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The climate-growth relationship of Scots Pine (*Pinus sylvestris)* exposed to soil dry condition in the Dolomites, eastern Italian Alps

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DEDICATION

TO MY DEAREST MOST BELOVED FIANCE, ANDREW SHINTON

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Preface

This dissertation research was conducted in the Forestry and Forest Ecology Department of Padova University and is submitted as part of the Erasmus Mundus European Forestry double masters degree that is organized by the European Sustainable Forestry and Nature Management (SUFONAMA) consortium (five universities) in which Padova University is a pioneer member. This thesis was produced by following a series of scientific research steps that included finding information in the relevant literature, developing academic writing skills and facilitating the communication, cooperation and team work within a specific time frame using the available capacity-buildings and resources within the research institute.

I would like to express my sincere gratitude to Dr. Marco Carrer for his kind supervision and assistance, to Dr. Vincenzo D'Agostino for his helpful and valuable comments, and to all the Forestry Department staff who tutored and taught so well throughout this year.

I would also like to convey my sincere thanks to both the administration and teaching staff from Bangor University, as well as to all the Erasmus Mundus European Sustainable Forestry and Nature Management (SUFONAMA) master programme staff, in particular mentioning Dr. Neils Strange from Copenhagen University and the secretariat staff, all of whom work to make this project a success.

Soura N. S. Goussous
2009

Abstract

Dendroclimatological techniques were used to assess the impact of climatic factors on radial tree growth (total ring-width) of successive twenty-five Scots pine (*Pinus sylvestris)* trees exposed to soil dryness and nutrient deficiency on the Monte Antelao dolomite landslide at Col de la Roa, San Vito Di Cadore, a small village located in the Italian Dolomites.

Climatic reconstruction potential of Scots pine trees was investigated using monthly instrumental records of temperature and precipitation provided by Histalp gridded dataset, from 1850-2003. Climate-growth relationship within the assigned period was analyzed using the standardized chronologies, by means of the correlation and moving correlation functions.

The strongest and temporally significant climatic signal shown by Scots pine ring-width indices is a positive response to July's prior year's temperature (0.173), and a negative response to its current year's precipitation (-0.199). A failure of cambial activity to develop normal, wide rings following extraordinary dry events was depicted in Scots pine chronologies after the year 1921, but was surprisingly not recorded after the hottest and relatively dry year of 2003.

Scots pine growth in the study site is a proxy of excessive July's precipitation, possibly because Scots pine trees at Col de la Roa have developed a higher water use efficiency in the last few decades which is associated with the enhancing fertilization effect of the recent elevated atmospheric carbon dioxide levels (Knapp *et al.*, 2001), especially during drought years or conditions. Furthermore, this finding suggests also that trees within the study area have acclimatized to the recent increase in temperature since the 1940s.

Key words: Dendroclimatology, *Pinus sylvestris*, carbon dioxide, moving correlation coefficient and Italian Dolomites.

Chapter 1 Introduction

1.1 Dendrochronology

Diverse aspects of past climate were revealed by using tree rings creatively, showing climate phenomena not only on the spatial scale, ranging from a few hectares to a hemisphere, but also on the temporal level, i.e. a few ice-storm hours to decades of drought, as well as to globally changed atmospheric circulation in different centuries (Hughes, 2002). Specific examples include monsoon timing and intensity changes (Fein and Stephens 1987), as well as fluctuation in the frequency and intensity of the El Nino-Southern Oscillation associated events (Glantz 2001; Philander 1990), which maybe related to 'changes in systematic multidecadal circulations over the Pacific Decadal Oscillation' (Mantua *et al.* 1997; Gershunov and Barnett 1999; Minobe 1997). On the other hand, recorded climatic data (temperature and precipitation) were correlated with tree rings to explain the change in size and state of their measurements (Hughes, 2002).

Furthermore, the strengths of using tree rings as natural archives to study climate variability have been addressed, including the following: 'the capability to date tree rings to the calendar year with a very high degree of confidence; the development of very extensive, shared networks of tree-ring chronologies meeting common standards; the surprising effectiveness of very simple linear models of tree ring/ climate relationships; and the growing understanding of the mechanisms leading to variability in tree-ring features' (Carrer and Urbinati 2006; Hughes 2002). However, these natural archives may not respond directly to monthly or seasonal climate variability and can be limited to a certain fraction of capturing them and it is also assumed that the formation of tree rings in the past century is based on the same factors, acting in the same way (Carrer and Urbinati, 2006; Hughes 2002).

Dendrochronologists prefer to select trees from stressed situations, where some climatic factor has been critical to growth. Wood production will be reduced at times of stress, and this is shown by a sensitive series of rings, reflecting a clear and immediate response to some limiting factors (Lowe and Walker, 1997). Tree-ring chronologies have therefore been derived largely, from semi-arid or arid sites where low moisture or high temperatures produced stressed situations, or from sites at higher altitudes and latitudes where low temperatures in particular have restricted growth (Lowe and Walker, 1997; Oberhuber *et al.*, 1998).

In the European forests, the tree-ring growth response of several species, coniferous or broad leaved, to climatic variability were studied widely. These included the reconstruction of past temperature and precipitation records for the last decades or centuries (Schove, 1954; Lindholm, 1996; Briffa *et al.*, 1988, 1990), long term growth investigations for the recent increase in growth trends and changes in growth conditions within various sites (Kenk and Spiecker, 1988; Elfving and Tegnhammar, 1996; Spiecker, 2002), to investigate in depth the effect of these changes on high altitude and high latitude forests that are sensitive to climate variability, simply because they are located at the limited edge of their tree species distribution areas (Grace *et al.*, 2002; Carrer *et al.*, 2007) and to understand the ecological interpretation of the dominant climatic factors influencing radial tree-growth (e.g. drought conditions, water table balance and soil conditions) (Fritts 1976; Oberhuber, 1998).

The aim of this study was to illustrate the site characteristics of Col de la Roa, in the eastern Italian Dolomites, to help interpret tree-growth of a possibly water-stressed stand of Scots pine (*Pinus sylvestris*) within a most sensitive rock-slide area to climatic factors.

1.2 Study background: History of the Dolomites and the study site

The Dolomites are located in the South Alpine mountain range which has the Insubric lineament providing a northern boundary and the south-verging Valsugana Over-thrust (Doglioni, 1987) providing a southern boundary. The geological landscape is mainly dominated by the majestic Triassic carbonates, which provides a good example of early Mesozoic stratigraphy (Bosellini *et al.*, 2003). The Dolomites are also characterised by their active geomorphic processes which take place on high altitudes and steep catchments, spread over a large area of downstream river channels (Lenzi, 2005), and are recognized for their frequent landslides and debris flows, caused by heavy urbanization of transportation routes, alluvial fans and valley floors (Marchi and D’Agostino, 2004).

San Vito di Cadore is a small town in the province of Belluno, Veneto, northern Italy. It is located 9 km from Cortina d'Ampezzo, in the Italian Alps, and is next to Monte Antelao, the highest mountain in in the eastern Italian Dolomites (Guzzetti *et al*., 2005). Large meteorological events often took place within the range of this mountain and have resulted in casualties produced by both landslides (rock avalanches) and debris flows, for example the Cancia village debris flow just south of Mt. Antelao (Guzzetti *et al*., 2005). The study site of Col de la Roa (the gravel hill) is located to the south west of Mt. Antelao, on an old rock avalanche landslide, that took place in April 1814, destroyed two villages and left hundreds of victims (Guzzetti *et al*., 2005). The canyon of Cancha is historically well known for the formation of debris during intense event of rain, especially during the months of July and August

Col de la Roa is part of a rock-slide slope, south-west of Mt. Antelao (1200 m a.s.l.) and located within the San Vito di Cadore village (46° 27' N and 12° 12' E) (Figure 1). The area has an Alpine climate, categorized as having bitterly cold dry winters and relatively warm and humid summers with an average annual rainfall of 1214mm. The substrate consists of rendzic leptosols, a soil surface that rests directly on the bedrock (dolomite and limestone) and is free from clayey impurities. There is restrictive tree-growth at the study site as the soil has a low water holding capacity and inherent low nutrient content. Low direct human-related disturbance (i.e. logging, livestock grazing, fire, etc.) could be found within the study area. Water balance is strained due to low water holding capacity of the shallow, stony soils.

Figure 1 The Dolomites National Park within the Italian Eastern Alps, to the right is the Antelao Mountain and the study site, Col de la Roa, adjacent to San Vito di Cadore village, BL (Source: Google Earth).

Apparently, Col de la Roa Scots pine trees managed to survive the Antelao massive landslide (cross-dating chronologies of the site's trees), which dominate most of the study area nowadays and amazingly survive in harsh, shallow and dry soil conditions.

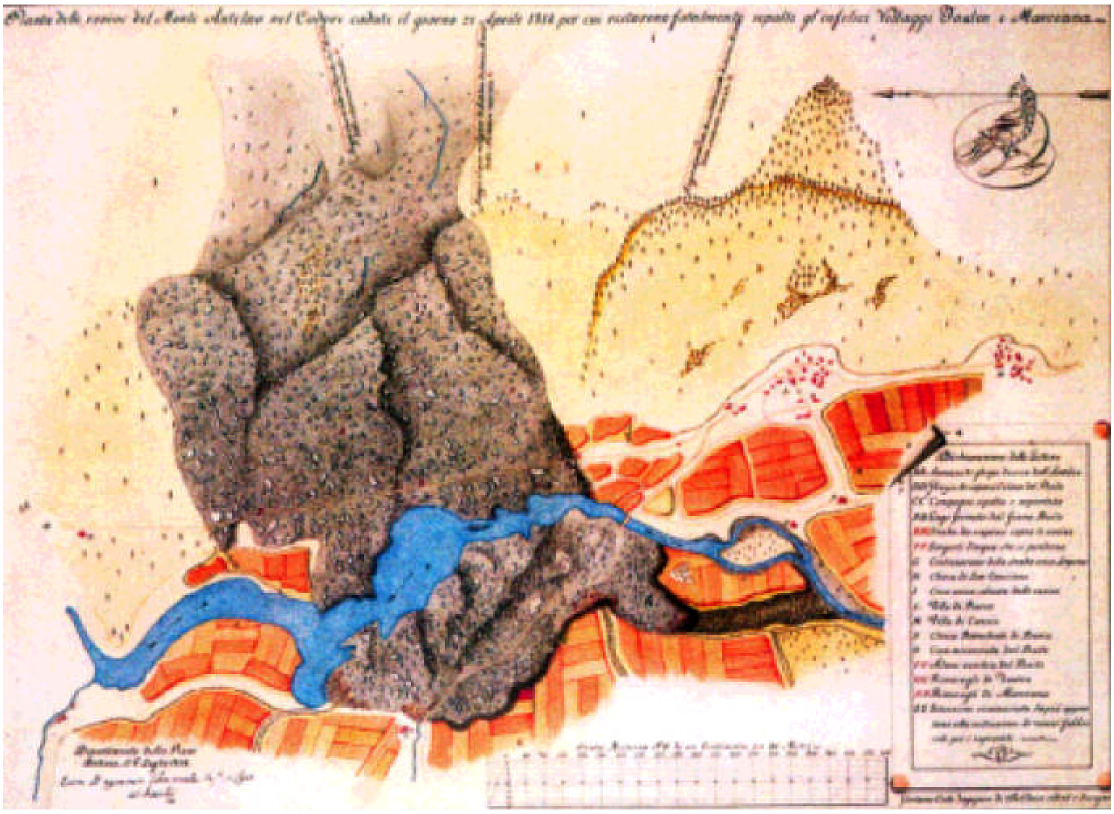


Figure 2 Casting of 21/04/1814: "Map of the ruins of Monte Antelao in Cadore which remained fatally buried (De Nardi, 1988)

In order to maximise the chance of multi-centurial sensitivity of *P. sylvestris* trees to possible drought stress (Fritts, 1976), dendrochronological criteria was adopted to identify the study area. Scots pine trees in Col de la Roa are characterized by their irregular crowns, large branches, with little or absent under-story vegetation

1.3 Meteorological data

The meteorological data used are first those of Cortina d'Ampezzo’s stations (1275 m a.s.l.), which are the closest to the study site (around 10km distance), and the most reliable in terms of long climatic series and continuity over time, i.e. from 1925 to 2002 (Carrer & Urbinati, 2004), then those of the Histalp gridded dataset (Auer, 2007). The average annual precipitation is 1197 mm, recording the maximum in the summer, and an average annual temperature of 6.7 °C, with extremes ranging from -25 to 30 °C. The coldest and warmest months are January and July, respectively, while the growing season extends, usually between April and September (Rossi, 2003).

