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Faculty of Science

**Reconstruction of the climate-growth relationship of major tree  
species in NP Hallasan, Jeju Island, South Korea**

Master Thesis

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**Annotation:**

This study deals with climate-growth relationship of main tree species on Hallasan Mountain, Jeju Island. Dendrochronological methods were used for tree-ring data processing. Correlation analysis using monthly climate data revealed different climate-growth responses among species, influenced by climate change. Possible effects of increasing temperature on the future specie's distribution are discussed.

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# 1 Introduction

The climate has experienced unprecedented changes in the past decades, expressed by frequent occurrence of weather extremes (Littell et al.; 2009, Altman et al., 2013a), changes of quantity and distribution of precipitation (New et al., 2001; Di Luzio et al., 2008), increasing CO<sub>2</sub> concentration in the atmosphere and increasing temperatures (Jones et al., 1999; Buntgen et al., 2005, 2013). How these changes affect tree growth remain a challenging issue.

Rigorous approaches are needed for answering questions about tree responses to climate change. A discipline dealing with this topic is dendroclimatology, a subfield of dendrochronology. While dendrochronology primarily deals with examining and dating of tree-rings (Fritts, 1976), dendroclimatology uses dated tree-rings to reconstruct and study current or past climate (Drápela and Zach; 1995, Speer, 2010). Source data come from trees, which serve as unique archives or bioindicators, both in living and dead wood. Moreover, wood from dead trees of different forms enables capturing of events further back in time and thus extend the entire tree-ring series, called chronology (Speer, 2010). Basic unit of every tree-ring series is width of a single tree-ring. Important is that each single tree-ring contains not only the information about past climate, but also information about different types of disturbances (e.g. wind storms, landslides, avalanches, pest outbreaks or fires), species interactions (competition), human activities (silvicultural measures) as well as human-caused changes in the environment (pollution).

Considering many different types of information included in a tree-ring increment, a special attention must be paid to the site selection to gain records with the strongest signal (Stokes and Smiley, 1996). The locality should be placed, where trees are most likely to be stressed by studied variable, otherwise the remaining factors may blur the signal (Speer, 2010).

When studying global climate changes, a place with high sensitivity is required. Small islands represent suitable study site as they are strongly affected by air and ocean temperature variation, ocean chemistry, precipitation, wind strength and the rising level of world's ocean (Nurse et al., 2014). Islands with high peaks add extra sensitivity, since trees along a steep elevation gradient vegetation can be particularly sensitive to temperature changes (Schweingruber, 1996; Buntgen et al., 2005).

Jeju Island in South Korea represents such ideal study system, where the climate changed rapidly over last decades. Specifically, mean annual temperature has risen from 1923 to 1998 about 1.4°C (Kim and Kim, 2000). Jeju Island is exceptional by biological diversity thanks to its position on a crossroad of several migration routes in coastal East Asia, resulting in particularly high plant species diversity and high degree of endemism. The uniqueness is further supported by the status of UNESCO Biosphere Reserve and World Heritage Site designated to Hallasan National Park. There is more than 1800 plant taxa on an elliptical island with area about 80x40 km<sup>2</sup>. The high plant diversity is achieved by combination of several factors. One of them is the latitudinal position of the island on the border between mild and subtropical climate. Another factor is a steep altitudinal gradient ranging from sea level to nearly 2000 m elevation on Hallasan Volcano (1950 m a.s.l.), located in the middle of the island. Interaction between all these factors contributes to a broad variety of different habitats and vegetation types from a coastal maritime vegetation to arcto-alpine formations at the top of the mountain. The most valuable component are the extensive native old-growth forests. Despite the long lasting presence of human influence on the island, the natural forests at higher elevations remain well-preserved (Yim et al., 1990). The rich flora results also from the role Jeju played in the past. According to its position, the island served during the Last Glacial Maximum (LGM) when the sea level of shallow East China Sea and Yellow Sea was much lower (Fairbanks, 1989; Lee and Nam, 2003), as a migration bridge between China, Korean peninsula and Japan (Kong, 2000; Lee et al., 2008).

Study conducted on such unique locality promises results revealing changes in tree growth, forest dynamics and species composition. New findings could be further implemented especially in sustainable forest management and biodiversity protection.

## 2 Review

### 2.1 Formation of tree-rings

Tree-rings or annual rings constitute a basis of dendrochronological analysis. Since there are more underlying factors of tree-ring width variation, comprehensive evaluation of abiotic and biotic triggers is required. Tree-rings are result of radial growth that proceeds over a distinct growing season which regularly alternates with a period of dormancy, thus making a boundary between individual tree-rings. This concerns temperate and boreal zone and some other places with distinctive seasonality, such as changing of periods of rain and drought in the tropics.

Tree-rings consist of so-called earlywood and latewood. Earlywood is produced at the beginning of the growing season and is characterized by usually thin-walled large cells of the conductive elements. The latewood is on the other hand produced later in the season and is composed of smaller thick-walled cells making the wood denser. Transition between earlywood and latewood is species specific (Schweingruber, 2007). Conifers produce large, thin-walled tracheids which diameter gradually diminishes and their walls get thicker as the growing season proceeds. Trees are divided according to the anatomy of the wood into four main groups. Non-porous wood is typical for conifers as the main feature is the absence of vessel cells. Ring porous wood is found in trees like oaks or ashes. They produce large earlywood vessels in a short time of few days or weeks, often before the expansion of leaves. Later, small vessels and thick-walled fibres form the latewood. The boundary is very distinct. Semi-ring porous or semi-diffuse porous trees like elms or walnuts have large vessels in earlywood which get smaller toward the latewood. The zoning is not so distinct as in ring porous. The last group represents broadleaved trees like maples or poplars with diffuse porous wood. Almost the entire ring consists of earlywood which is formed over several months and latewood is just a narrow layer of flat fibers (Schweingruber, 2007).

Radial growth is not equally distributed along the stem. Old trees, for example, cease growing approximately in the middle of the season at the base of the stem while continuing to grow in the higher parts (Kozlowski and Pallardy, 1997). Some extreme cases like dense, overcrowded stands can cause even a complete absence of growth along just a portion of the stem, especially near the base (Kozlowski and Peterson, 1962; Fritts, 1976).



### **2.1.1 Factors influencing radial growth of trees**

Radial growth of trees is influenced by genetic, abiotic and biotic factors (Schweingruber, 1996). All of them play important role and it is not possible to choose the most important factor, since their impact on trees may vary, making one factor at any time more limiting than the others.

Another thing is that the effect of any single factor may be difficult to quantify since it can change over time. Moreover, there are always more factors affecting tree growth at a time, each of different strength and duration (Kozłowski and Pallardy, 1997).

#### **2.1.1.1 Genetic factor**

The influence of genetic factor was discovered when studying growth and shape of different species on a homogenous site (Schweingruber, 1996). Basically, different species have different life strategies according to their lifespan and thus different ability to react on environmental conditions. Life strategy express itself through the trend of growth which will be described later. Direct consequences of genetic predisposition are size, shape of crown and stem and finally longevity (Pallardy, 2008).

#### **2.1.1.2 Biotic factors**

The common feature of all biotic factors is that they are not directly of climatic origin, which means their effect on tree growth can differ between trees of the same species and between sites also. In dendroclimatological studies the biotic factors act like noise which needs to be recognized and removed from the tree-ring data to strengthen the climatic signal (Fritts, 1976). But there are also ecological studies that use this “noise information” to reveal some past events of the site. Namely it is different types of disturbances (e.g. Zielonka et al., 2010), browsing (e.g. Querrec and Fillion, 2008) or human activities and neighborhood interactions (e.g. Kobayashi et al., 1997, Dolezal et al., 2009b).

Among biotic interactions, neighbor competition is one of the most important driving forces influencing tree growth (Dolezal et al., 2004). Competition shows itself through differences in vegetative growth, seed production and mortality (Grime, 2006). This effort of neighbouring trees to use as much of light, nutrients, water and space as they can (Grime, 1979) can be well recognized using tree-ring data (Drápela and Zach, 1995). Trees under strong competition pressure do not thrive and usually exhibit narrow radial increments or the tree-rings do not create at all (Lorimer et al., 1999).

### **2.1.1.3 Human impact**

Since the former times, people have been trying to increase the production (i. e. growth) by several activities. One of them is pollarding. Pollarding comprises almost complete crown removal initiating a rapid growth of the shoots, which served in former times as livestock fodder. The stem increment is usually much smaller in the years following the event until the crown fully regenerates (Schweingruber, 2007). Some studies (e.g. Sebek et al., 2013), on the other hand, show opposite (although not significant) effect of pollarding on stem increment. Another method that was formerly extensively used is coppicing (e.g. Altman et al., 2013b). People profited from the ability of some species (hornbeam, lime, oaks and other) to resprout after the main stem was removed. Shoots of these species show rapid growth thanks to the storage of assimilates in the roots and opened space providing enough of light. Thinning, pruning, fertilization and other activities can have both negative and positive effect on tree growth. For example soil compaction as a result of using heavy machinery in forest management. The main indirect way people affect tree growth is via the climate change and pollution (Kobayashi et al., 1997). The impact of pollution may be distinguished for example by knowing the onset of the effect. Then, tree ring chronologies are simply compared before and after the pollution took effect (Cook and Kairiukstis, 1990).

Since the half of the 19<sup>th</sup> century CO<sub>2</sub> concentration has increased rapidly as a result of human activities. Increased CO<sub>2</sub> concentrations in the air stimulate the growth but only for several years. After several years the growth starts to diminish probably due to N limitation (Norby et al., 2010).

### **2.1.1.4 Abiotic factors**

There are several abiotic factors influencing tree growth which can be further divided into two groups. Temperature and precipitation form a group of crucial climatic factors and the rest – topography, substrate, and nutrient availability represent the group of site factors.

#### **2.1.1.4.1 Topography**

Topography represents one of the basic factors influencing radial growth, since it strongly predetermines the development of soils and thus affects the amount of water and nutrients available to the plants (Kang et al., 2003, 2006) and also via the orientation of slopes together with latitude determines the total amount of solar radiation (Buffo et al., 1972). One of the effects of topography or relief is the formation of compression wood. The effect of

different topographical features on tree growth studied for example (Fritts, 1969; Kujansuu et al., 2007).

#### **2.1.1.4.2 Elevation**

Elevation goes hand in hand with mean annual temperatures and precipitation and hence affects the two most important factors of tree growth. Regarding the temperature, there is a decrease with elevation in the troposphere called temperature lapse rate. It is usually specified as change of 0,65°C/100m (Barry and Chorley, 2009). As the temperature goes down with increasing elevation, the rate of evaporation is slower as well. This dependency together with the fact that high mountains act like barrier for clouds, results in higher precipitation at higher altitudes.

#### **2.1.1.4.3 Light**

Solar energy is a key driver of climatic conditions. The variability of its intensity is stored within tree-rings which allows reconstructions of solar cycles (Rigozo et al., 2007). The tree growth is dependent on photosynthesis which is controlled by the availability of light (Kozłowski and Pallardy, 1997). Trees growing under a dense canopy get little solar energy resulting in reduction of ring width. After the canopy opens the tree gets much more illumination which leads in wider rings for the few following years (Schweingruber, 1993; Altman et al., 2013a). Differences in amount of solar energy change along altitudinal gradient also. Plants at high elevations are often exposed to high radiation loads and even high daytime temperatures when there are no clouds (Fritts, 1976).

