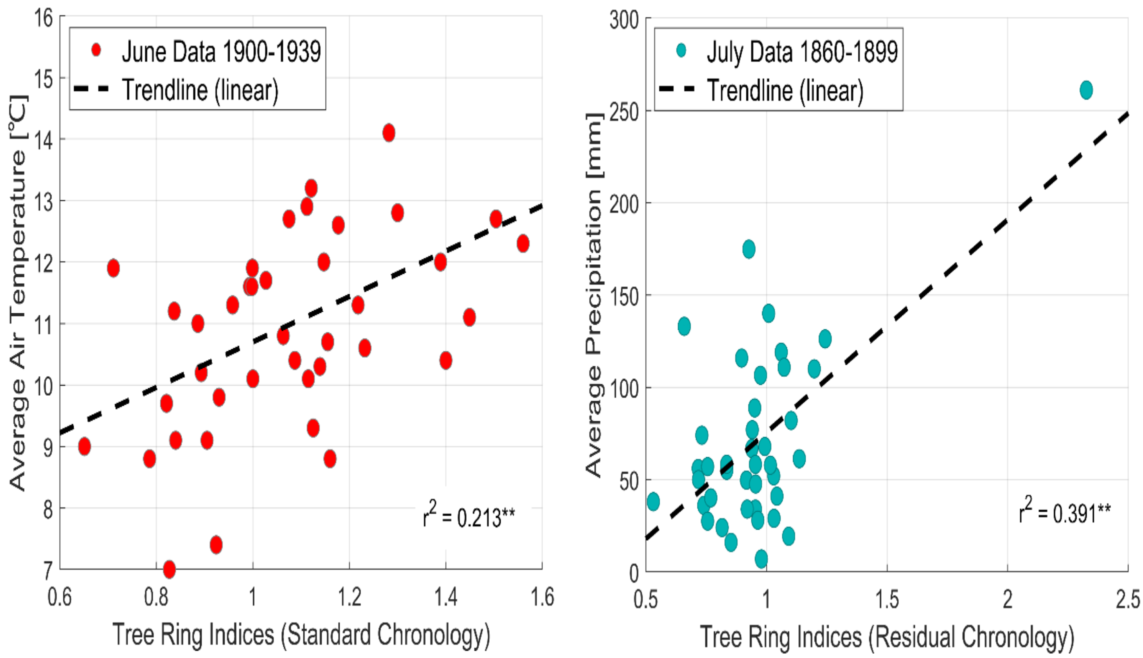


*Figure 1*. Significant Correlated tree ring chronologies with temperature and precipitation data.