1.4 Dendrochronological studies of Scots pine (Pinus sylvestris):

Ecological characteristics of tree species, i.e. the ability to survive the prevailing site conditions, are believed to determine their distribution (Weber *et al.*, 2007). However, Meusel *et al.* (1965) noted that Scots pine is known as the most widely distributed conifer, covering the whole Euro-Siberian range, as it is also thought to be the most extensively used species in dendrochronological researches. A dendrochronology database search in 1999 revealed 366 papers involving Scots pine, of which, over a hundred are cited to involve problems in archaeology and around the same number dealing with climate studies (Gymnosperm Database, 2009). Indeed, it is the wide geographical range that has led to so much research with this particular species. Its natural range stretches from the Okhotsk Sea in eastern Siberia to western Scotland, and from north of the Arctic Circle in Scandinavia to southern Spain (Gymnosperm Database 2009).

Scots pine chronologies were correlated with climatic data and used as key targets to help understand frequent climatic changes i.e. summer drought incidences, radial and height increments, ring width in response to spring-summer fluctuating temperature and precipitation and the reconstruction of the past decades or centuries of climatic elements in northern Europe (Schove, 1954; Aniol and Eckistein, 1984; Irvine *et al.*, 1998; Mäkinen, 1998; Helama *et al.*, 2005; Pensa *et al.*, 2005; Tuovinen, 2005). Moreover, the south European Mediterranean Scots pine forests have been recently exposed to stronger summer water stresses caused by the lack of sufficient rainfall and high recorded temperatures (Thabeet *et al.*, 2009).

During the last few decades, Scots pine populations in the inner central European Alpine dry valleys have recorded high mortality (Vertui and Tagliaferro 1998; Rigling *et al.*, 1999; Bigler *et al.*, 2006; Eilmann *et al.*, 2006; Weber *et al.*, 2007). Weber *et al.* (2007) studied the low altitude Scots pine forests in the dry Valais valley, the Swiss Alps, and concluded that '*Pinus sylvestris* may increasingly face problems related to drought stress as it depends on summer moisture and has a smaller adaptive capacity due to its long-lived photosynthetic tissue'. In a similar study within the same valley, Eilmann *et al.* (2006) noted that the tree-ring widths and the number of tracheids in a radial row in Scots pine decreased in response to dry conditions. Furthermore, in pine during the driest year of the period (1976), the mean radial diameter increased in latewood and decreased only slightly in earlywood, concluding that pine may have difficulties to adapt the size of its water-conducting cells to strongly reduced water availability in drought years.

A physiological suggested explanation of Scots pine reaction to drought conditions was proposed by Irvine *et al.* (1998) at a Scottish site. Irvine *et al.* (1998) noted that once volumetric water content reached a max of 12% over the top 20cm of soil, Scots pine transpiration rate declined in a close to linear function of soil water content. The hydraulic resistance between soil and Scots pine needles tripled as the water soil deficit developed (Irvine et al, 1998). Thereafter, needle and shoot growth as well as basal area significantly declined in response to drought conditions, which was recorded as a reduction in the basal area increment the year after the drought, even if the tree could recover in the next growing season, i. e. the next year (Irvine et al, 1998).

However, drought conditions can be also related to the soil dryness and nutrients deficiency, not only to the incline in summer temperature or the decline in precipitation. Oberhuber *et al.* (1998) assessed the impact of ‘climatic factors on radial tree growth (total ring-width and latewood-width) of stunted Scots pine trees (*Pinus sylvestris* L.)’ in eight scattered populations exposed to soil dryness and nutrient deficiency on a dolomite substrate, using dendroclimatological techniques. After response function and cluster analysis were performed, results showed the significant association of wide rings with high, April to June precipitation, and May’s cool conditions of the current year (Oberhuber *et al.*, 1998), as well as the preceding year’s high August to September’s precipitation. Site characteristics main differences were recorded between the studied habitats, i.e. ‘slope magnitude, slope aspect, soil depth and vegetation cover’ (Oberhuber *et al.*, 1998). The study area stands’ reaction to climatic events depends mainly on their ‘susceptibility to soil dryness, which is, in turn, determined by the site’s topography’ (Oberhuber *et al.*, 1998).

Apparently, and after the 1814 Antelao rock avalanche event, Scots pine, which is defined by its drought resistant ability in central Europe (Ellenberg 1988), has managed to survive this south-west-facing slope, which is characterised by its stony, lime rich, slow weathering dolomite substrate. However, high annual precipitation and predominant humidity in the Alps do not play a major role in controlling tree-growth (Oberhuber *et al.*, 1998), except within inner Alpine dry valleys. High altitude forests are known to be highly sensitive to climatic factors changes, as well as being first indicators of climate change. Dry site conditions can be correlated with recorded meteorological data and dendroclimatological techniques, to give a clearer understanding of the overall climatic changes developed within the study area.

1.5 Objective and research questions

Dendroclimatological techniques will be used to assess the impact of climatic factors on radial tree growth (total ring-width) of twenty-five Scots pine trees exposed to soil dryness and nutrient deficiency on an Italian Alpine dolomite landslide at Col de la Roa, San Vito Di Cadore. The research aims to depict drought signals, possible climate-growth correlation and significance response to recent changes in climatic factors, i.e. temperature and precipitation, within the specific site's conditions, which will be studied and discussed in depth.

Chapter 2 : Materials and methods

2.1 Sampling and dendrochronological analysis

Sampling was carried out in Col de la Roa in November 2008, where 25 Scots pine trees were randomly selected, allowing the collection to be biased towards the most climatologically representative trees. The basic and most traditional way of collecting tree-ring samples is to use the increment borers, which has changed a little since its original development in Germany around 1855 (Presseler, 1866; Grissino-Mayer, 2003; Schweingruber, 2001). Two increment cores were extracted with an increment borer from each tree which had to be collected at 50cm from the ground as trees are very short and stunted, on a cross side of the trunk. The diameter at breast height (DBH) and tree heights were measured and recorded for each tree in the study.

Table 1 Characteristics of the study area Col de la Roa

Location	**Eastern Italian Alps**
Altitude	**1200m a.s.l.**
Aspect	**South west**
Soil type	**Rendzic leptosols (dolomite and limestone rock)**
Degree of tree cover	**40%**
Average of DBH	**24.6**
Average tree height	**3.8**

All cores were glued on a wooden stick with careful assigning of the vessels orientation and were left to dry for an over night (Stokes and Smiley, 1968). The surface of the cores was prepared using sand paper prior the start of the ring widths measurements. The ring widths were measured using the ANIOL measuring-device, with 0.01mm precision using the CATRAS-software (Aniol 1983). Measurements of the different cores were cross-dated using the dendrochronological program CATRAS (Holmes, 1994). However, in order to assess the quality and accuracy of the tree-ring series measurements and cross-dating, COFECHA program had to be used (Holmes *et al.*, 1986). Thirty one cores were then elected out of the 50 and the samples had 75 – 184 rings with the mean of 130 rings.

2.2 Standardization

The annual radial growth would biologically decline with age within the open canopy environments, and so this declining trend has to be removed before the final use of the tree-ring chronologies in order to study past climate variations (Cook and Petters, 1981). Climate signals maximization is indeed a crucial step that follows tree-ring measurements to minimize other factors' effects (Lopatin *et al.*, 2007). To extract the climatic signal from the non-climatic variance (age trends, exogenous disturbances... etc) in the ring-width measurement series, they were detrended (standardized) by using the ARSTAN program (Holmes *et al.*, 1986; Holmes 1994; Grissino-Mayeer *et al.*, 1996). By using a spline curve as the output of standardization, the represented data values depart from the expected value for a given year (Lopatin *et al.*, 2007), which is then 'used to interpret a proxy environmental signal in the data' (Lopatin *et al.*, 2007). Therefore, the obtained tree-width indices are supposed to reflect only the environmental factors.

2.3 Climate-growth relationship analysis

Tree-ring chronologies were calibrated against instrumental climate records (precipitation and temperature) using the DENDROCLIM2002 software, which 'uses bootstrapped confidence intervals to estimate the significance of both correlation and response function coefficients' (Biondi and Waikul, 2004). Input files used to run this program where basically the standardized chronologies, the precipitation and temperature row data, recorded for the last 158 years, saved in txt format. Afterwards, these files where selected and analyzed by this user-friendly program. Final results were saved in ASCII format, and were plotted on screen in color-coded symbols (Biondi and Waikul, 2004) Standard correlation function (CF) analysis was used afterwards to assess climate–growth relationships (Fritts, 1976). A fifty year interval was adopted, that slid progressively across time, to obtain the moving correlation coefficients (Biondi, 1997, 2000), all of which was also achieved by using the DENDROCLIM2002 software (Biondi and Waikul, 2004).

Chapter 3 : Results

3.1 Chronological analysis

Thirty-one chronologies were adapted in the results, selected on the basis of quality and in being least problematic from the 25 duplicated core samples of Scots pine collected and measured in this study. The selected Scots pine trees' characteristics are represented in Table 2. In contrast to the growth potential of Scots pine at favourable sites where the maximum tree height can reach up to 40 metres, the growth-limiting factors within this study site were both observed and represented by an average tree height of 3.93m and an average DBH of 27.45cm (Table 2).

Table 2 Selected *Pinus sylvestris* trees numbers, heights and DBH measurements and chronologies codes

Tree Number	***Height (m)***	***DBH (cm)***	***Core number***	**Number of years**
1	3.5	20	RAO PS 01L	144
1	3.5	20	RAO PS 01R	132
3	4	25	RAO PS 03L	120
3	4	25	RAO PS 03R	121
4	5	32	RAP PS 04L	115
4	5	32	RAO PS 04R	132
6	4	20	RAO PS 06L	167
6	4	20	RAO PS 06R	143
7	2.2	20	RAO PS 07L	153
7	2.2	20	RAO PS 07R	152
8	4.8	26	RAO PS 08L	151
8	4.8	26	RAO PS 08R	131
10	3	26	RAO PS 10R	117
11	3.4	21	RAO PS 11R	162
13	2	22.5	RAO PS 13L	169
13	2	22.5	RAO PS 13R	168
17	5.5	35	RAO PS 17L	165
17	5.5	35	RAO PS 17R	159
19	6	35	RAO PS 19R	159
20	4.6	34	RAO PS 20L	160
20	4.6	34	RAO PS 20R	162
21	2.8	25	RAO PS 21L	171
21	2.8	25	RAO PS 21R	196
22	3.3	23	RAO PS 22L	177
22	3.3	23	RAO PS 22R	162
23	4	26	RAO PS 23L	152
23	4	26	RAO PS 23R	183
24	5	45	RAO PS 24L	103
24	5	45	RAO PS 24R	129
25	4	31	RAO PS 25L	169
25	4	31	RAO PS 25R	169

Scots pine chronologies showed a typical coniferous age-related exponential decrease in total ring-width (Figure 3). Narrow ring-widths (mean total ring-widths range from 0.38 mm to 0.89 mm) are more noticeable during the last fifty years of the represented chronological period (1850-2008). Although the thirty one chronologies selected were dated to 1825, for accuracy purposes, the actual plotted period starts from 1850, in order to guarantee at least six chronologies included in the total averaged curve. Scots pine chronologies recorded a maximum age of 183 and a minimum of 103.