#### **2.1.1.4.4 Substrate**

Substrate plays crucial role as well. Soil properties derived from the parent material influence the content of soil water and the associated root distribution that has a direct impact on tree growth. These include mainly size of soil particles and the soil structure. Sufficient amount of essential minerals and moisture content together with nutrients in organic matter are the major requirements for growth of woody species (Kozłowski and Pallardy, 1997). Poor and dry soils in combination represent very unfavorable conditions for growth; however, specific species might take the advantage of low competition and reach a very long life. This is particularly true for the oldest trees with the most datable and varied tree-rings which are often pines (*Pinus longaeva*, 4843 years old, found by E. P. Schulman in the White Mountains of Inyo County, California) – normally a competition weak species.

It is necessary, however, to add that soil properties and site conditions do not vary much from year to year and hence are not those factors that shape the year to year growth variability of a site (Fritts, 1976).

## **2.2 Climate-growth relationship**

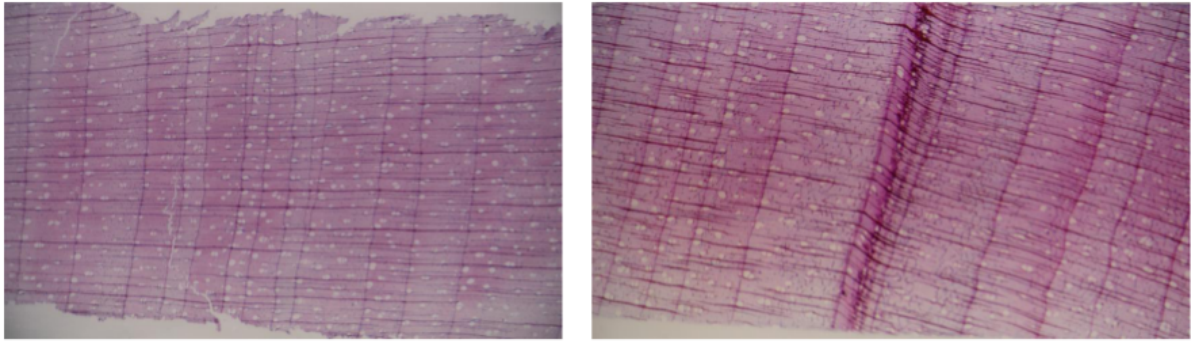
The two basic climatic variables which control tree growth are temperature and precipitation (Fritts, 1976). The occurrence of trees itself on a particular site is determined chiefly by availability of water and a long enough period of favorable temperatures (Pallardy, 2008). Both variables are usually correlated which means that rising precipitation causes temperature decline and vice versa. The rise of both factors at the same time usually promotes favorable growing conditions. The relationship between these two factors and tree growth is best to be studied at the tree limits, since the prevailing harsh conditions cause growth variability and thus make the signal strongest and more visible here (Schweingruber, 1996). The climatic information is stored in form of the width of the tree-ring and also in differences of wood density.

### **2.2.1 Temperature**

The first climatic variable is temperature. It controls the rate of major life processes like respiration and assimilation (Pallardy, 2008). In combination with photoperiod it initiates or stops growth. In temperate and boreal zone its impact on tree growth is mostly observed in spring, at the beginning of the growing season.

Sometimes there are unusually low temperatures in spring which cause a delay in dormancy breaking and thus shortening of the growing season. Much serious growth problems, however, are caused by those abrupt changes of climatic factors which occur over the running season. Temperature extremes (Palakit et al., 2012) and/or severe droughts (Copenheaver et al., 2010; Palakit et al., 2012) before the end of the season may cause cell reducing and wall thickening. When the conditions get better, large cells with thinner walls start to form again. This abrupt cambial activity results in creation of growth layers which look like tree-ring boundaries (Fig. 1). Such intra-annual growth bands are also called false tree-rings and often lead to mistakes in tree-ring measurement (Fritts, 1976). In some species, however, the false tree-rings are attributed rather to some non-climatic triggers like growth rate, tree age, massive defoliation caused by insect outbreak and canopy position than to the climatic ones (Copenheaver et al., 2006). If very unfavorable conditions last over

the whole growing season it may happen that tree-rings create only partly (Fig. 1) or do not create at all. The highest percentage of missing rings is typical for suppressed trees on poor and high-alpine sites (Drápela and Zach, 1995). Whatever the case, false or missing tree-rings cause problems in a process called “crossdating”. It is a process of matching tree-ring patterns between trees on a site to create the site chronology (Fritts, 1976).



**Figure 1.** Two diverging tree-rings prove that in some part of the stem tree-rings are completely missing. This is usually caused by high competition pressure or extremely adverse climatic conditions (left). Extremely unfavorable climatic conditions during the growing season may also result in formation of intra-annual growth bands which look like tree-ring boundaries (right). Both pictures taken from *Betula ermanii* stand on Mt. Halla at an elevation of 1900 m.

### 2.2.2 Precipitation

The second climatic factor, water, plays a crucial role among all environmental factors. It controls main processes in a tree, thus has a strong impact on the growth as well. The amount of available water affects the final ring width (Pallardy, 2008). This dependency is widely used in studies dealing with hydrological regimes in the landscape (Herrera and Del Valle, 2011). Shortage of water, same as too much water, induces water stress events and thereby growth deterioration. Floodings, for example, affect tree growth differently depending on the species, duration and part of the year when it occurs (Kozłowski and Pallardy, 1997). The limiting factor of growth in flooded soils during the growing season is the lack of soil oxygen combined with number of soil and plant changes (Kozłowski et al., 1990).

The most common stress affecting tree growth in semi-arid conditions is water deficit (Speer, 2010). At the level of cells, water deficit limits the cambial activity directly through lowering the turgor which is necessary for cell enlargement (Kozłowski and Pallardy, 1997). Water deficits usually occur in summer. In spring there is usually enough of soil moisture

thanks to melting ice and snow. On the other hand, deep snow cover may postpone the onset of spring making the growth delayed and slow (Fritts, 1976). Snow, at the same time, acts as a soil isolation and protection against frost for both the aboveground and belowground parts of a tree. These findings lead to a conclusion that winter precipitation has a strong impact on tree growth despite no growth during winter takes place.

When spring droughts occur, it usually deeply affects the growth for the rest of the season. The degree of the effect of drought is also modified by the spatial distribution of individual trees. Trees growing close to each other are much severely influenced by drought than those growing in open stands (Waring, 1987). Drought may even cause wood to crack. This is more probable to happen in trees which experienced optimal growing season, because they usually form less dense wood. Such events often happen in conifers in the late summer and are followed by creation of resin ducts (Schweingruber, 1996).

A global increase in the land amount of precipitation of 0.89 mm per decade has been recorded during the 20<sup>th</sup> century (New et al., 2001). It is a result of increased water vapor in the atmosphere caused by the warming of the oceans. This is, however, relatively small change when comparing with the inter-annual and inter-decadal variability (New et al., 2001). Another point is that this trend is not coherent on a smaller scale. Some regions exhibited even a decrease in precipitation over the 20<sup>th</sup> century, e.g. central Europe (Dolezal et al., 2010).

## **2.3 Long-term growth characteristics**

### **2.3.1 Growth rate**

The rate of stem growth is not stable during the whole season. It is highest in the spring after the breaking of the dormancy and then slowly decreases as the season progresses, till it diminishes totally at the end of growing season and dormancy starts again. Diurnal, seasonal and longer-term growth rates are accurately studied using automatic dendrometers (e.g. Deslauriers et al., 2003). The growth rate also depends on the age of the tree. Tree seedlings usually show increased growth after the root system is fully established and reach maximum rates as it becomes a flourishing sapling. Once it becomes a mature tree, the growth rate starts to decline because of physiological and environmental conditions, while the mass production does not (Stephenson et al., 2014).

### **2.3.2 Growth variability**

Growth exhibits variability depending on the degree of specie's sensitivity to environmental conditions (Schweingruber, 1996). Growth variability represents the averages of the shortest day-to-day and longer season-to-season variations. Year-to-year and even longer term variations are captured as well, showing the occurring climate changes (Fritts, 1976). Thus, growth variability is crucial for dendroclimatology. In general, sites with harsh conditions provide sufficient growth variability, since the growth is much more influenced by limiting factor. Sites with optimal conditions, on the other hand, provide tree-rings about the same width and carry just a little or even no climatic information (Speer, 2010).

Changes in the shorter time horizon represent the diurnal rhythms of water storage depletion and replenishment (Kozlowski and Winget, 1964). Studies on the diurnal rhythms show that if a specific type of weather occurs for a period of time, the rhythms play important role in the variation of the ring width (Fritts, 1976). Moreover, studying the diurnal rhythms using dendrometers allows us to precisely determine the start of the growing season (Deslauriers et al., 2003).

Growth variability depends also on the length of growing season which greatly depends on the elevation and latitude (Schweingruber, 1996). In temperate forests the growing season may start in April, May or June and finish in September, August or October but it may vary from year to year according to climate conditions of the particular year. This year-to-year length variability of growing season is particularly important, because conditions in the preceding growing season affect tree growth of the current year as well (Drápela and Zach, 1995). Specifically, earlywood or the vessels of ring porous genera are often produced at the beginning of the growing season before leaf-out. It means that these vessels develop from derivatives stored since the autumn of preceding year (Speer, 2010).

### **2.3.3 Growth trend**

Growth trend represents persistent long term deviations from the expected growth. Growth trends reflect the long-term growth rate which is a phenotypic expression of ageing, site quality and conditions and competition. The value of growth trends lies in the information about stand history that it carries (Frelich, 2002). Thus, it finds a wide use in analyses dealing with disturbance regimes of the stands (Frelich and Lorimer, 1991; Niukkanen and Kuuluvainen, 2011). Growth trends are species specific and disclose a specie's life strategy related to the plant's light demands. Frelich (2002) distinguishes several types of growth

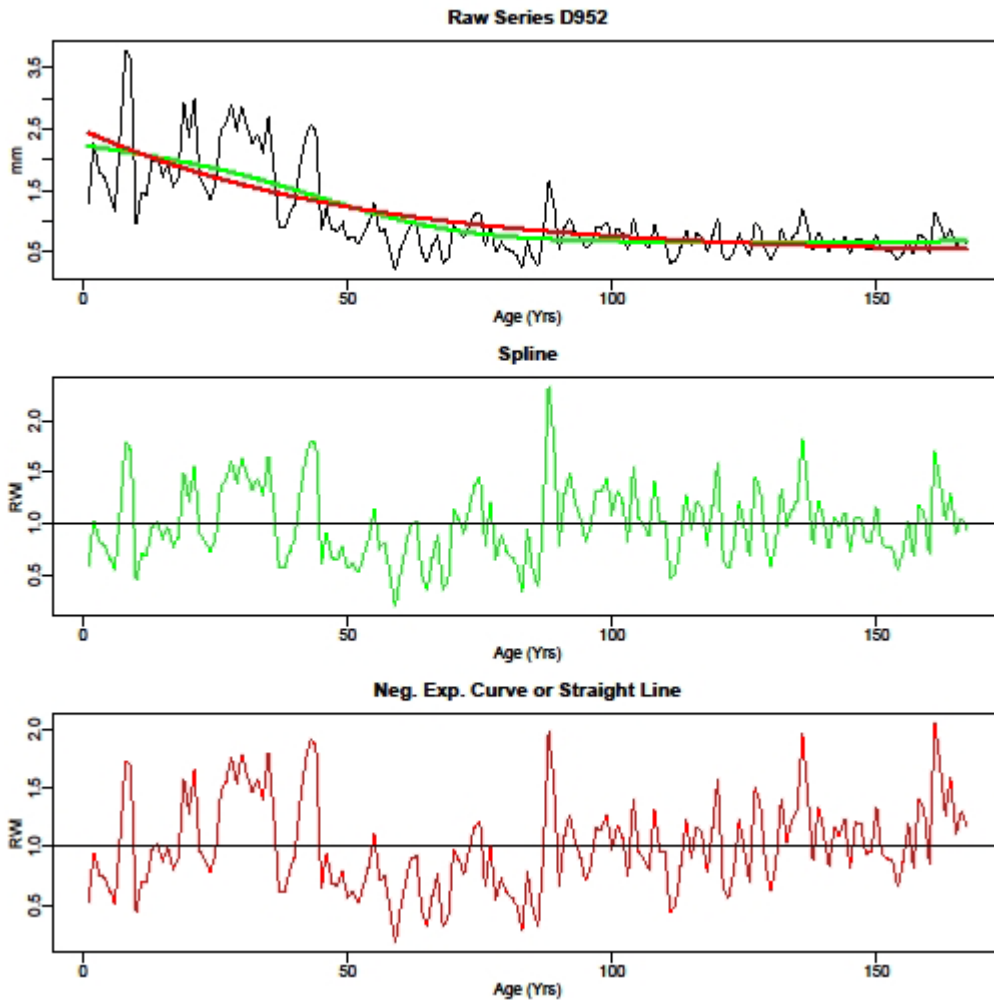
trends according to the shape of the growth curve. For example, common types of growth trends of trees which established after a disturbance and thus avoided suppression of bigger trees are declining, balanced and parabolic.

## 2.4 Standardization

As was indicated, in dendroclimatology, there is an effort to get samples with the strongest climatic signal. Several steps are usually followed to obtain the best input data. Primarily, it is selection of suitable site, proper sample collecting and ample sample depth. After the tree-ring series are successfully crossdated a crucial data transformation follows. It is collectively referred to as standardization. Standardization is a complex process of data preparation in order to create stationary time series (Drápela and Zach, 1995). It comprises mainly of fitting curves to trends contained in tree ring series. The purpose is to remove age-related growth trends and other long-term variability unrelated to climate (Speer, 2010). The reason is that these trends weaken the climatic signal. Many statistical methods were developed to remove this factor. They are usually divided into deterministic and stochastic group.

First group represents functions that follow a model of tree growth. It includes the most common negative exponential function and linear regression. The usage is substantially restricted to curves with a simple growth trend which is common in undisturbed trees growing in sparse canopy (Cook and Kairiukstis, 1990). Second group consists of functions based on experiments to find the best fit. Among the most commonly used methods belong digital filtering i.e. running mean (Drápela and Zach, 1995). Widely used are also cubic smoothing spline functions in which tree-ring series are divided into several sections, each spaced with a polynomial of 3<sup>rd</sup> grade to link to each other (Cook and Peters, 1981) (Fig. 2). The absence of a universal method for removing long-term growth trend (i.e. “detrending”) shows the complexity of the problem (Frank et al., 2007). Moreover, detrending may lead to unintended removal of long-term changes in climate which is usually a subject of study to dendroclimatologists (Fritts, 1976; Speer, 2010). To preserve such information, special age-related detrending methods were developed (Briffa et al., 2001; Esper et al., 2003; Nicault et al., 2010).





**Figure 2.** An example of detrending raw tree-ring series using two different methods (spline – green curve and negative exponential function – red curve).

## 2.5 Event years

A useful aid in tree-ring research and dendroclimatology in particular, are the event years (Schweingruber, 1996). Their importance derives from their indispensable role in crossdating, which is a basic procedure in dendrochronological analyses.

Event years are tree-rings that distinctly differ from the neighboring tree-rings. They can be usually distinguished visibly as they considerably differ in ring width or in conifers they might contain rows of resin ducts. Other properties serving for their identifying are larger or smaller proportion of latewood or fluctuations in density during the year (Cook and Kairiukstis, 1990). The difference arises from a tree’s response to extreme conditions which occurred during the season. As the climate changes, weather extremes occur more often. Such extremes act like stresses triggering a series of different dysfunctions in the tree that lead to alterations in growth (Kozlowski and Pallardy 1997; Pallardy, 2008). The probability

that an event will become an event year is species specific because some reactions are inherent to species rather than the site (Schweingruber, 1996). Some pointer years may be caused by different drivers than by climatic extremes. Among others, especially mast years or insect infestation have negative effect on tree growth (Schweingruber, 1996) but also pollution (Kobayashi et al., 1997). If event years appear repeatedly in several tree-ring series then they are called pointer years.

### 3 Aims

The main aim of this study is to reveal the climate-growth relationship of major tree species on Jeju Island with emphasis on changing environmental conditions.

Specific aims are:

- 1) create site chronologies for each species (*Quercus mongolica*, *Taxus cuspidata* and *Abies koreana*),
- 2) compare growth response between species,
- 3) identify pointer years and link them to the driving climate factors.

### 4 Hypotheses

Main hypothesis: Species respond to changing climate differently

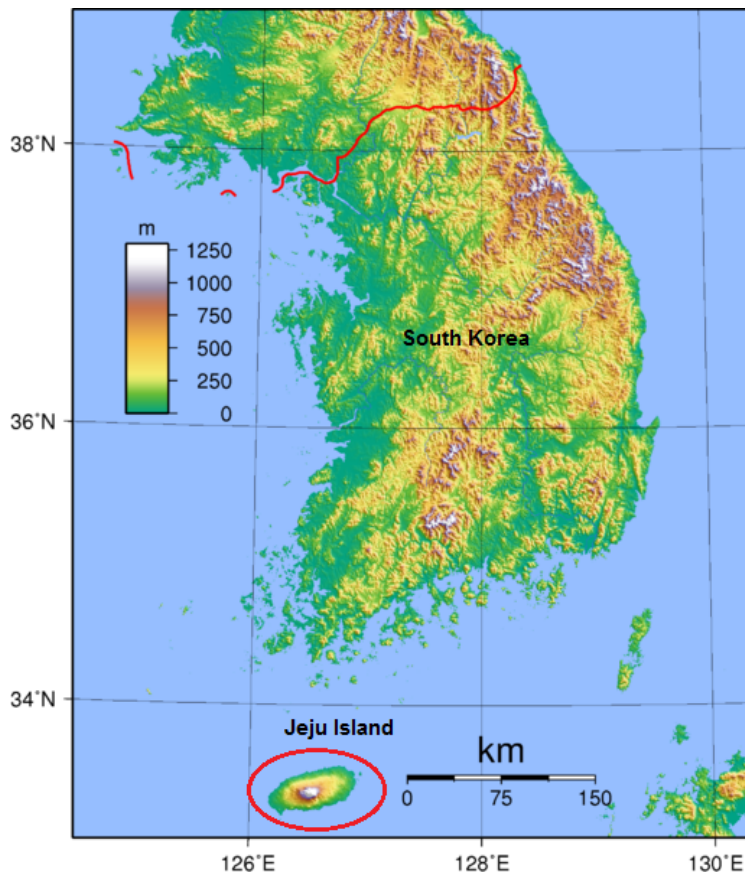
Specific hypotheses:

- 1) There is a trend of increasing temperature and precipitation on Jeju Island.
- 2) Growth of *Quercus mongolica* is driven especially by precipitation rather than by temperature.
- 3) The effect of increasing temperature on tree growth is changing with time.

## 5 Materials and methods

### 5.1 Site description

The study was carried out in NP Hallasan on Jeju Island (33°10' - 33°34' N, 126°10' - 127° E), 90 km from the southern tip of Korean peninsula (Fig. 3). It is a separate island of volcanic origin with one dominant mountain (Hallasan volcano 1950 m a. s. l.) which is a shield volcano formed during Pliocene and Pleistocene. This made porous basalt to cover all of the island.

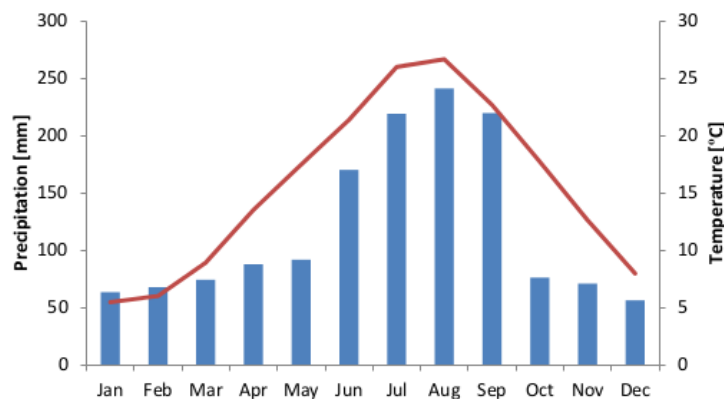


**Figure 3.** Position of Jeju Island (circle).

#### 5.1.1 Climate

Climate of the island is shaped both by the East Asian monsoon and a branch of warm northward Kuroshio Current called Tsushima (Lee and Nam, 2003). The summer monsoon with typhoons brings a lot of precipitation and warmth resulting in humid and warm summers, causing about 40% of annual precipitation falls from June to September (Fig. 4). Winters are usually dry and cold because of the influence of cold air masses formed in Siberia. Mean annual temperature for the period 1924-2010 was 15.5°C and mean annual precipitation 1618 mm according to observations at the Jeju Regional Meteorological Office,

24 m a.s.l. Orimok weather station situated at 970 m a.s.l. shows mean annual temperature of 9.7°C.



**Figure 4.** – Graph showing mean monthly precipitation (columns) and temperature (line) for the period 1924-2010 from Jeju Regional Meteorological Office (24 m a.s.l.).

### 5.1.2 Vegetation

The vegetation of Hallasan NP may be divided into three follow-up zones replacing each other according to altitude and abundance of dwarf bamboo *Sasa quelpartensis* (Dolezal et al., 2012, Cerny et al., 2013). At the elevation of 500-1000 m lie warm-temperate forests dominated by *Quercus serrata*, *Carpinus laxiflora*, *C. tschonoskii*, and some evergreen shrubs or small trees in the understory (*Daphniphyllum macropodum*, *Ilex crenata*). These warm-temperate forests were present on the island even during the last glaciation period in coastal refuges when the rest of Korea was covered by sagebrush steppe (Chung, 2007). This was probably achieved by the buffering effect of the ocean (Lee et al., 2008).