However, this can also be an indication of stressful environmental and soil conditions. Raw tree ring-width measurements were detrended to extract the climatic signal from the non-climatic variance (age trends, exogenous disturbances... etc) (Holmes et al., 1986, Holmes 1994, Grissino-Mayeer et al., 1996), which are depicted in Figure 3.

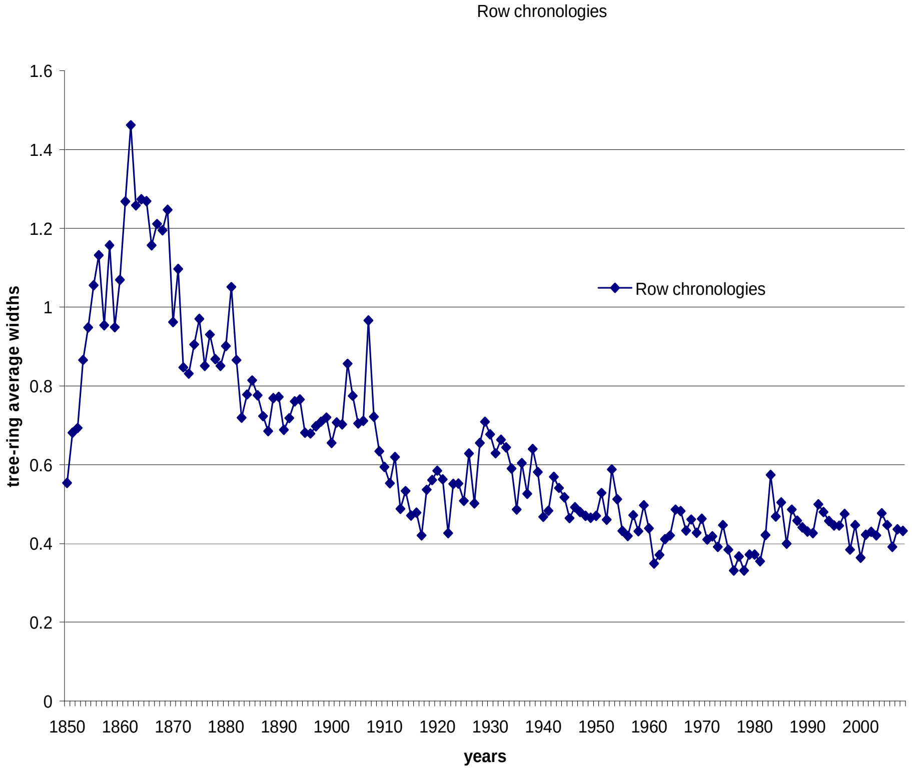


Figure 3 Col de la Roa thirty one *P. sylvestris* row averaged chronologies.

Whilst tree rings are integrated records of the influence of environmental conditions, their anatomical characteristics record growth rate changes produced by these changing conditions (Vaganov *et al.*, 2006). Following the standardization process, detrended Scots pine chronologies showed relatively average variations in tree-rings for the study period (1850-2008). However, some significant wide and narrow ring-widths were identified, especially in the year 1907, and 1922. Seasonal dynamics of temperature and precipitation through the years are believed to be the major external factors to integrate with the anatomical growth characteristics, in other words, early and late wood formation (Vaganov *et al.*, 2006). Nevertheless, the assumption of failure of cambial activity to develop normal, wide rings, in extraordinarily dry years, was shown after the year 1921 (Figures 3 and 4) (Weber *et al.*, 2007). However, the expected growth response to the extraordinary dry hot summer in the year 2003 (Oberhuber *et al.*, 2008) was surprisingly absent.

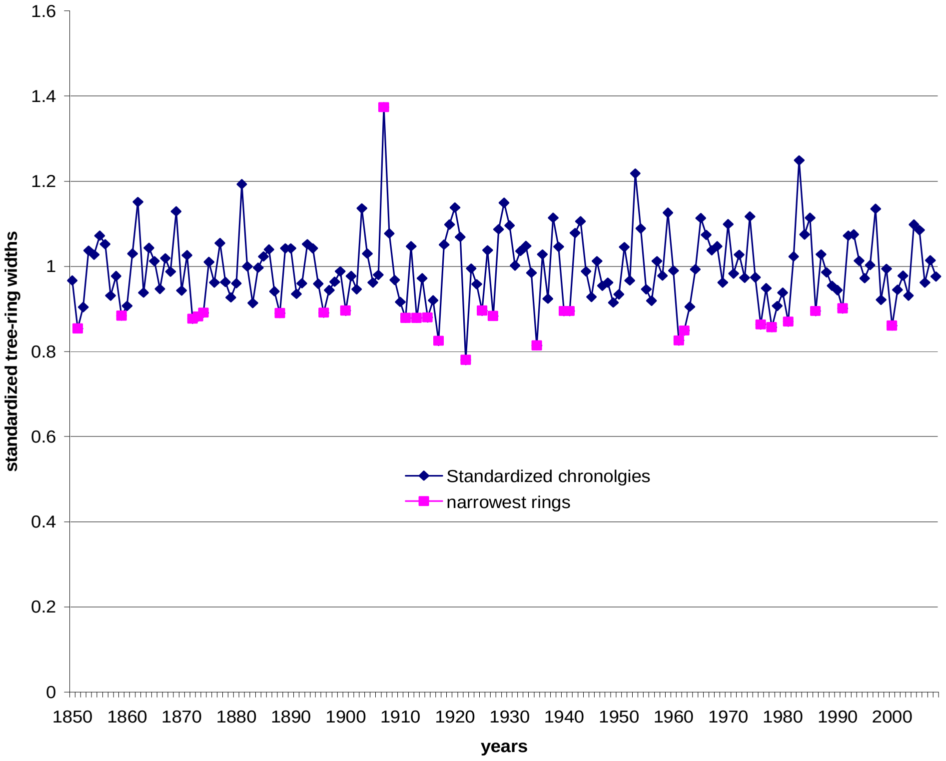


Figure 4 Col de la Roa transformed measured tree ring-width values to ring-width indices (standardized chronologies). The narrowest indices were also depicted.

3.2 Climate data

A recent warming trend was recorded in the Alps after the 1820s (Büntgen *et al.*, 2005; Oberhuber *et al.*, 2008) and particularly in the second half of the twentieth century, which is represented by the meteorological data obtained from Histalp gridded dataset (Auer, 2007) plotted in Figure 5. It is worth pointing out the significant increase in the average temperature values recently, precisely in the year 2003 (mentioned above).

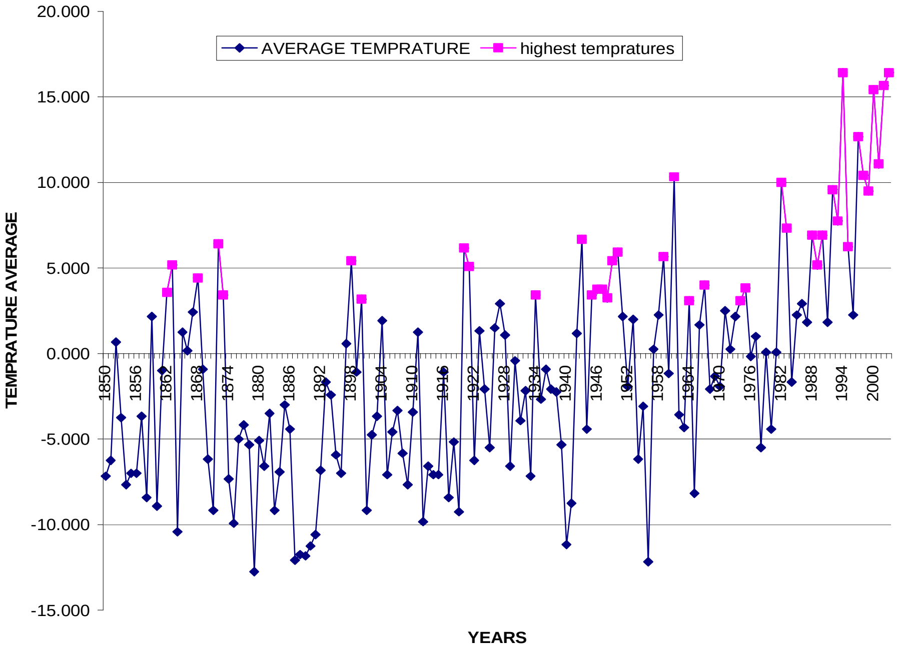


Figure 5 Meteorological temperature data (expressed as anomalies respect the 1900 – 1999) and taken from Histalp gridded dataset (Auer, 2007) and covering the period AD 1850 – 2003.

Even though the overall trend within the study period is showing an increase, a further understanding of the specific pattern of change on a monthly basis is required (Figure 6). Temporal changes in variability are more observed on average in autumn and winter months as would be expected in an Alpine complex mountain region, and indeed less recorded within the spring-summer time, i.e. April to August. However, the summer meteorological depicted temperature data (May-August) matches the overall temperature increasing trend (Figure 5), which is significantly recorded in the last few decades.

Some studies have already shown that a 0.5 °C deviation in the mean April-May temperature caused a significant shift in the initiation of cambial activity in coniferous species, especially in boreal and temperate regions (Vaganov *et al.*, 2006). Notably, May temperature data seems to show a significant increase throughout the last few decades (Figure 6), to suggest that a possible shift in the starting date of cambial activity may have already taken place, and thus led to changes at the start of the growing season for Scots pine trees in the study area.