At middle elevations (1000-1400 m) cool-temperate broadleaved forests (Supplementary Fig. 5) composed mainly of Mongolian oak (*Quercus mongolica*) and maple (*Acer pseudosieboldianum*) occur. At the highest parts (1400-1900 m), mountain-temperate forests of *Abies koreana* and *Betula ermanii* can be found (Song, 1991; Kang et al., 1997). The alpine zone hosts species like *Empetrum nigrum* var. *japonicum* and *Diapensia lapponica* subsp. *obovata* which has its southern area of distribution here on Jeju Island.

The richness of herbaceous layer increases with increasing altitude and is strongly influenced by the cover of bamboo (Altman, 2009). Specifically, the higher bamboo cover, the lower richness of vascular plants. This leads to highest species richness in fir forests with less developed bamboo cover and lowest species richness in oak forests with highest density of bamboo (Altman, 2009; Dolezal et al., 2012). Similar relationships have been documented also in Japan (e.g. Dolezal et al., 2009a).

Tree species used in this study represent either a canopy or sub-canopy dominant species of the forest types described above. First of them is *Quercus mongolica*. It is a deciduous oak species distributed throughout the Korean peninsula, northern Japan, northeastern China, eastern Russia and Sachaline Islands. According to Suh and Lee (1998) Mongolian oak is rather a pioneer species forming stands soon after a disturbance, but decreasing in dominance as other deciduous species invade the stand. As a ring-porous, long-living woody plant it is very suitable for dendrochronological analysis.

*Taxus cuspidata* is a quite common species in oak stands. This yew grows under the canopy of broadleaved. It is extremely shade tolerant and long living with distinct rings. However, stem deformations resulting from growth under the canopy make them often problematic in dendrochronology, as documented by Schweingruber (1993). This probably contributed to the fact that there are very few dendroclimatological studies on Japanese yew.

Next species that was a subject of this study is *Abies koreana*. It is an endemic species in Korea. It is characterized as light-demanding fast-growing species vulnerable to wind-breakage and uprooting. Especially at the upper tree line, strong winds and heavy snowfall in winter are common, resulting in high mortality which makes the canopy opened, allowing coexistence with light-demanding herbs (Dolezal et al., 2012). This fir may be considered as glacial relict since it was able to survive on the island during the warmest period of Holocene due to high elevation of the mountain.

## **5.2 Data collection and preparation**

### **5.2.1 Meteorological data**

The whole dataset of mean monthly temperatures and precipitation was obtained from the database Climatic Research Unit (CRU TS 3.21) using the KNMI Climate Explorer ([www.climexp.knmi.nl](http://www.climexp.knmi.nl)). These data are interpolated from climatological stations. Climatic data were taken for the area 33 – 34 °N and 126 – 127 °E and range from 1901 – 2009. To evaluate the suitability of these data, instrumental data from climatological station in Jeju city (1923 – 2010) was obtained. There was a strong correlation between these two datasets (mean correlation coefficient for temperatures was 0.987 and for precipitation 0.62 for the period 1923 – 2009).

## 5.2.2 Tree-ring sampling

Permanent plots (20x20m and 50x50m) were established along altitudinal gradient (1130, 1230, 1320, 1430, 1530 and 1600 m a.s.l.) on the north-eastern slope of the Mount Halla, representing the main vegetation levels of the mountain. Cores from all stems (> 10 cm DBH) of *Quercus mongolica*, *Abies koreana* and *Taxus cuspidata* were taken at a height of 0.5-1.3 m in May 2011, using Swedish increment borers (Mora, Sweden). One core was taken from each tree in the direction of the contour. A total of 261 cores were taken. Cores were moistened and a thin layer was sliced off using core-microtome (Gartner and Nievergelt, 2010) to get a plane surface for precise measuring of the ring widths which was carried out in the laboratory of the Institute of Botany AS CR in Třeboň. Tree-rings were measured using microscope and a dendrochronological application PAST4 ([www.sciem.com](http://www.sciem.com)). The measuring was performed from pith to bark with a precision of 0.01 mm.

## 5.3 Data analysis

### 5.3.1 Standardized chronology creation

PAST4 was used for crossdating of the individual series to get mean chronology from each plot. Tree-ring series obtained from the cores shorter than 40 years and those that did not match with the site chronology (the lowest acceptable value of Baillie/Pilcher or Holstein T-Test was set to 3 and the percentage of slope equivalence – Gleichläufigkeit at least 60%) were excluded. This resulted in final 213 trees which were used for creating standardized site chronologies (Tab. 1).

To determine the standardized (residual) chronology, ARSTAN (Cook, 1985) was used. First, heteroscedasticity was removed using adaptive power transformation. Next, to remove the non-climatic effects (ageing, stand dynamics and site quality) detrending was performed using negative exponential function. Because of changing number of samples in time, variance stabilization was made via 100-year spline. The remaining autocorrelation was removed from the standard series by autoregressive modeling. Finally, residual series of the samples were averaged to create final residual chronology for each plot. The maximum number of cores included in each final chronology differed between plots. The least number of cores at the beginning (the oldest part) of each final chronology was set to 5. The reliability of the residual chronologies was determined according to mean expressed

population signal (EPS) calculated for intervals of 30 years with 15 years of overlap and mean sensitivity (sens). All chronologies had the mean EPS higher than 0.85 and mean sensitivity around 0.2, so they were reliable for climatic studies (Speer, 2010). Altogether 7 standardized site chronologies were created, 5 for *Quercus mongolica*, 1 for *Taxus cuspidata* and 1 for *Abies koreana*. The longest chronology spanned from 1832-2010 (for more details see Table 1).

**Table 1.** Details of investigated site chronologies

Site	Altitude [m]	Species	No. of trees	Dating	Mean sens	Mean EPS
1130Q	1130	<i>Quercus mongolica</i>	14	1844-2010	0.228	0.885
1130T	1130	<i>Taxus cuspidata</i>	18	1936-2010	0.2	0.883
1230Q	1230	<i>Quercus mongolica</i>	29	1832-2010	0.21	0.947
1320Q	1320	<i>Quercus mongolica</i>	59	1899-2010	0.22	0.922
1430Q	1430	<i>Quercus mongolica</i>	43	1921-2010	0.184	0.927
1530Q	1530	<i>Quercus mongolica</i>	27	1922-2010	0.205	0.932
1600A	1600	<i>Abies koreana</i>	23	1938-2010	0.215	0.861

### 5.3.2 Dendroclimatological analysis

Two types of correlations were performed to reveal the effect of climatic factors on radial growth of selected species. The first type was the partial correlation which was calculated in Statistica 12 (StatSoft 2013). The second type was the bootstrap moving correlation (Biondi and Waikul, 2004) in program R (R Development Core Team, 2011) using packages *dpIR* (Bunn, 2008) and *bootRes* (Zang and Biondi, 2013).

Both methods can deal with the high degree of multicollinearity, which is often found in climatic data and which does not allow the use of ordinary least square regression (Zang and Biondi, 2013). Both correlations were computed between the standardized (residual) site chronologies and mean monthly temperatures and precipitation for the period 1902-2009 for each site. Climate data were sorted from September of the preceding year to August of the current year in both cases. The bootstrap moving correlation was calculated with 35-year window shifted in time by one year.

### 5.3.3 Pointer years analysis

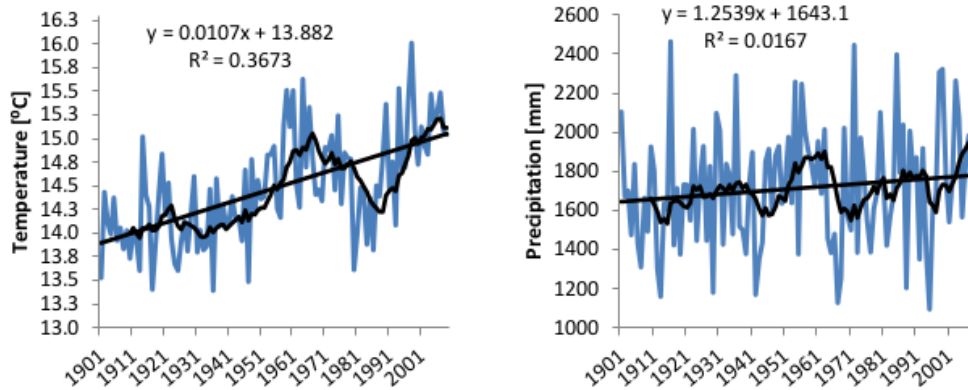
Pointer years were detected for each site, defined as single years in which the value of sudden change of growth pattern falls above or below a determined threshold (Schweingruber, 1996). Threshold in this case was set as an increase or decrease higher than 10%, shown in more than 75% of all trees on the site.



## 6 Results

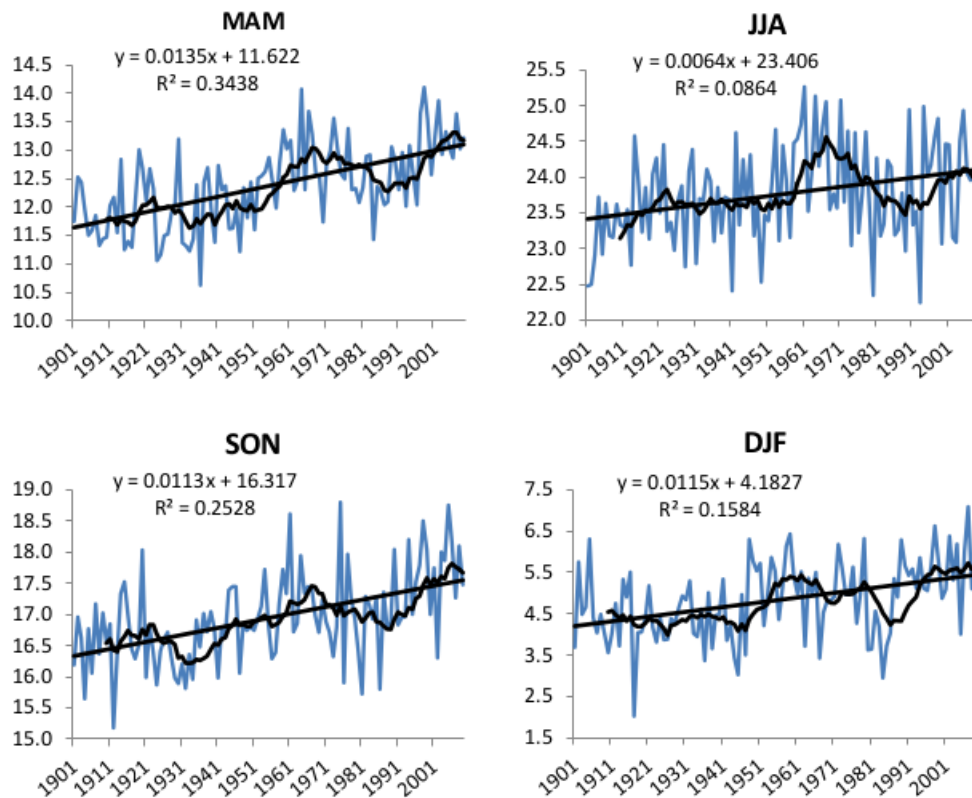
### 6.1 Climatic data

The interpolated climatic data from CRU database spanning 1901 – 2009 show increase of mean annual temperature approximately about 1.1°C. Mean annual precipitation do not express any obvious trend (Fig. 6).



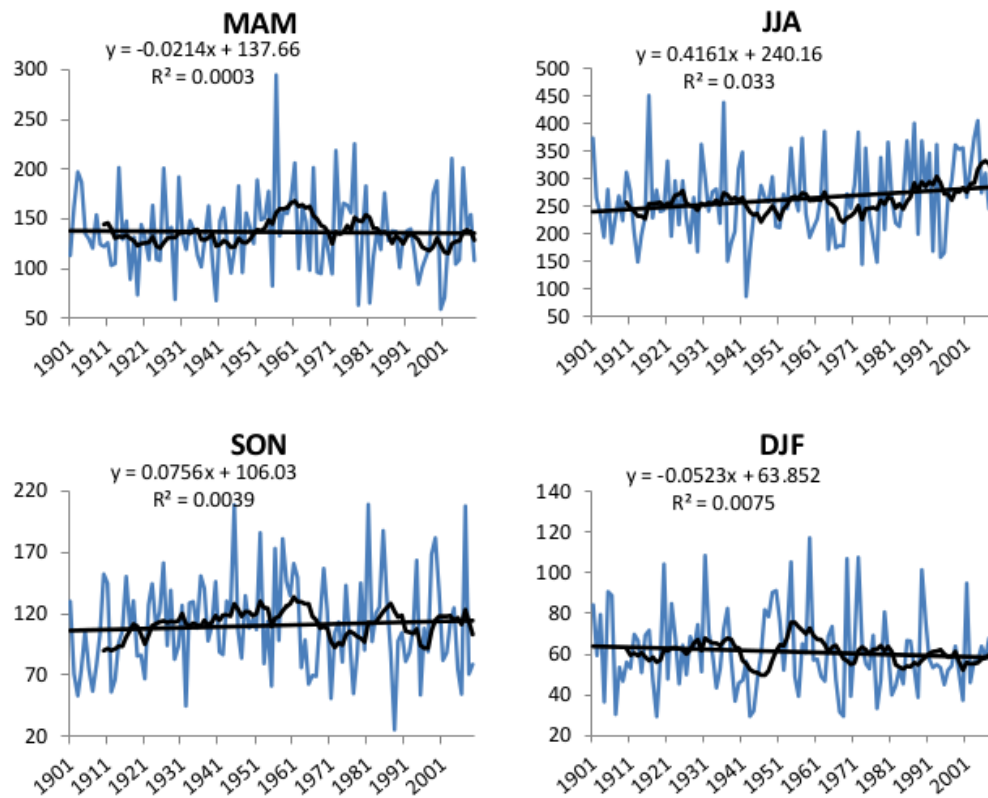
**Figure 6.** Mean annual temperatures (left) and rainfall (right) for the period 1901 – 2009. Curves are fitted with linear regression and smoothed by 10-year mean.

When focusing on seasonal variability of climate a significant increase of temperatures in all seasons appears. The highest increase is in spring, represented by change of about 1.5°C. The second strongest change is in autumn, then in winter and the smallest change takes place is summer (Fig. 7). The coldest month is January with temperature of 3.7°C, warmest is August with mean temperature of 25.7°C.



**Figure 7.** Graphs showing mean seasonal temperature for spring (MAM –March, April, May), summer (JJA – June, July, August), autumn (SON – September, October, November) and winter (DJF – December, January, February) from 1901 to 2009. Curves are fitted with linear regression and smoothed by 10-year mean.

Regarding the precipitation, except a slight increase in summer, no obvious changes in the amount are present (Fig. 8). The driest month is December with mean rainfall of 56.1 mm. The wettest month is July with mean precipitation of 293 mm. Together with the other two wettest months (June and August) represent 46% of mean annual precipitation which is a result of summer monsoon.

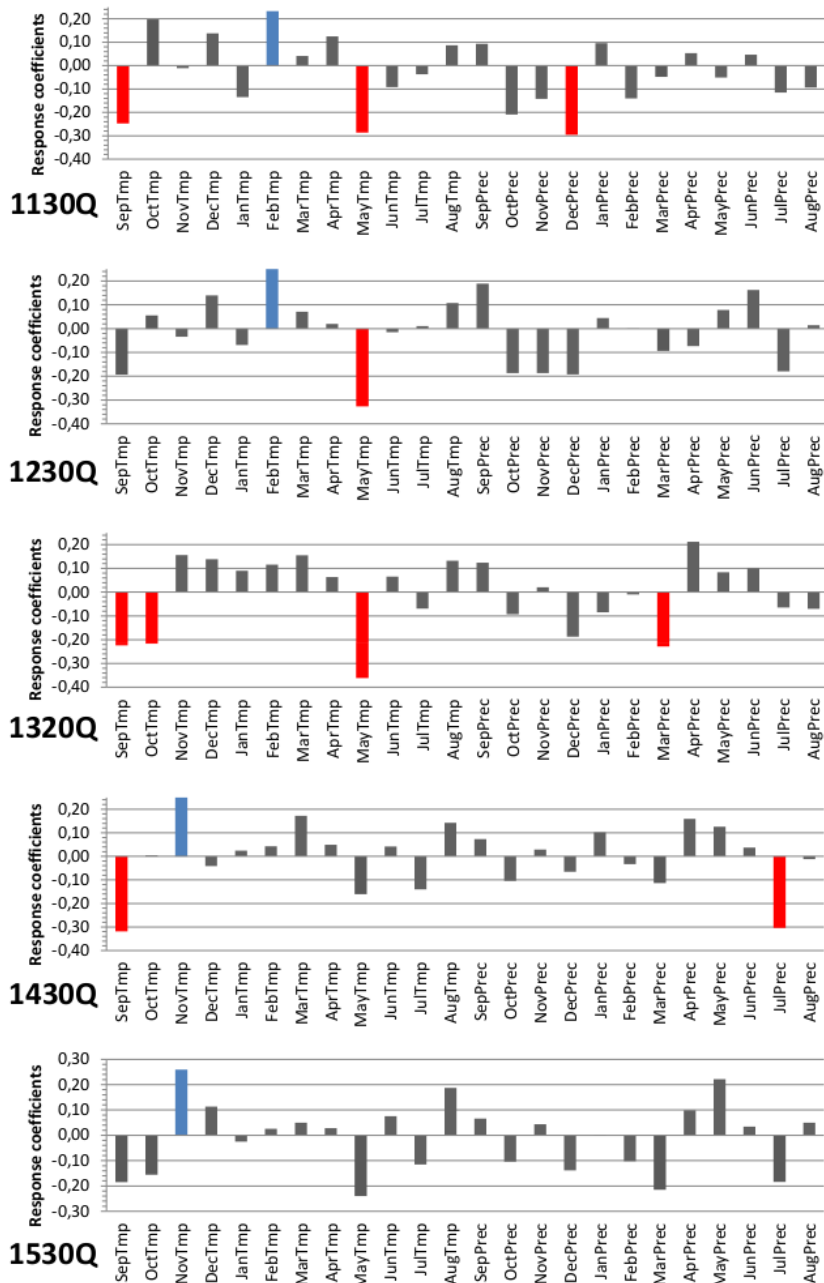


**Figure 8.** Graphs showing mean seasonal precipitation for spring (MAM), summer (JJA), autumn (SON) and winter (DJF) from 1901 to 2009. Curves are fitted with linear regression and smoothed by 10-year mean.

## 6.2 Correlations

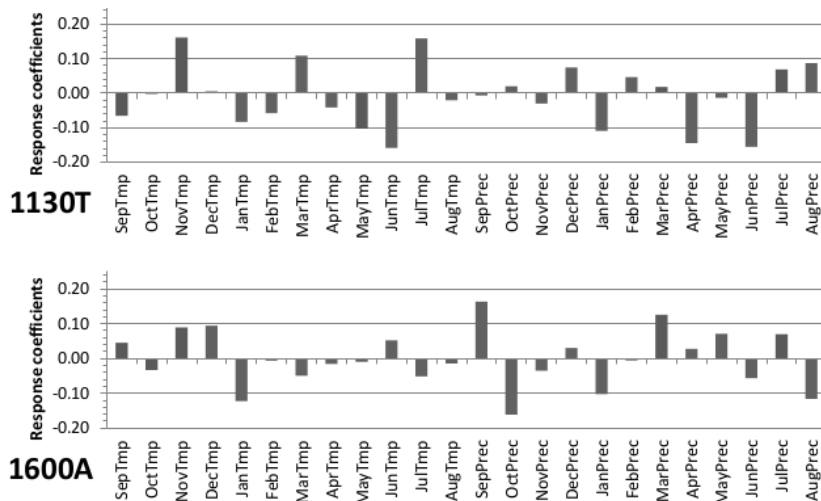
Partial correlations between climate variables and standardized site chronologies were calculated, starting in September of the preceding year and ending in August of the current year. One correlation coefficient for each month was obtained over the whole period.

For *Quercus mongolica*, a negative effect of May temperature of the current year, significant in lower and middle altitudes (1130, 1230 and 1320 m a.s.l.) was determined. Another variable having a negative effect on growth of Mongolian oak common in three elevations (1130, 1320 and 1430 m a.s.l.) is temperature in September of preceding year. There are only two variables showing positive effect. These are temperatures in February for the two lowest elevations (1130 and 1230 m a.s.l.) and November temperatures of the preceding year in the two highest elevations (1430 and 1530 m a.s.l.). Precipitation showed negative correlation in December at the elevation of 1130, in March at 1320 and in July at 1430 m a.s.l. (Fig. 9).



**Figure 9.** Partial correlations between climate variables (temperature and precipitation) sorted from preceding September to current August and residual chronologies of each elevation. Negative response coefficients represent negative relationship and vice versa. Statistically significant values are in red for negative relationship and blue for positive relationship, respectively.