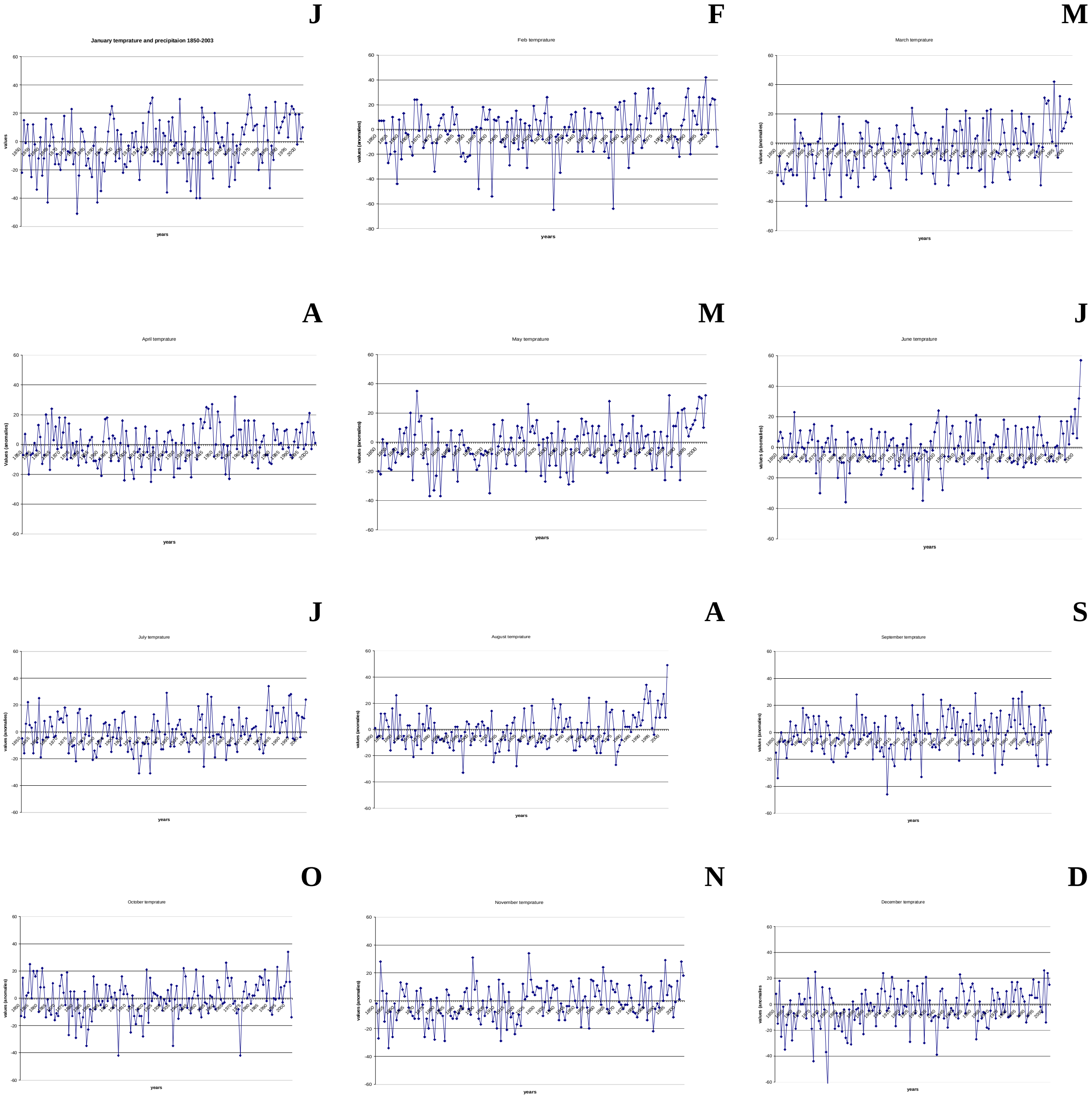


Figure 6 Meteorological monthly temperature data (expressed as anomalies respect the 1900 – 1999) and taken from Histalp gridded dataset (Auer, 2007) and covering the period AD 1850 – 2003.

As for precipitation, the general trend of the period studied shows a temporal stability with some extreme events ranging from very humid to very dry years (Figure 7). As explained above, Scots pine chronologies revealed the negative effect of the year 1921, which can be clearly depicted in Figure 4. Furthermore, precipitation meteorological data reflects the well-known higher variability of rain (and snow) distribution in this complex mountain regions; the variable frequency of September–March precipitation (Figure 8). In general, precipitation is not considered a major limiting factor of tree-growth in the Alps because of the prevailing humid conditions (Tranquillini 1979; Oberhuber, 1998). However, the growing season precipitation starting from May–August, is more crucial for tree growth, and has been reported as being significantly associated with wide rings formation (Oberhuber, 1998). In fact, Scots pine chronologies (Figure 3) reveal a similar case from the widest ring (1.774mm) in the year 1907, being formed following three years of a high average precipitation of 1315.5mm. Moreover, precipitation data shows a lower variable frequency and higher precipitation values for the growing season, significantly in June (Figure 8).

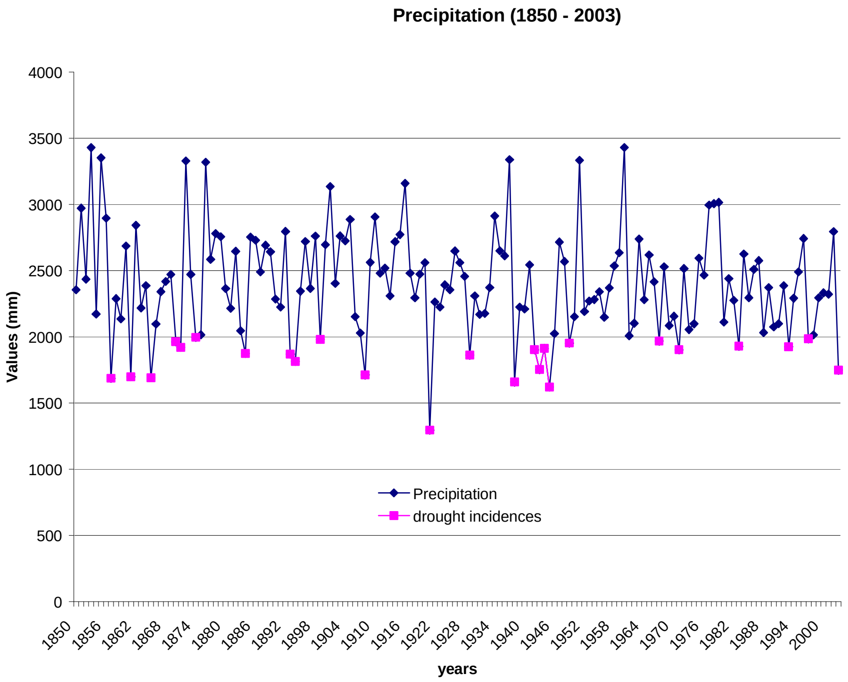


Figure 7 Meteorological precipitation data taken from Histalp gridded dataset (Auer, 2007) and covering the period AD 1850 – 2003.

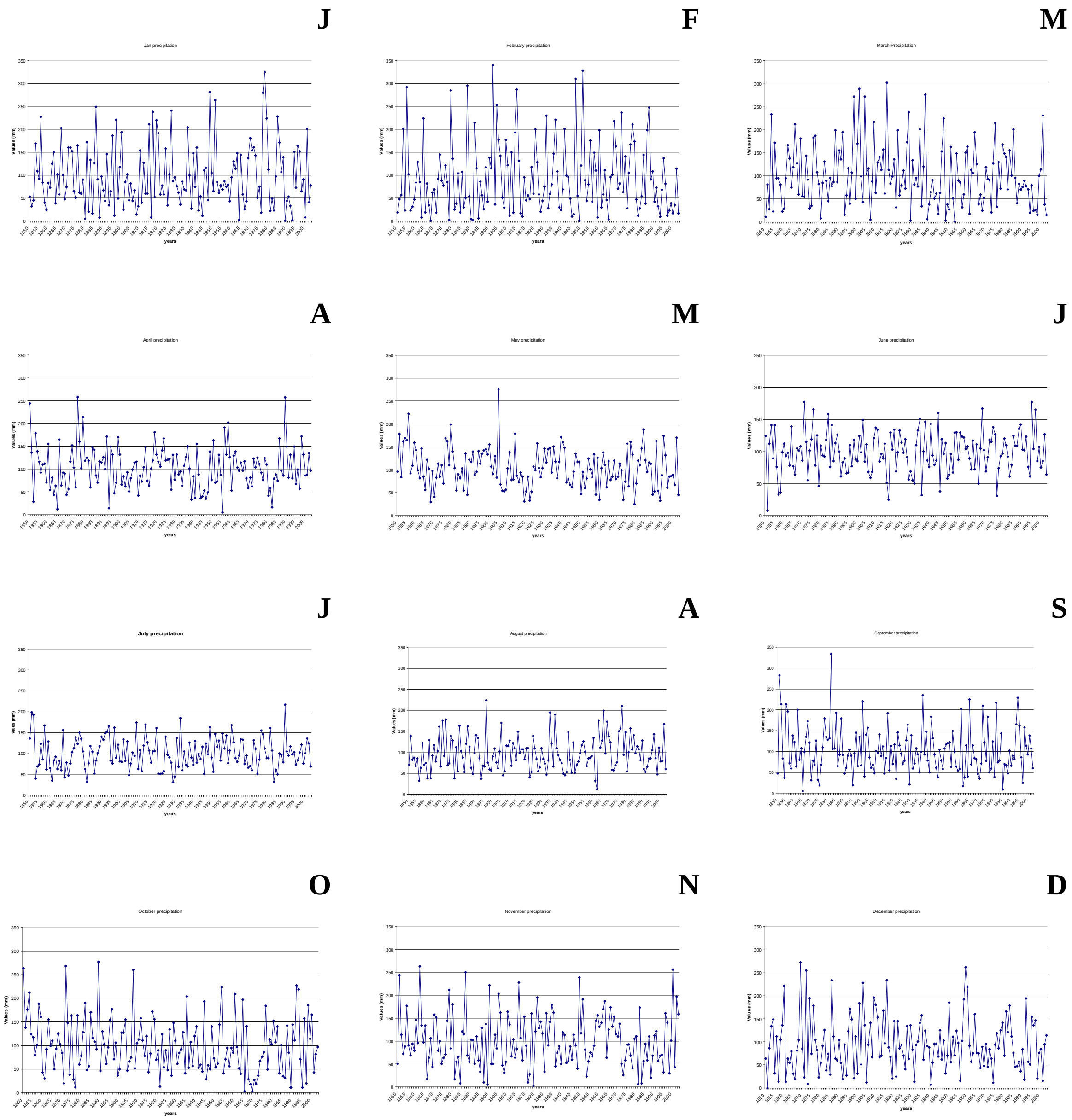


Figure 8 Meteorological monthly plotted precipitation data taken from Histalp gridded dataset (Auer, 2007) and covering the period AD 1850 – 2003.

3.3 Climate influence on tree growth

The year-by-year climate–growth responses of Scots pine were identified and assessed in applying the correlation function analysis (CF) (Figure 9). The CF analysis reveals a maximum response to May–August of both prior and current years, which is to be expected in such an Alpine climate, in which the growing season is controlled by the summer season temperature growth-triggering effect (Oberhuber, 1998; Carrer *et al.*, 2007). It was also possible to identify a positive response to May-August temperatures of prior year and June's precipitation of the current year, and a negative reaction to precipitation of May-August prior year and June's temperature of the current year. Of all monthly variables considered, the analysis indicates that ring-width at Col de la Roa study site is significantly affected (P > O.O5) by July conditions in the previous and preceding year (Figure 9). In other words, it reacts positively to its high temperature of the prior year (0.173), and negatively to its current year's high precipitation (-0.1992) (Figure 9).