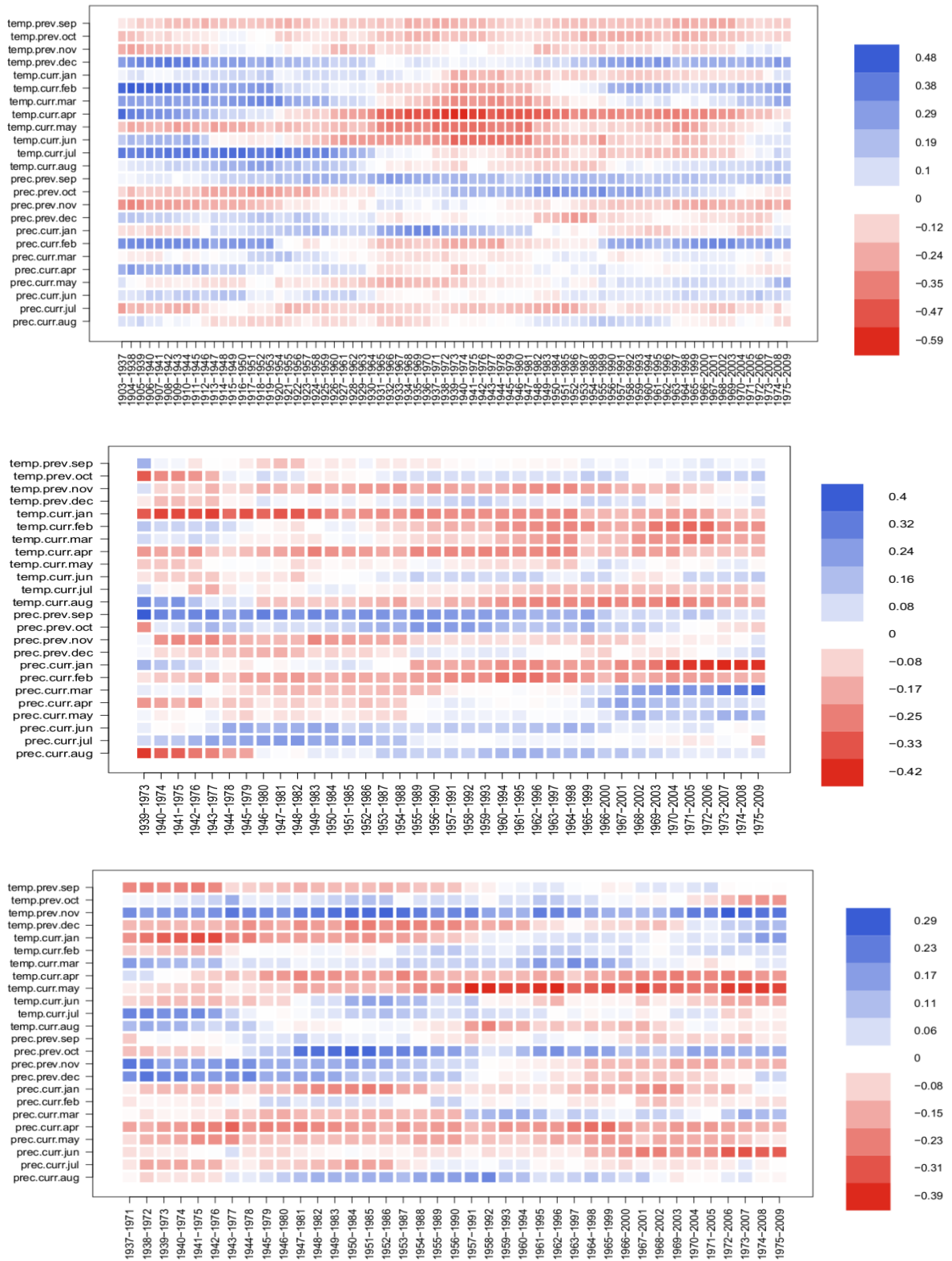
In terms of conifers (*Taxus cuspidata* and *Abies koreana*) partial correlations did not reveal any significant effect of climatic variables (Fig. 10).



**Figure 10.** Partial correlations between climate variables (temperature and precipitation) sorted from preceding September to current August and residual chronologies of each elevation. Negative response coefficients represent negative relationship and vice versa. No statistically significant relationship was found.

Moving correlations were calculated for all elevations. Tree-ring widths and climate variables were sorted in the same manner as for partial correlations. Each cell represents relation between growth and climate in a particular month calculated with a 35-year window shifted in time by one year. Higher values of the correlation coefficients (positive/negative) suggest that higher values of climatic characteristic in a given period are linked with stronger positive/negative effect on tree growth.

Results of moving correlation analysis show the same prevailing negative effect of May temperature on oak growth as partial correlations (Fig. 11 and Supplementary Fig. 12), however in a detailed form. The trend of increasing temperature demonstrated in Chapter 6.1 has been proved to have changing effect on tree growth. The results show that the temperature in spring (March and April, specifically) had positive effect on growth in the past, but as the temperature continued to increase, it gradually turned to negative effect, especially in lower elevations (Fig. 11 and Supplementary Fig. 12).



**Figure 11.** Moving correlation function for *Quercus mongolica* stand at 1230 m a.s.l. (upper), *Taxus cuspidata* at 1130 m a.s.l. (middle) and *Abies koreana* at 1600 m a.s.l. (lower). A gradual change from a positive effect of March and April temperatures on growth of Mongolian oak to negative effect can be seen (upper).

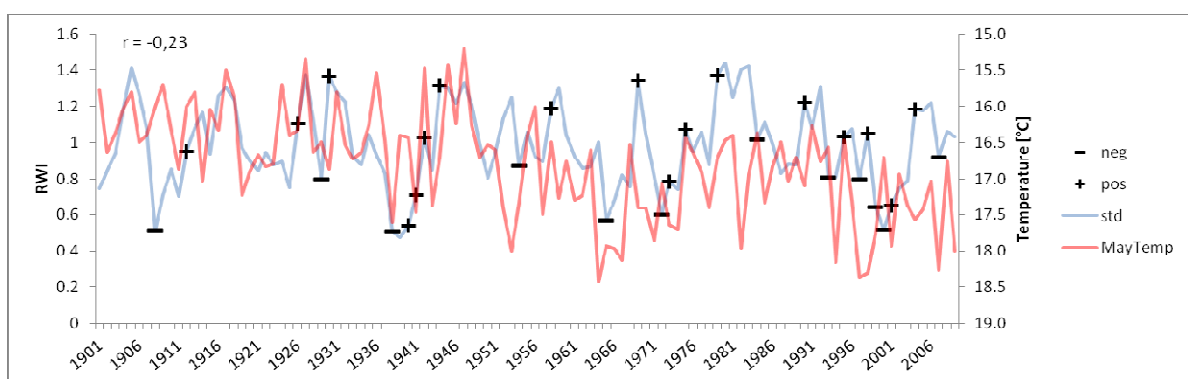
### 6.3 Pointer years

Altogether 81 pointer years were found for all species. 35 pointer years were classified as negative, 27 positive and 19 were for some species positive and for other negative (Tab. 2). Moreover, only 7 out of a total of 28 common pointers with at least one of the conifers showed the same growth changes, the rest showed exactly the opposite. Thus, detected pointer years were divided into two subgroups (oaks and conifers) regarding different reactions to environmental variables of species included in the analysis. In the subgroup consisted only of oaks there were 66 pointer years detected in total. 31 of them were negative, 31 positive and only 4 pointer years were in some plots negative and in other plots positive (Tab. 3).

**Table 2.** The total number of detected pointer years among all elevations.

	1130Q	1130T	1230Q	1320Q	1430Q	1530Q	1600A	TOTAL
Negative years	17	16	14	12	6	10	10	85
Positive years	18	13	13	17	10	11	10	92
Total	35	29	27	29	16	21	20	177

Negative pointer years were closely related to high temperatures in spring, especially in April and May (Fig. 13). Long-term (1901 - 2009) mean temperature in April is 12.5°C and in May 16.8°C. The closest relation was found in 1938 (May 17.6°C), 1954 (April 13.3°C and May 17.3°C), 1971 (April 13.0°C and May 17.9°C), 1972 (April 13.1°C and May 17.1°C), 1997 (April 13.4°C and May 18.4°C), and in 1999 (April 13.4°C and May 17.8°C).



**Figure 13.** Standard chronology of *Quercus mongolica* at 1320 m a.s.l. correlated with mean temperature in May with positive pointer years shown as crosses and negative pointer years as minuses. Correlation coefficient is given by the r value. Note the inverted temperature axis.

Positive pointer years are mostly associated with higher summer temperature, since there is usually a lot of humidity due to summer monsoon. Mean summer temperature (JJA) for the period 1901 – 2009 is 23.8°C and 263 mm is the mean precipitation. Closest association was found in 1930 (24.4°C), 1942 (24.6°C), 1944 (24.2°C), 1973 (24.6°C), 1975 (24.6°C), 1990 (24.9°C), 1998 (24.8°C), 2001 (24.5°C), and in 2004 (24.5°C).

**Table 3.** Both positive (blue) and negative (red) pointer years for all oak plots, determined as an abrupt change in growth >10% experienced in at least 75% of all trees in the plot. Numbers represent mean relative growth change.

Year	1130Q	1230Q	1320Q	1430Q	1530Q	Year	1130Q	1230Q	1320Q	1430Q
1902	-36.93	-58.02				1954	-41.71	-47.23	-27.13	
1904	58.64	85.71				1955		-26.33		
1908	-27.21	-32.75	-51.28			1957		49.73		
1909	63.54	39.55				1958			43.08	
1911	-49.8	-50.95				1960				
1912		80.53	42.58			1964	-34.81			
1913	144.57	67.82				1965			-51.14	
1916	51.5	30.98				1966				56.05
1917	29.62					1969			96.36	55.78
1919	-30.16					1971	-19.36	-24.15		-26.99
1920	24.52					1972	-30.41		-32.78	
1921	-34.28	-28.71				1973			55.42	43.98
1923		-29.85				1975	66.95	61.23	63.43	
1924		-23.12				1977	34.76			
1925		-33.32				1978	-22.23			
1926			53.24		22.91	1979	23.46		66.58	49.88
1928					-25.35	1981				
1929			-27.21		21.49	1982				
1930	113.83	128.66	115.87		15.83	1984		-28.16	-26.74	
1933	-31.63	-34.38				1985		34.19		
1934						1986				
1935		26.37				1987	25.39			-21.08
1938	-24.41	-35.04	-46.94			1990		38.42	49.93	43.55
1940	52.96	35.25	52.81			1993			-40.61	-32.85
1941	3.1		64.8			1995			37.21	40.61
1942	42.15		76.66			1997	-36.23	-31.8	-29.52	
1943	-32.94					1998	42.82		43.54	43.46
1944	33.36		78.41			1999			-48.61	-63.65
1946	-23.64					2000	-16.36		-38.13	-42.56
1947	55.82	119.03				2001	61.01		97.01	104.3
1948				-16.41		2002				51.92
1950					-28.09	2004			67.83	39.56
1951	34.89				46.81	2007			-26.96	



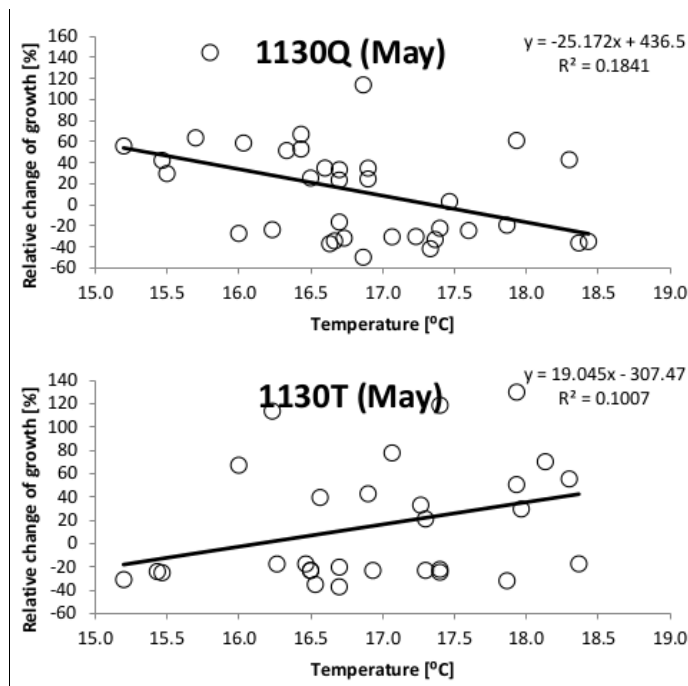
The second subgroup represents conifers *Taxus cuspidata* and *Abies koreana* (Tab. 4). There were 45 pointer years detected in total. 22 of them turned out to be negative, 21 positive and 2 are opposite. Only three pointer years are common for both species. These are negative pointers 1947 and 1979 and positive pointer 1967. Pointer years 1947 and 1979 are exactly the opposite of those found in oak plots, while the positive pointer 1967 is not a pointer for oaks.