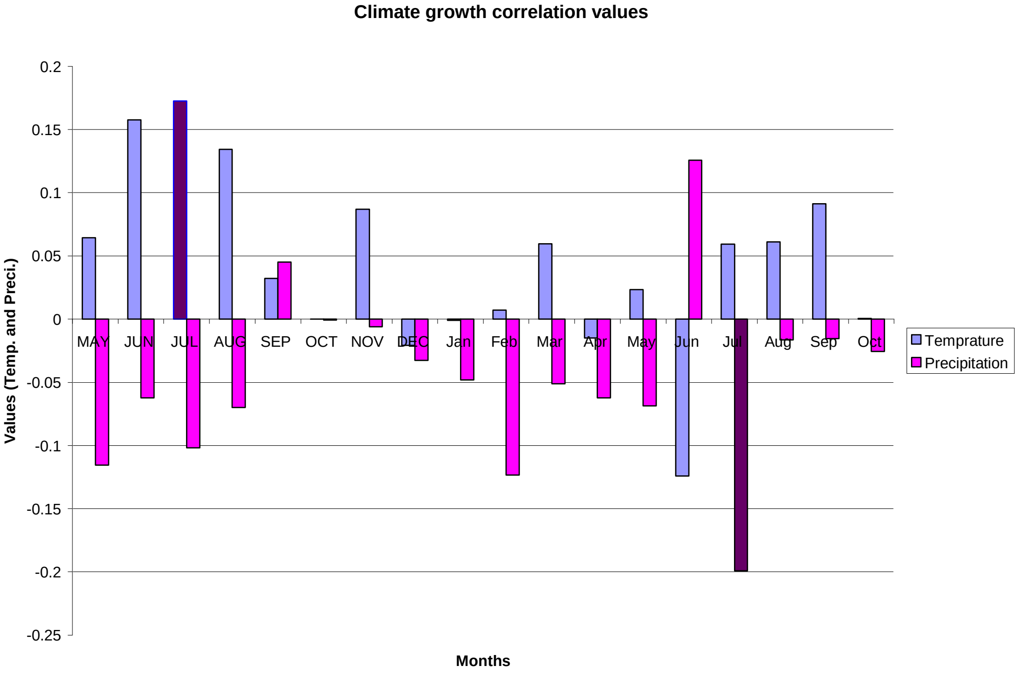


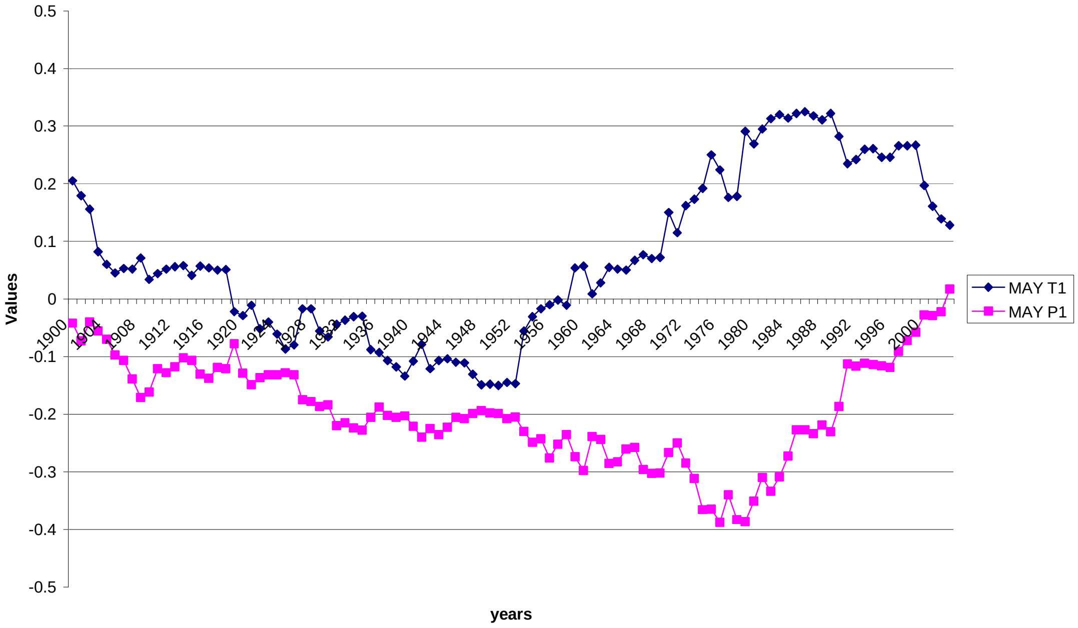
Figure 9 Monthly (May of the prior year to October of the current year) temperature and precipitation effect on tree-ring growth of Scots pine (*Pinus sylvestris)* during the period 1850–2003, using correlation function. The significant values of July temperature and precipitation of the previous and the current year correlation, respectively, are highlighted.

Allowing for a wider understanding of the dynamic growth features and further reliable long-term growth response testing, moving correlation coefficient (MCF) analysis was performed. In general, MCF monthly precipitation and temperature patterns (Figures 10, 11 and 12) of both prior and current years confirm the results obtained with the above CF test (Figure 9). None of the plotted graphs show a flat response to climatic conditions, even within winter dormancy season, where no cambial activity can be reported, simply because trees react in different ways to temporal changes in the surrounding environmental conditions (Figures 10 and 11). However, a higher response can be noticed within the growing season of May-August the prior year, and June-August the current preceding year (Figures 10 and 12).

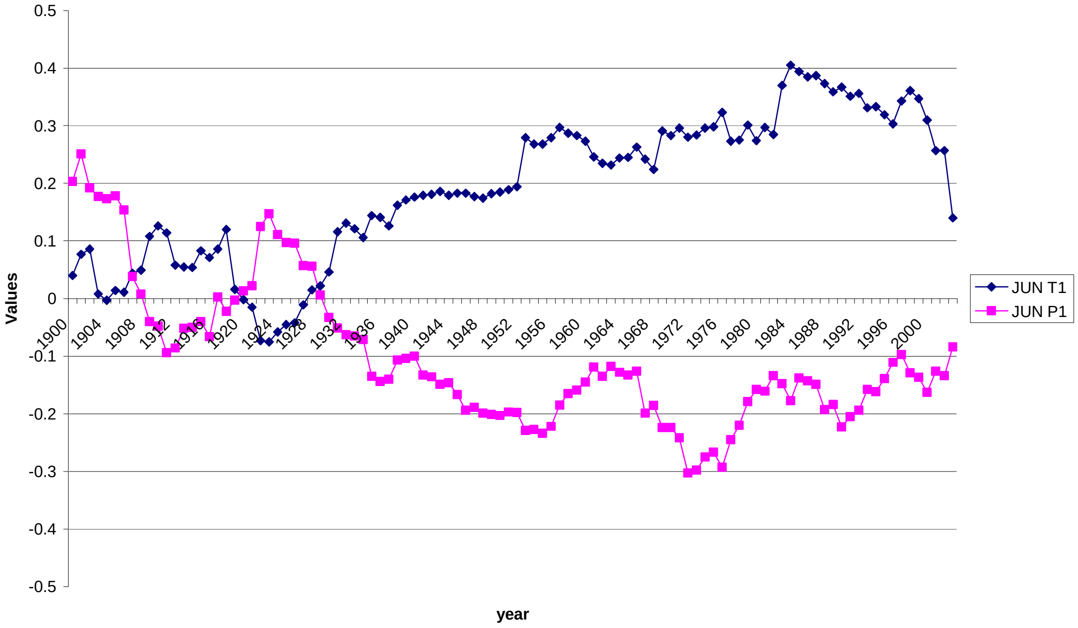
Furthermore, MCF reconfirms the significance of July’s temperature and precipitation on Scots pine ring-width and growth within the site, which surprisingly assures the negative response to its high precipitation in the current year, and the positive correlation with its previous year’s high temperature (Figures 10 and 12). It is worth noting that the MCF correlation also showed the wide temporal change in the climate-growth relationship, especially in the last century, which can be clearly noticed in May-August the prior and preceding years (Figures 10 and 12).

The other interesting result obtained from the MCF test is that Scots pine chronologies showed a positive correlation of the previous year’s May-August high temperatures, but at the same time reacted slightly negative to their precipitation of the same year. On the other hand, the response was slightly positive to the preceding year’s June precipitation, though it reacted negatively to its temperature of the same year (Figure 12).

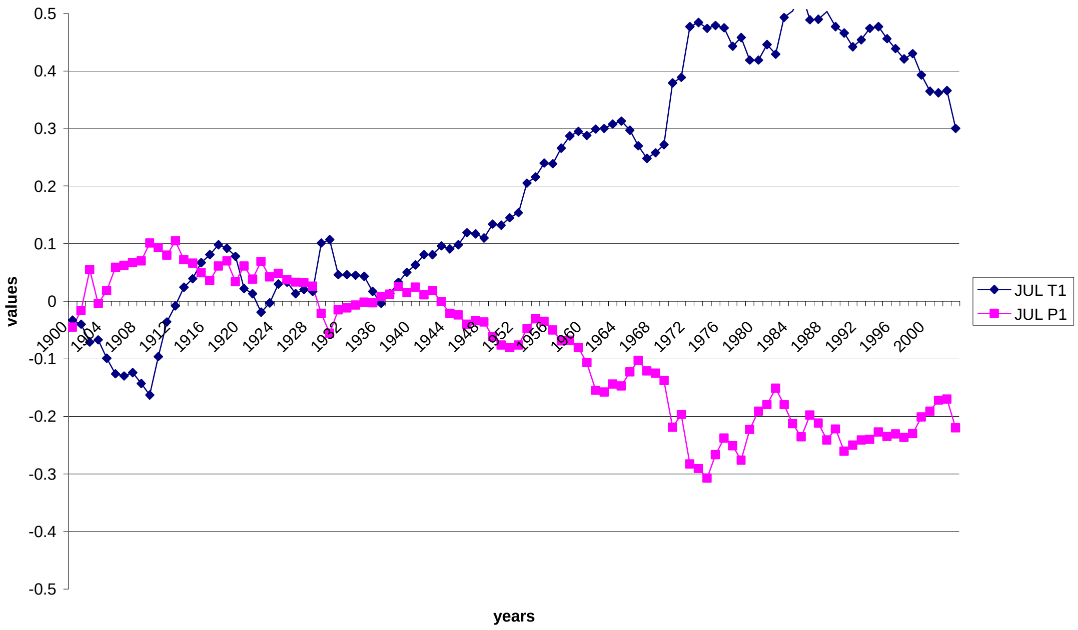
May moving correlation function of the previous year
figure 10 A



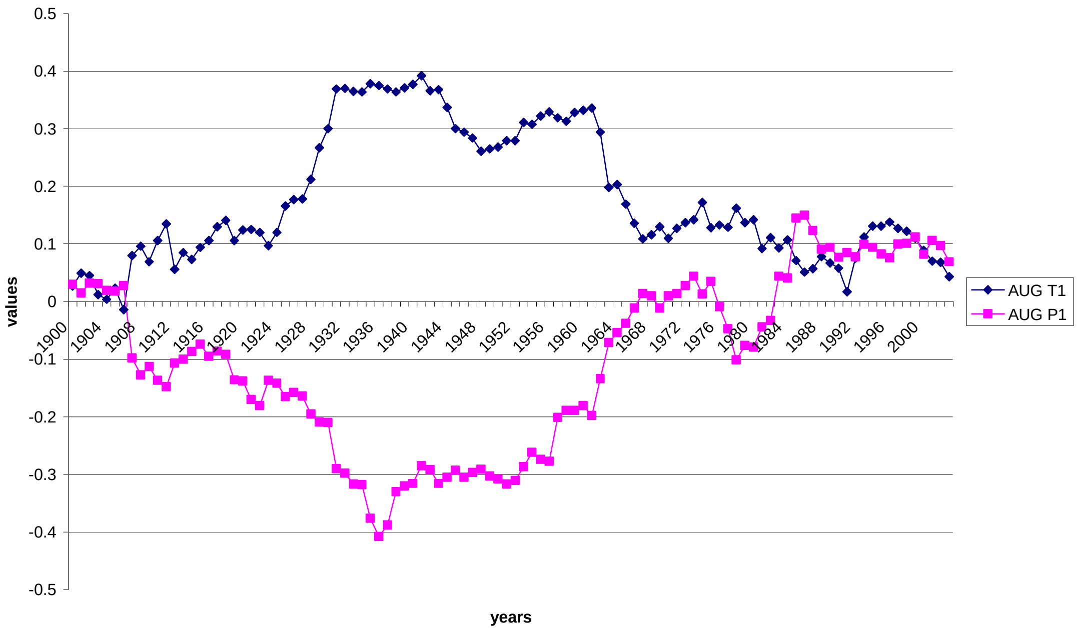
June moving correlation function of the previous year
figure 10 B

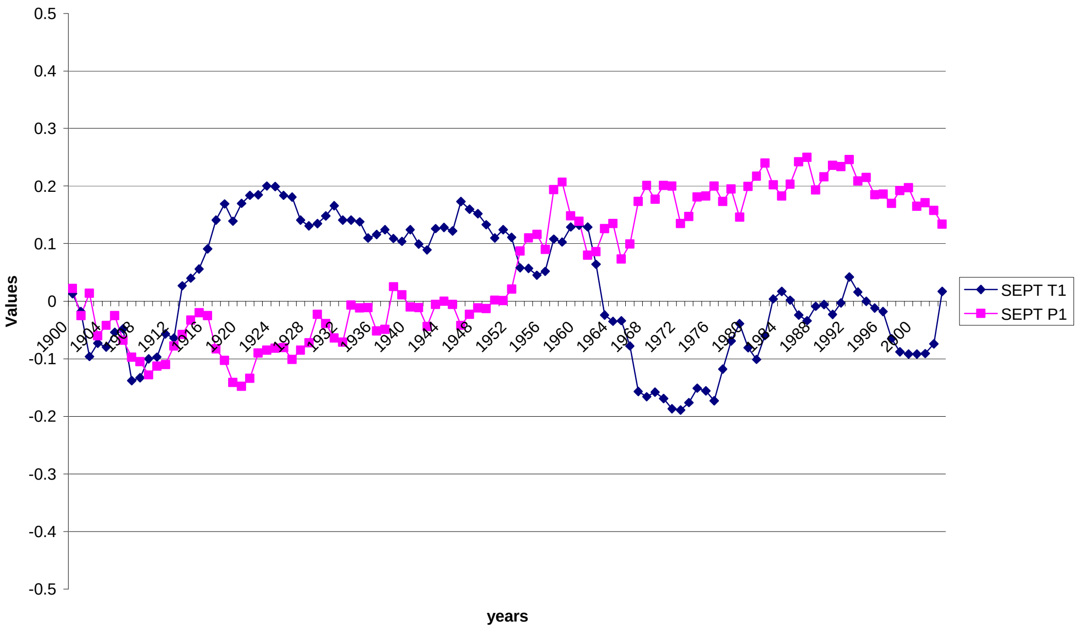


July moving correlation function of the previous year
figure 10 C

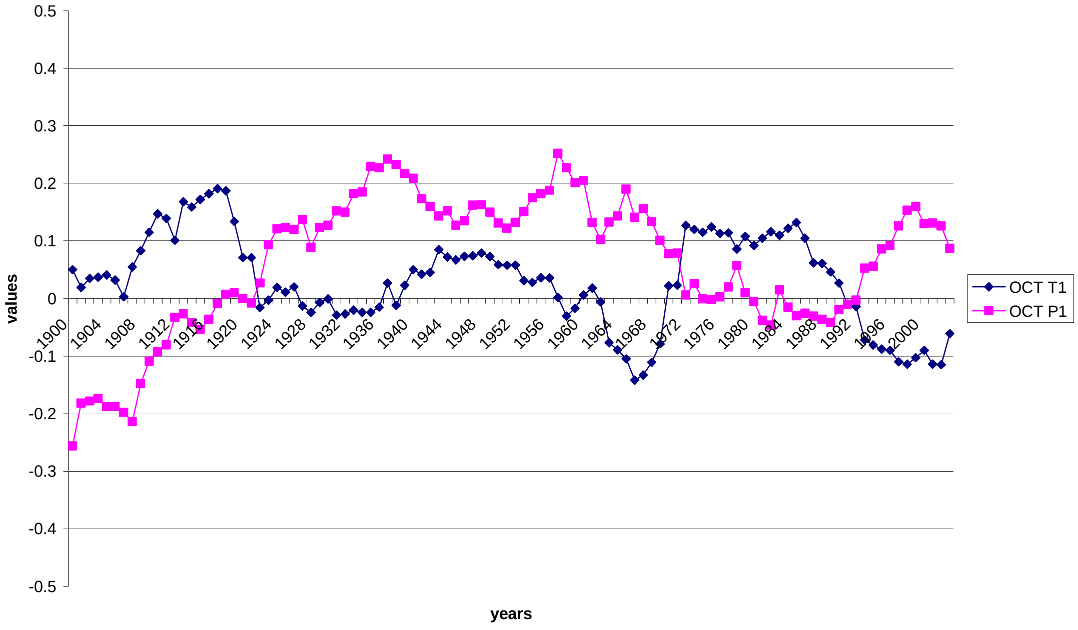


August moving correlation of previous year
figure 10 D





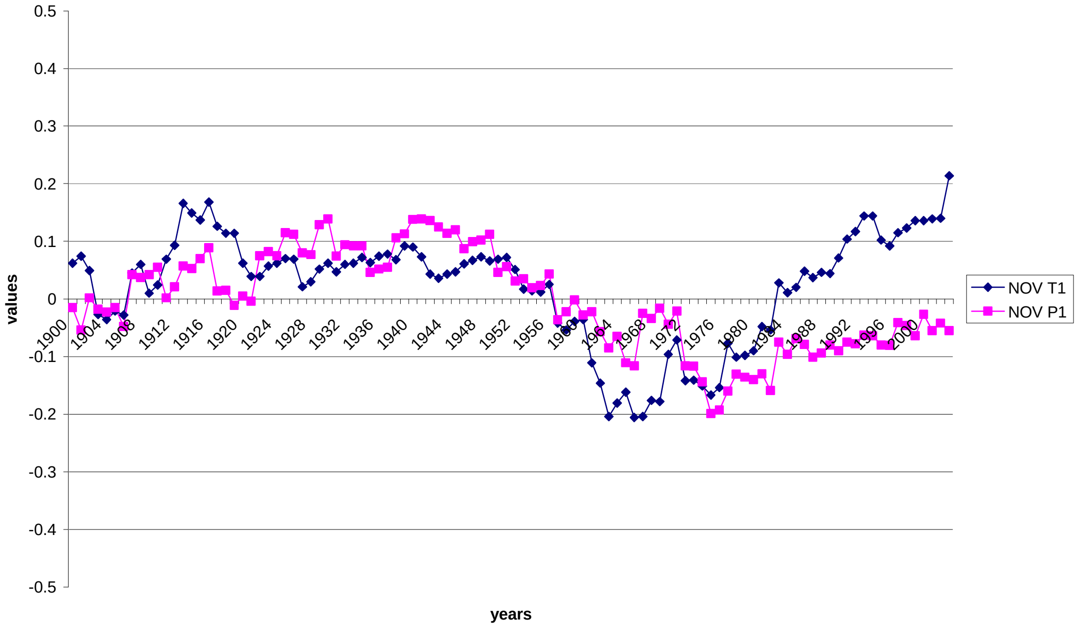
September moving correlation function of previous year
figure 10 E



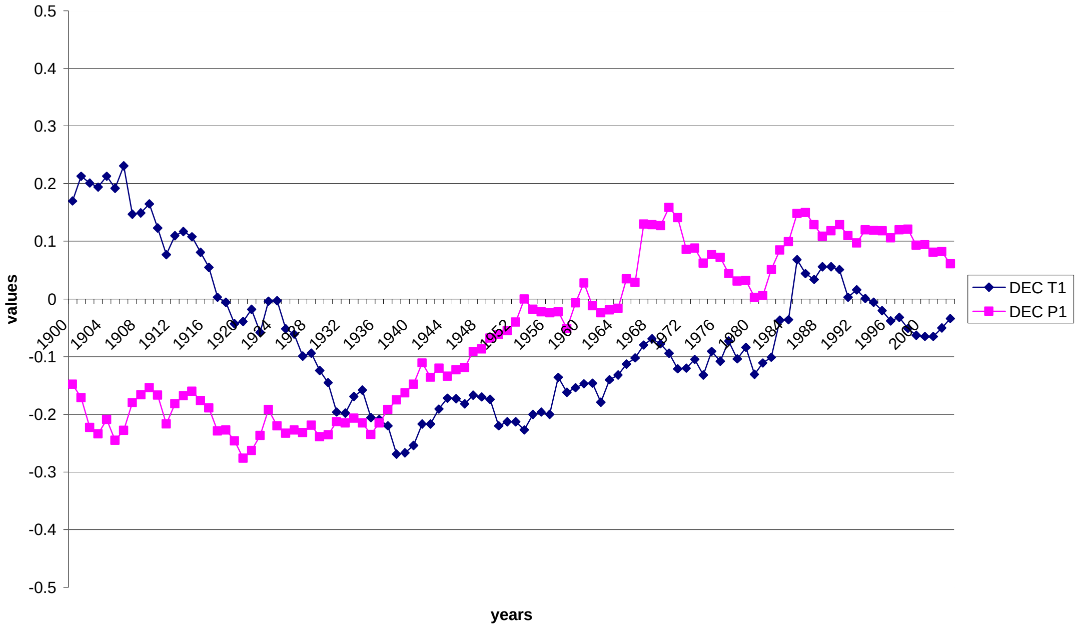
October moving correlation function of previous year
figure 10 F

Figure 10 (A-F) May-October (previous year) temperature and precipitation effect on tree-ring growth during the period 1850–2003, using moving correlation function with a 50-year time window.

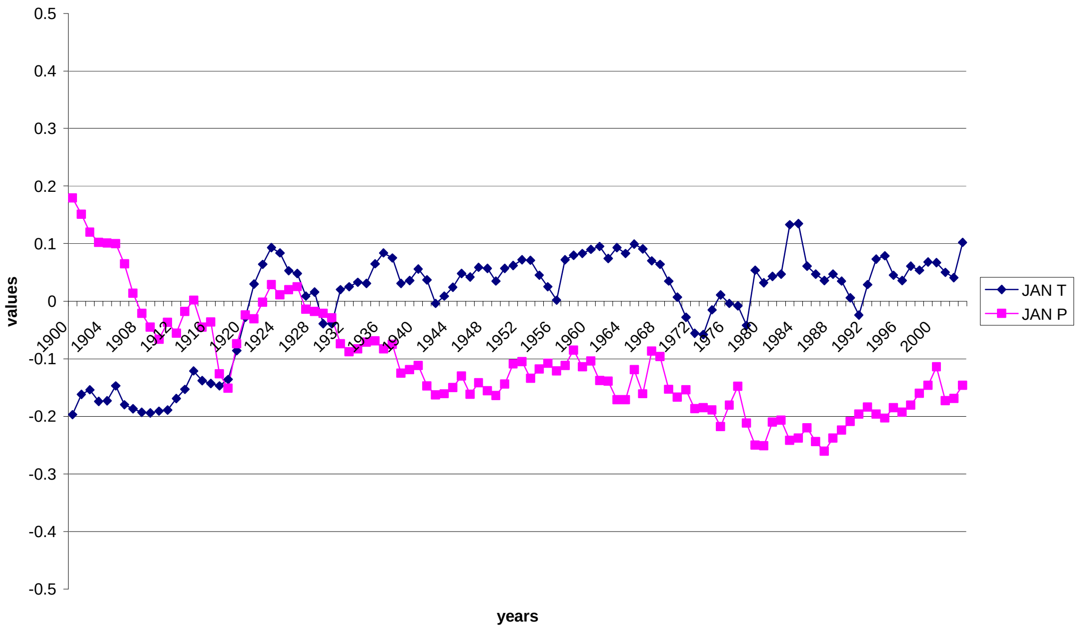
November moving correlation function of previous year
figure 11 A