Negative years are associated with warmer winters as documented by higher mean winter temperature (DJF) of a particular year than the long-term average (4.8°C). Specifically, years 1941 (5.3°C), 1949 (5.8°C), 1958 (6.1°C), 1964 (5.4°C), 1979 (6.3°C), 1989 (6.3°C), 1991 (5.4°C), 1997 (5.6°C) and 2002 (6.4°C) show such relationship. Positive pointers are again connected with above normal temperatures in May, specifically 1943 (17.4°C), 1959 (17.3°C), 1965 (17.9°C), 1967 (18.1°C), 1969 (17.4), 1982 (18.0°C), 1996 (17.3°C), 1998 (18.3°C), 1999 (17.8°C), 2001 (17.9°C) and 2005 (17.4°C).

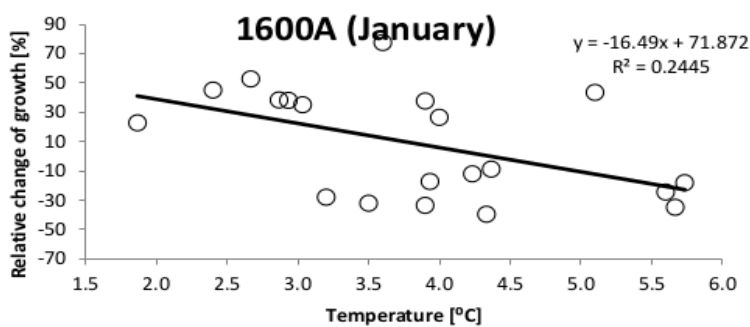
**Table 4.** Both positive (blue) and negative (red) pointer years for *Taxus cuspidata* and *Abies koreana*. Numbers represent mean relative growth change.

Year	1130T	1600A	Year	1130T	1600A
1939		-27.9	1970	-22.15	
1940		52.76	1971	-31.9	
1941		-8.73	1972	77.73	
1942	-25	38.43	1977	42.69	
1943		22.83	1979	-37.12	-24.36
1944		-32	1980		26.57
1945	-24		1982	29.61	
1946	113.6		1983		-33.43
1947	-30.9	-12	1986		45.13
1948			1987	-22.92	
1949	-20.3		1989		-34.72
1951		37.72	1991	-17.55	
1952	-24.6		1993	39.52	
1955		38.16	1995	-17.49	
1956	67.19		1996	21.09	
1958	-23.2		1997	-17.4	
1959	32.97		1998	55.42	
1961	-23		1999		43.55
1964		-18	2000		-39.48
1965	129.9		2001	50.57	-17.16
1967	70.23	35.18	2002	-23.06	
1968	-35.1		2005		77.57
1969	118.7				

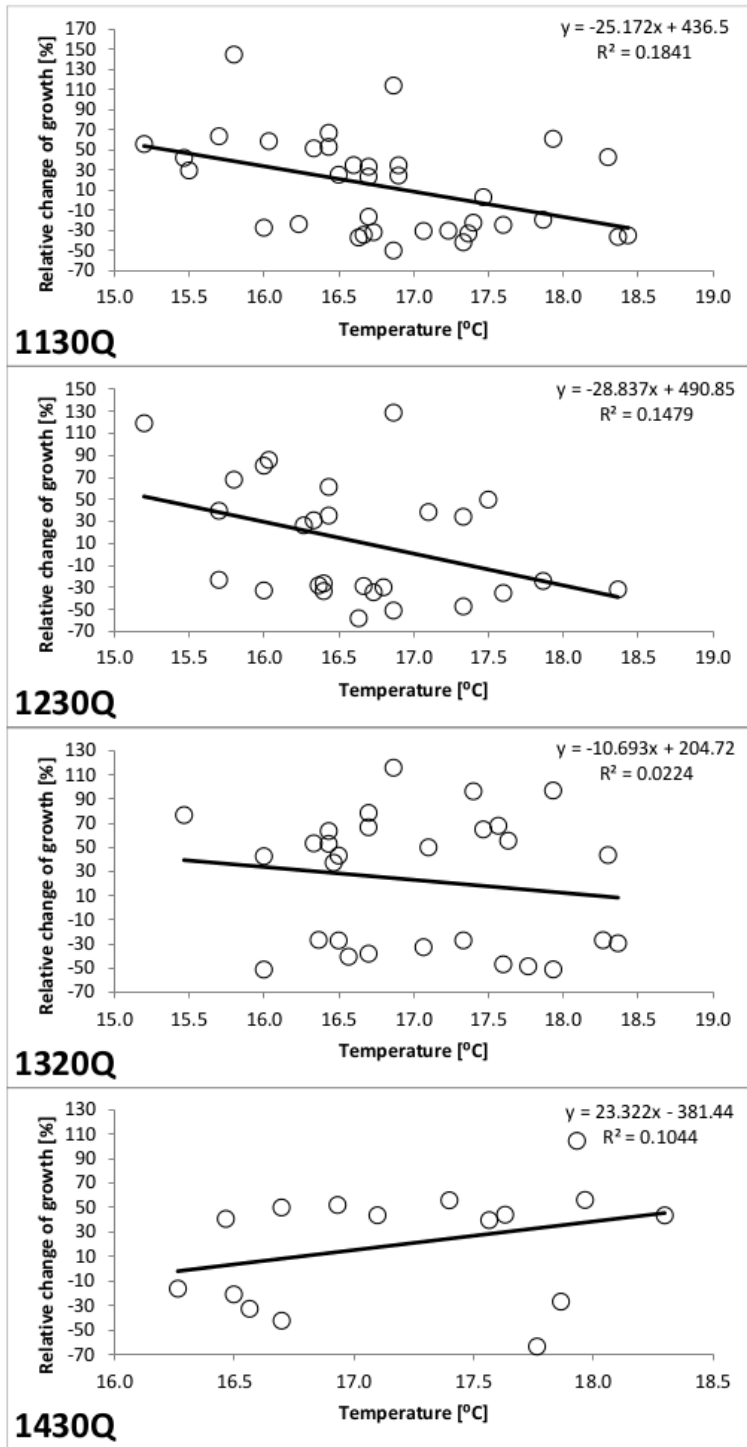
The relative change of growth was used for correlation with climatic variables. Opposite effect of May temperatures on growth was found for Mongolian oak and Japanese yew at the same elevation. (Fig. 14). When the same correlation was made for oak in higher elevations, a gradual change of May temperature along altitudinal gradient appeared (Fig. 15). *Abies koreana* at 1600 m a.s.l. showed negative association with temperature in January (Fig. 16).



**Figure 14.** Opposite response of different species (*Quercus mongolica* and *Taxus cuspidata*) on the same climatic factor (temperature in May), at the same elevation (1130 m a.s.l.).



**Figure 16.** Negative correlation with increasing temperature in January observed in *Abies koreana* stand at 1600 m a.s.l.



**Figure 15.** Correlation between May temperature and relative change of growth in oak stands. The effect is changing along altitudinal gradient.

## 7 Discussion

### 7.1 Climatic situation of the study area

Trend of increasing temperature during the past century has been documented in South Korea (Kim and Kim, 2000; Jung et al., 2002). In terms of precipitation, there is a positive trend in mean monthly precipitation as well as increase in intensity and frequency of heavy precipitation during summer (Jung et al., 2002, 2011; Altman et al., 2013a). Climatic data obtained from the CRU database for the period 1901 – 2009 also show a strong increase of temperature, but no significant trend in the monthly precipitation, however.

During much of the 20<sup>th</sup> century, many tree-ring records show accelerated growth (Spiecker, 1996; Briffa et al., 2008) often caused by increasing temperature, although some records showing decline do also exist (Barber et al., 2000; Girardin et al., 2014). Reason of this decline is still unknown, however increasing water stress and ozone damage are most often discussed (Vollenweider et al., 2003; Girardin et al., 2014). Linear regression of standard chronologies of each plot (data not shown) show neither accelerated growth nor a decline. This, however, does not mean that there is no effect of changing environment. The effect is apparent from the moving correlations between oak radial increment and spring temperatures.

### 7.2 Response to climate of individual species

Species that were used in this study are the representatives of main vegetation zones on Halla volcano. Although the potential of yews for dendroclimatic studies has been proved (Yadav and Singh, 2002; Galvin et al., 2014), low number of such studies on yews imply that genera is problematic. There are very few studies dealing with climate-growth relationship in Japanese yew (*Taxus cuspidata*). Zhang et al. (2009) discovered that this yew exhibits different climate-growth response depending on the sex. No significant response to climate of Japanese yew on Halla Mountain is probably a result of very specific life strategy. As a shade tolerant species growing under the canopy of broadleaved trees (e.g. *Quercus mongolica*), Japanese yew suffers from high competition pressure. Thus, abnormal growth response, expressed by stem deformations, probably weakens the climatic signal. Chaudhary et al. (1999), for example, completely disputes the dendroclimatic potential of *Taxus baccata* due to lack of variation and presence of micro-rings which make crossdating difficult. The similarity between these two yew species allows such comparisons.

The second conifer species studied on Mt. Halla was the Korean fir (*Abies koreana*). Several studies dealt with Korean fir within the Jeju Island (Kang et al., 1997; Koo et al., 2001; Woo et al., 2008). But only the work of Koo et al. (2001) handled the climate-growth relationship. They detected positive association with mean temperatures in April and previous November and with precipitation in previous December and January. The absence of obvious response to climate of Korean fir in this study is probably caused by the length of the fir chronology, which might be insufficient. Despite standardization of the ring width series, tree age influences the climate sensitivity. The variance explained by climate tends to be higher in older trees (Carrer and Urbinati, 2004).

The most represented species in this study is Mongolian oak (*Quercus mongolica*). Despite its large distributional area, dendroclimatic studies are almost completely missing. To my knowledge, only one is the study of Seo and Park (2010) but unfortunately in Korean. As expected from the low correspondence between conifer species and oak chronology (data not shown), oak response to climate was different to that of yew and fir and it was in general much stronger, simply because neither of the conifer species showed any significant correlation with climate while in Mongolian oak there were several.

Oak on all elevations exhibited negative correlation with temperature in May. However, the effect was significant mainly at lower elevations. This led to a conclusion that oak at these elevations experiences too much warmth in spring which causes intense evapotranspiration that reduces soil moisture, and thus limits tree growth.

The only two significant positive correlations accounted for temperature in preceding November and current February. While the positive effect of temperatures in preceding November is most strongly expressed in the two highest elevations, in February it refers to the two lowest elevations, especially.

Precipitation, in general, plays a minor role, deduced on the fact that there are only few significant effects of monthly mean precipitation scattered in different months and elevations, in addition. This is simply because of the main part of vegetation season is well supplied with water.

Positive, although not significant correlation with precipitation in April and May, is consistent with results of the study of Seo and Park (2010) conducted at lower elevations. At lower altitudes (<800 m) Mongolian oak is usually strongly influenced by precipitation in

early spring as it starts to grow before leaf budding, which is typical also for other oak species and ring porous species, respectively (e.g. Dolezal et al., 2010).