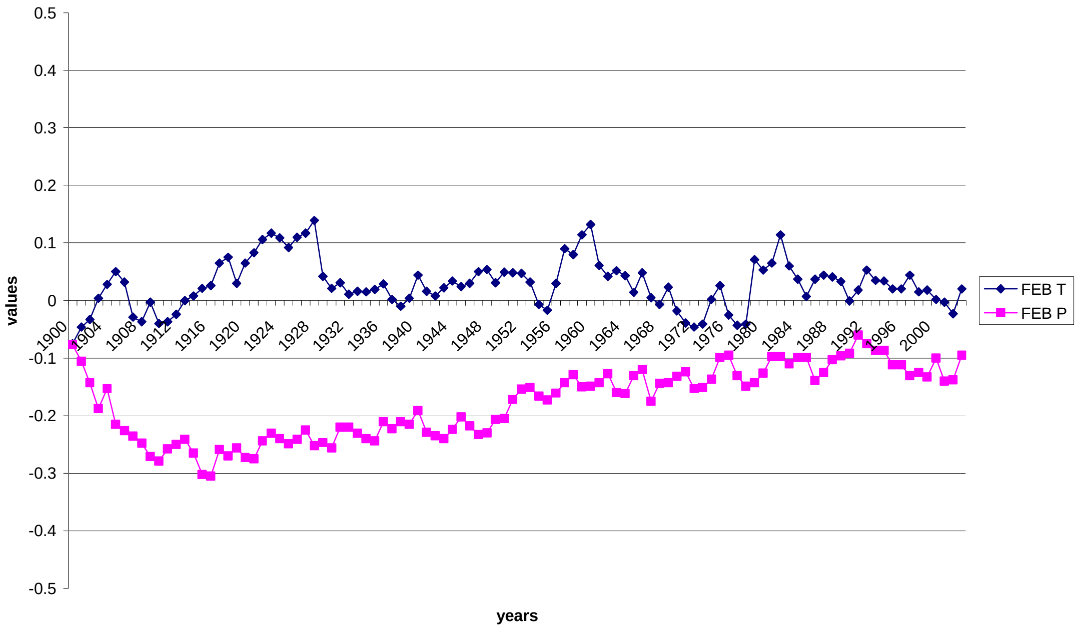
December moving correlation function of previous year
figure 11 B

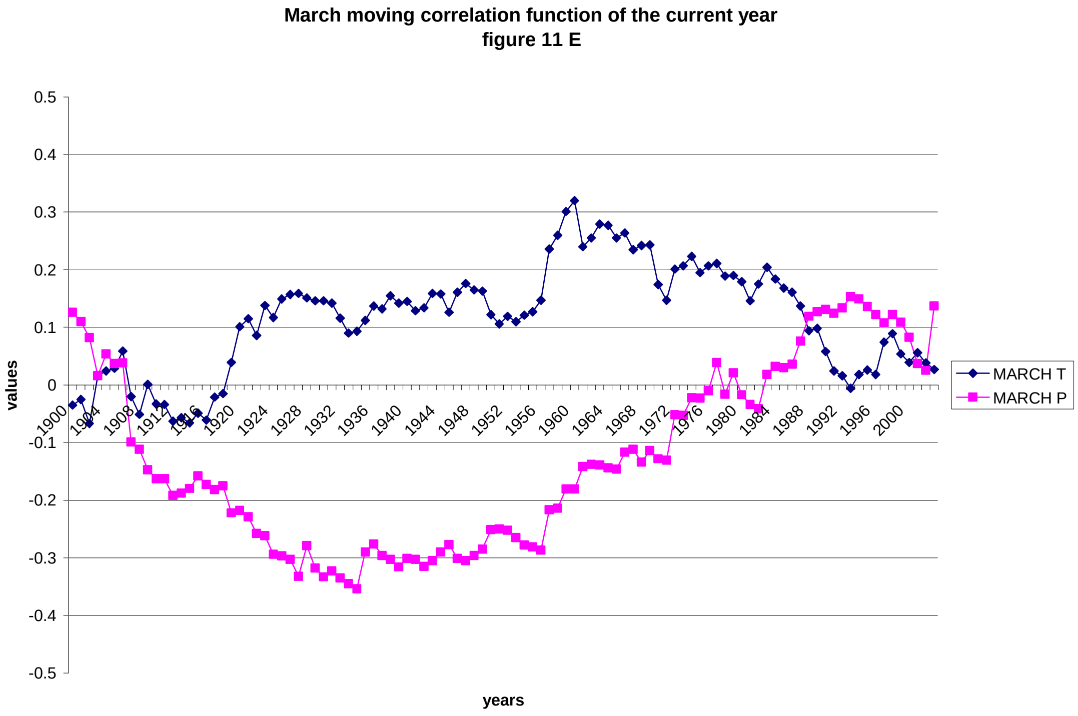


January moving correlation function of the current year
figure 11 C



February moving correlation function of the current year
figure 11 D




March moving correlation function of the current year
figure 11 E

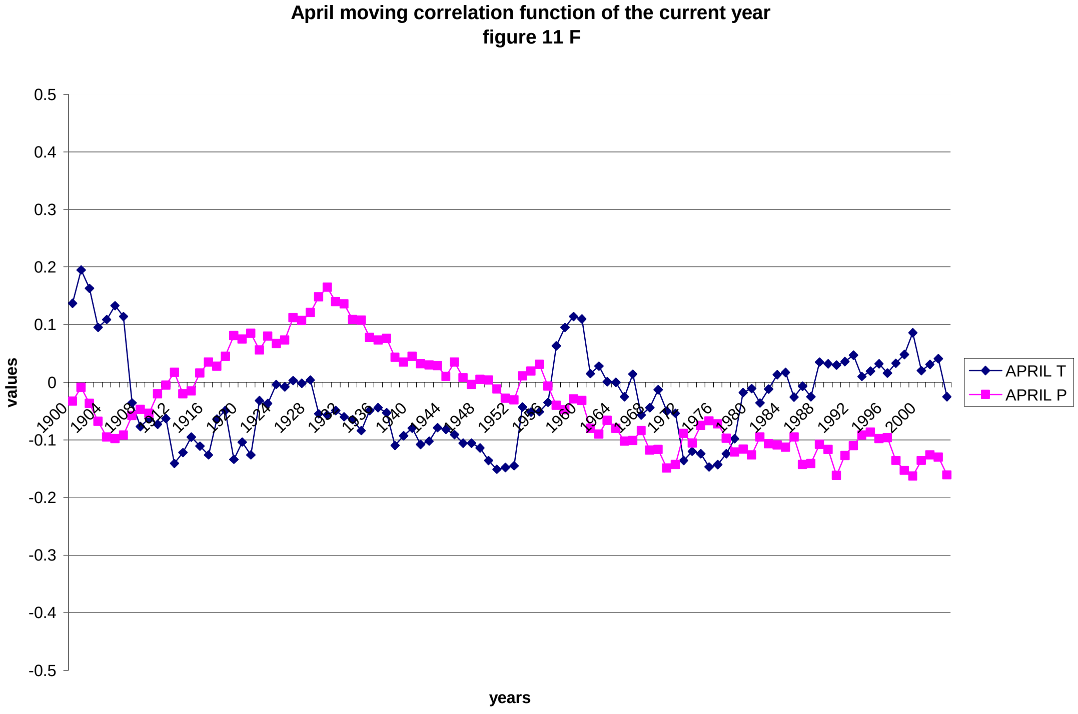
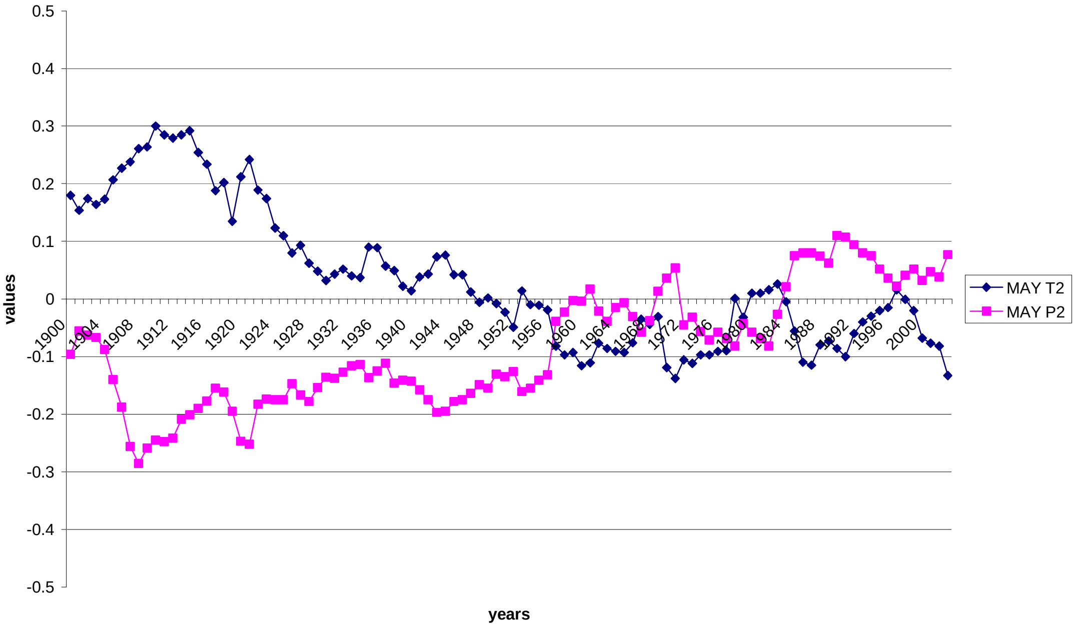
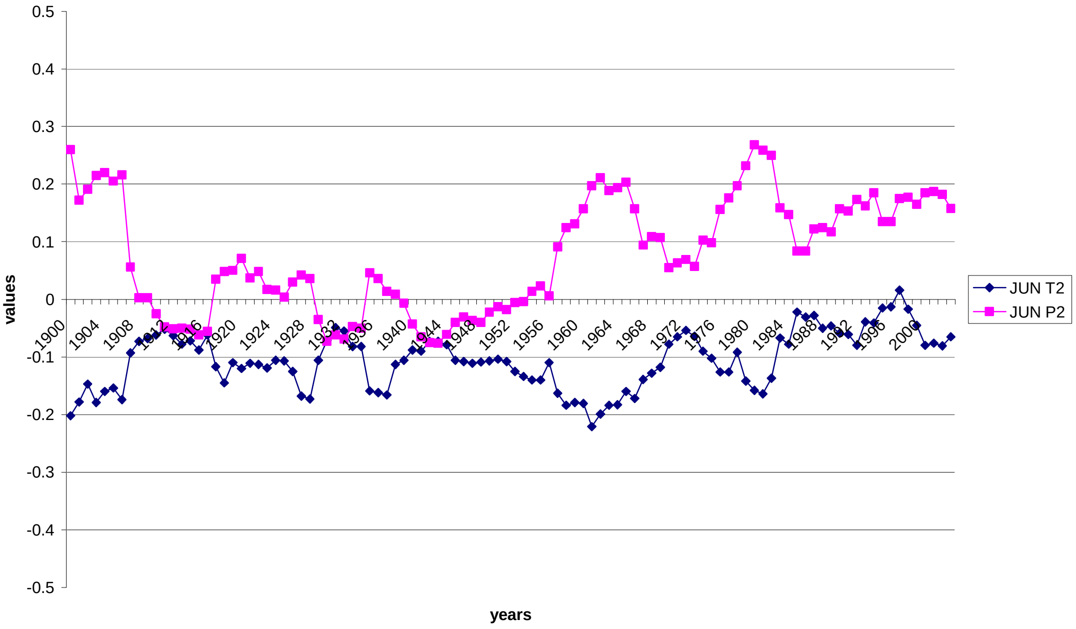