$\delta^{18}\text{O}$  of tree-ring cellulose which is closely related to precipitation and relative humidity showed low sensitivity of *Quercus crispula* (a subspecies of *Q. mongolica*) to summer precipitation (Tsuji et al., 2006). This is similar to Mongolian oak which response to summer precipitation was very low.

Unlike the partial correlations, moving correlations allow to see the climate-growth relationship in shorter intervals and thus evaluate the effect of climate change. The trend of increasing temperatures in spring resulted in a shift from formerly positive effect of temperature in March and April to a negative effect. This was observed in elevations 1130 and 1230 and partly in 1320.

### **7.3 Pointer years**

Pointer years appear to be a good index of extreme weather conditions. Assumption for this is that climatic extremes usually affect growth of all trees within the stand. However, only rarely do all species exhibit a pointer year in the same year (Schweingruber, 1996). The set of detected pointer years in this study is not an exception. After the division to oaks and conifers, three pointer years common for both conifers were recognized (negative pointers 1947 and 1979 and positive 1967), but none common for all oaks. This is explained by the different growth optimum between selected species and by the effect of changing altitude.

Most of negative pointer years in oak plots were associated with abnormally high temperatures in spring, especially in April and May. If low precipitation occurred simultaneously, the resulting drought made it even worse. In Korea, most drought events occur just from autumn to the next spring (Min et al., 2003).

Kim et al. (2011) detected 114 droughts over Korea for the period 1777 - 2008 including their long term variability. The most extreme drought occurred in 1897 – 1903 and it corresponds with the negative pointer year 1902 found in two oak plots. Several severe drought periods were detected.

The most replicated (5 plots) and hence strongest pointer year was 1971 when both high temperatures in April and May and low precipitation in March and April occurred simultaneously. Another negative pointer years directly connected with drought events are 1997 and period 1999-2000, showing that droughts in Korea have become more intensive

since 1980s (Min et al., 2003). One strong negative pointer year 1954, however, points to directly opposite event – extreme precipitation in all seasons accounting for 2256 mm/year (average is 1712mm).

Several positive pointer years appeared at the end of a severe drought periods determined by Kim et al. (2011). The positive year 1930 was the last year of a drought period 1927-1930. It was detected on 4 plots, making it a very strong pointer associated with above normal temperature in March and April and precipitation in all three months March, April and May. Ten years later (1940) a strong positive pointer year occurred, again at the end of a drought period (1938-1940) caused by cool and dry spring. The last of these end-drought-period years is 1969 captured at 4 plots, caused by higher precipitation in winter and warmer spring.

Among other positive pointer years belong years 1990 (4 plots), 1998 (4 plots) and some other years positive for oak but negative for conifers (1947, 1979 and 2001). These were all facilitated by warm and humid summer. Also the opposite cases were evidenced (1972 and 1993, both positive for yew and negative for oak, moreover, 1993 possibly connected with the eruption of Unzen Volcano in Japan).

#### **7.4 Relative growth change vs climate**

It has been documented that different tree species may respond to the same climate factor variously (Battipaglia et al., 2009; Schuster and Oberhuber, 2013; Castagneri et al., 2014). Same conclusion was made after comparing relative change in growth (values determining pointer years) with climatic variables among *Quercus mongolica*, *Taxus cuspidata* and *Abies koreana*. While Mongolian oak showed negative correlation with temperature in May, yew at the same elevation reacted positively.

On the case of Mongolian oak can be also demonstrated that the effect of a specific climatic variable changes with altitude. More specifically, May temperatures were negatively associated with tree growth in lower elevations, but gradually turned to positive along with increasing altitude. This is in conformity with the increasing effect of temperature on tree growth with altitude (Lenz et al., 2014).

Another application of relative change in growth revealed negative response of *Abies koreana* to higher temperature in winter (January). It is because of physiological stress due to disturbed dormant period resulting in over-usage of stored assimilates (Lim et al., 2005;

Matisons et al., 2013). According to Koo et al. (2001) high temperatures in winter resulted in the overall decline of Korean fir since the mid-1970s.

## 7.5 Range shifts

In relation with the temperature increase in last more than 100 years, a question arises how this can influence the specie's ranges. According to IPCC report (2014) many terrestrial species have moved their area of distribution, changed seasonal activities (Menzel et al., 2001), abundances and interactions between species as a direct impact of climate change. In trees it is expressed by downward and upward movements of tree limits (Schweingruber, 1996). On the global scale, observed climate warming has resulted in species range shifts about 6.1 km per decade towards the poles or several meters of vertical advance, analogously (Parmesan and Yohe, 2003).

Of course these shifts are not only a matter of temperature but also precipitation. As the distribution of precipitation throughout the year plays even more important role in species composition and productivity than the total amount of precipitation itself, it is probable to expect changes in this field as well (Kozłowski and Pallardy, 1997).

It is important to note, that the area of specie's occurrence is not shaped so much by global averages of climatic variables, but rather by local changes. Zimmermann (2009) shows the importance of measures of climatic extremes in assessing tree species climatic limits, also. The area of distribution of a certain species might be affected both by extremely adverse climate causing higher mortality (Honnay et al., 2002) and by extremely favorable climate connected with higher reproduction. Stronger influence is expected if the extremes occur over several consecutive years.

In addition, species on islands face the problem of limited space. Range shifts of indigenous species lead to range declines connected with diebacks (e.g. Krushelnycky et al., 2013), ranges of invasive species increase (Nurse et al., 2014). Some predictions of possible future species range shifts in Korea have been made (Song et al., 2012; Byun et al., 2013). For *Quercus mongolica*, the most abundant species in the studied elevations, future distributional extensions are predicted according to study made in China.



## 8 Conclusion

In this study, climate-growth relationship of trees was investigated with an emphasis on changing environmental conditions. These are the main findings: 1) mean monthly and annual temperature for 1901 – 2009 shows increasing trend but no clear trend is recorded in precipitation; 2) responses to climate of individual species differ both spatially and temporally; 3) the assumption that growth of *Quercus mongolica* is driven chiefly by precipitation than by temperature, was refuted. Precipitation played rather minor role in Mongolian oak growth in general, while temperature showed clear negative effect in May. 4) The effect of increasing temperature on tree growth is changing with time as evidenced from the moving correlations.

Findings made in this study show that this system is dynamic (changing climate-growth response) but also relatively stable at the same time. Specifically, the stability can be deduced from the long lasting presence of warm-temperate forests which were able to survive even during the last glaciation period in coastal refugies. This indicates both the absence of catastrophic event and a degree of long-term climatic continuity.

## 9 References

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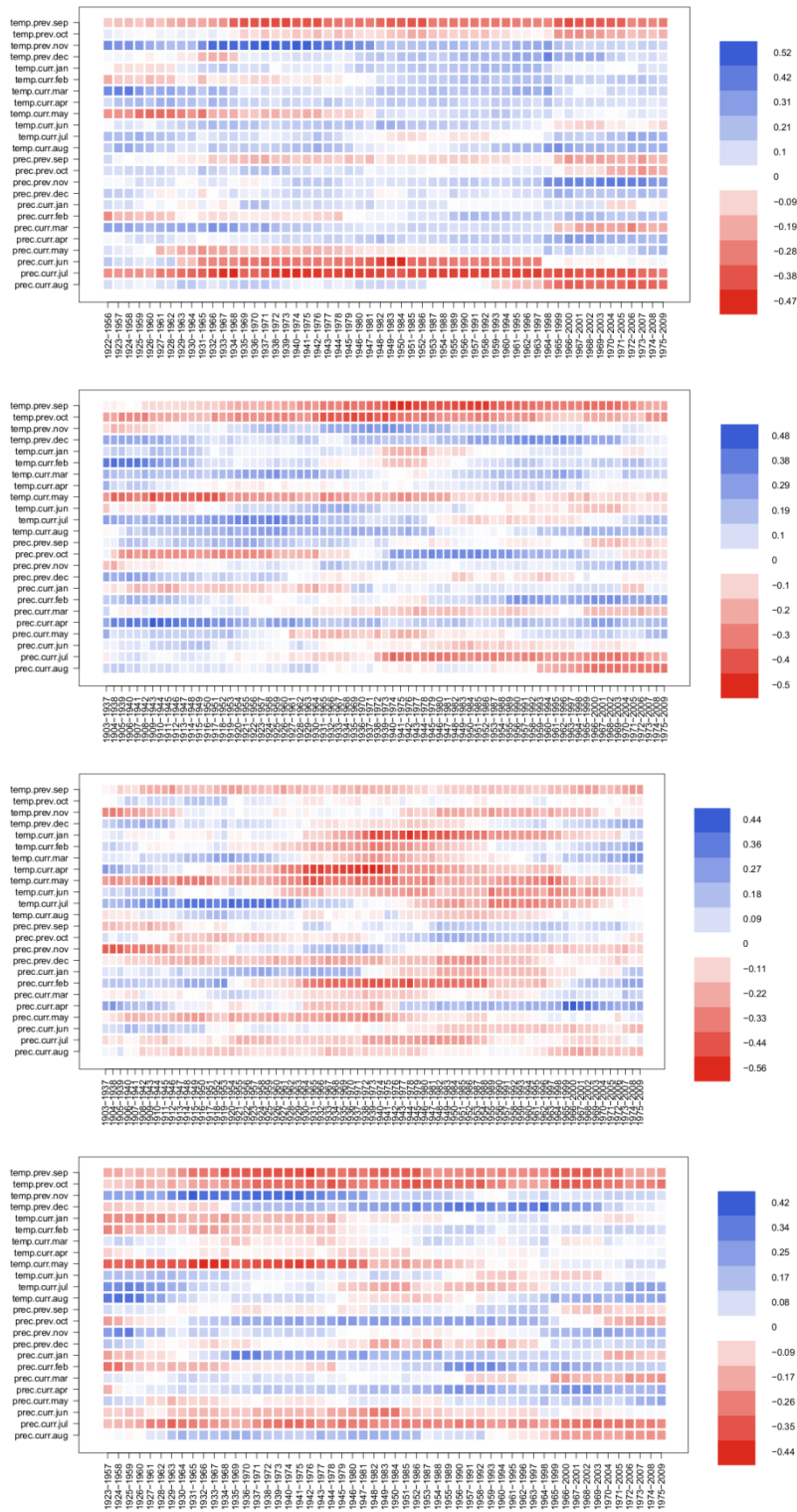
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## Supplements



**Figure 5.** A typical view of mixed forest around 1300 m a.s.l. with dominance of *Quercus mongolica*, *Carpinus tschonoskii*, and *Acer pseudosieboldianum*, *Taxus cuspidata* under the canopy and *Sasa quepartensis* in the understory.





**Figure 12.** Bootstrap moving correlations between climate and residual chronology. Climatic data are sorted from September of the preceding year to August of the current year. Each cell represents relation between growth and climate in a particular month calculated with a 35-year window shifted in time by one year. Higher values of the correlation coefficients (positive/negative) suggest that higher values of climatic characteristics in a given period are linked with stronger positive/negative effect on tree growth. Each diagram represents one plot: 1130Q, 1320Q, 1430Q and 1530Q (from the topmost to the lowest).