April moving correlation function of the current year
figure 11 F

Figure 11 (A – F) November-April (previous and current year) temperature and precipitation effect on tree-ring growth during the period 1850–2003, using moving correlation function with a 50-year time window

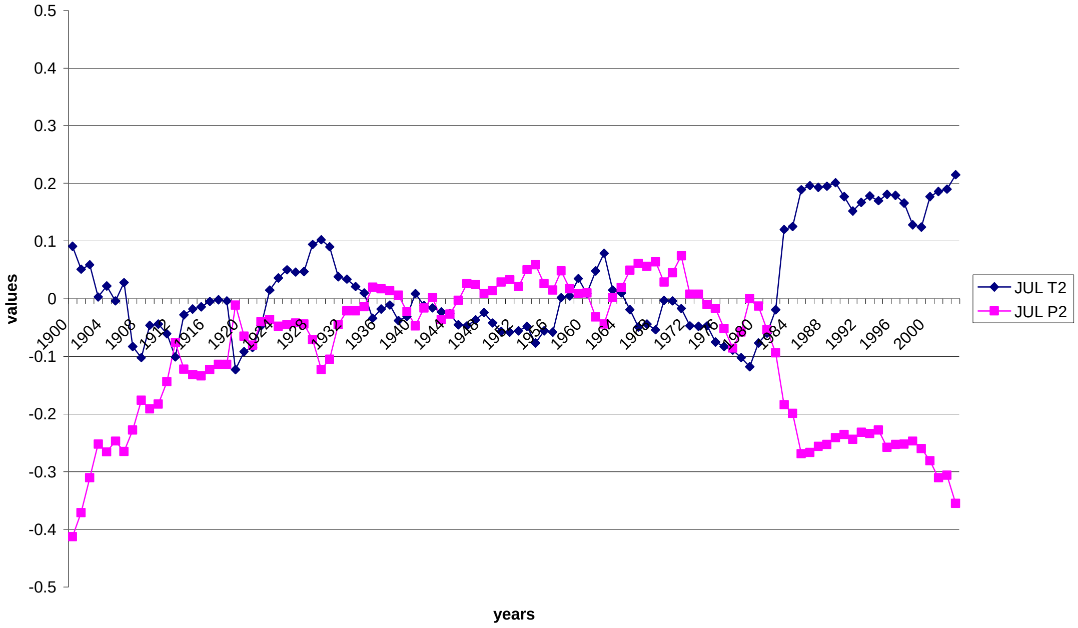
May moving correlation function of the current year
figure 12 A



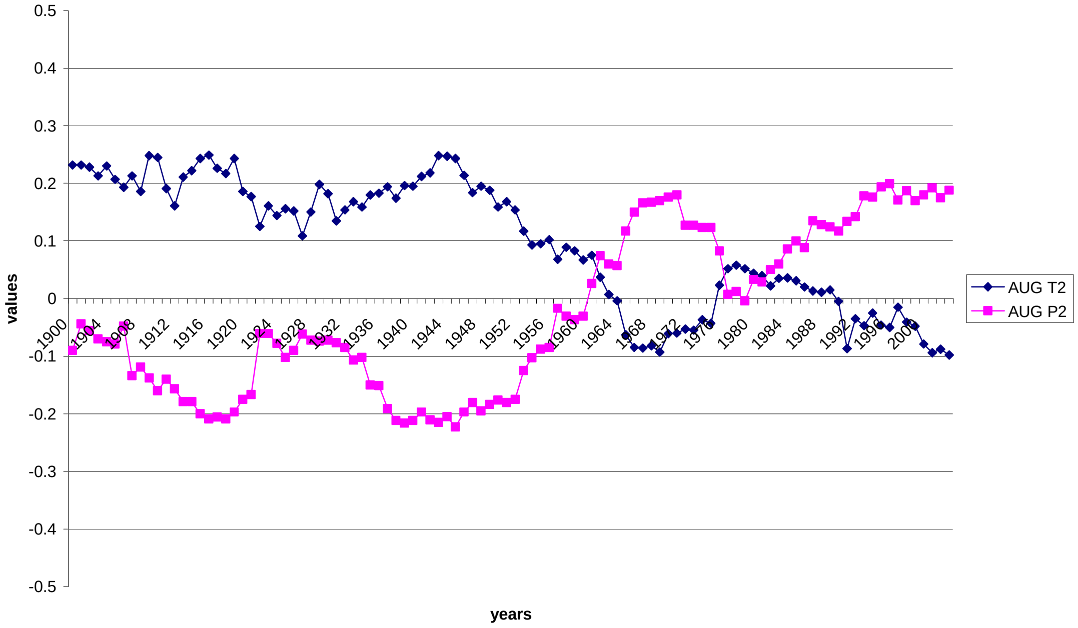
June moving correlation function of the current year
figure 12 B



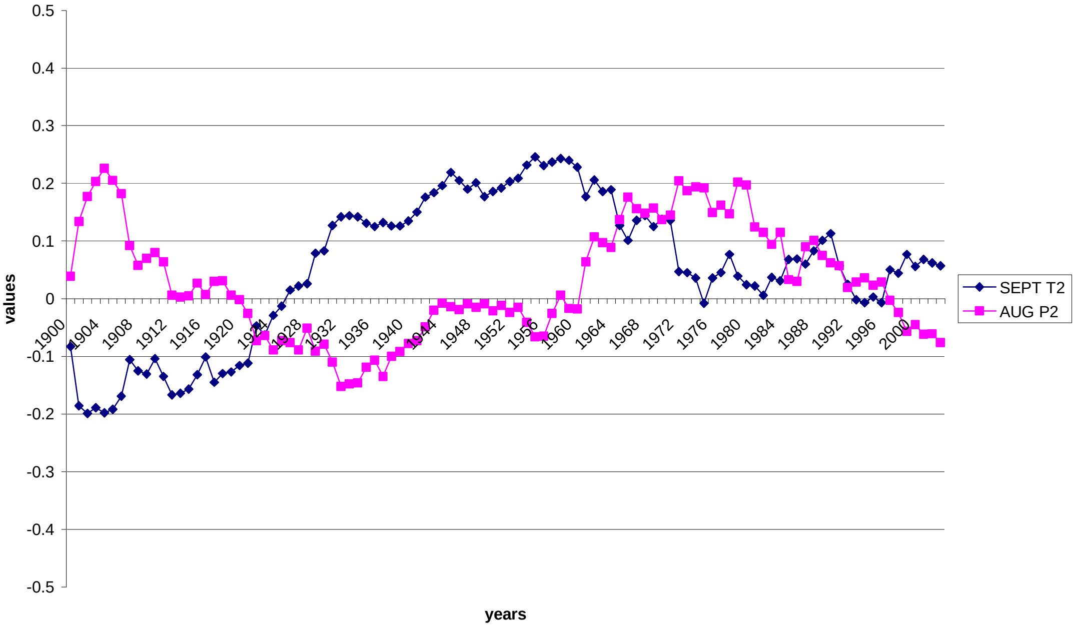
July moving correlation function of the current year
figure 12 C



August moving correlation function of the current year
figure 12 D



September moving correlation function of the current year
figure 12 E



October moving correlation function of the current year
figure 12 F

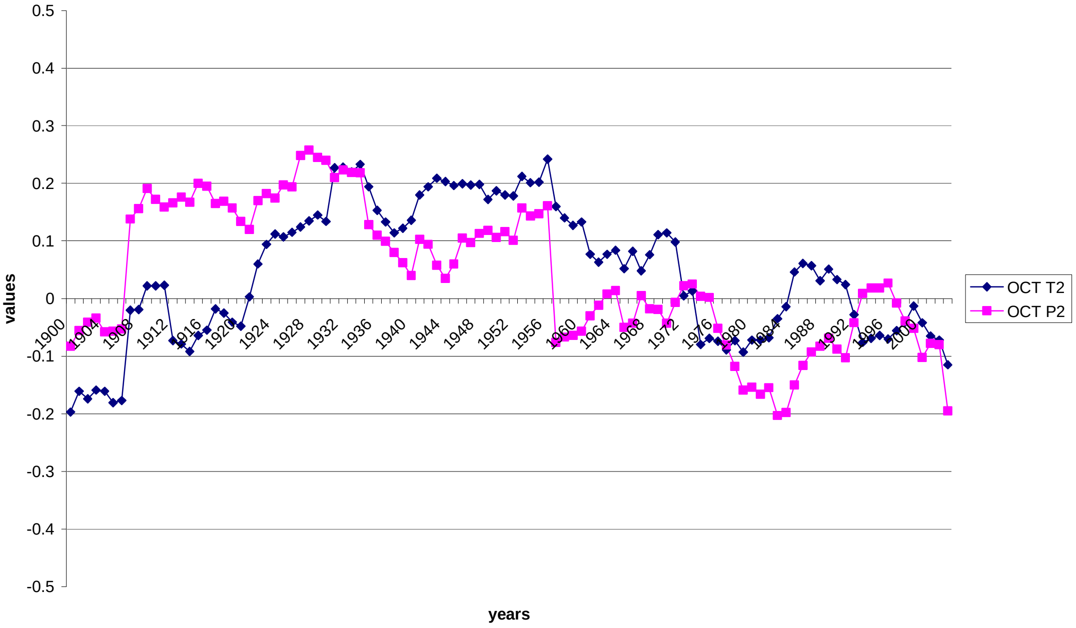


Figure 12 (A – F) May-October (current year) temperature and precipitation effect on tree-ring growth during the period 1850–2003, using moving correlation function with a 50-year time window

Chapter 4 Discussion

4.1 The impact of local site conditions on Scots pine development

After being cross-dated, Scots pine chronologies were found to date back to 1825, suggesting the hypothesis that some trees in Col de Roa managed to survive the landslide, which occurred back in 1814 (Guzzetti *et al*., 2005). Trees have managed to adapt to the unbalanced nutrient availability of the local Dolomitic soil (Oberhuber *et al*., 1998). In addition, this soil is also characterised by having a high infiltration and drainage rates, and therefore, low water availability was also assumed to be a key factor in tree growth limitation within the study site.

The evaluation of the growth response of a stand to its surrounding environment could be based on tree ring correlation to climate variability (Fritts *et al*., 1965), and therefore, possible drought signals were investigated within the Scots pine chronologies in conjunction with the meteorological data of the local stations to understand whether the climatic conditions also had a significant ecological effect on these trees, even if precipitation is not considered anywhere near being a growth limiting factor in the area because of the prevailing humid conditions (Tranquillini, 1979; Oberhuber *et al*., 1998).

4.2 Chronologies data and climatic-growth relationship

The strongest and temporally significant climatic signal shown by Scots pine ring-width indices ($P > 0.05$) is a positive response to July's prior year's temperature ($r = 0.173$), and a negative response to its current year's precipitation ($r = -0.199$). In other words, the higher its temperature and lower the precipitation, the wider the ring (Figures 10, 11 and 12). The combination of negative response to July's precipitation and the positive response to its temperature suggests that Scots pine growth at this site reacts negatively to excessive July precipitation. One possible explanation for this behaviour could be that Scots pine trees have developed in the last few decades higher water use efficiency which may be associated with the growth enhancement effect of the elevated atmospheric CO_2 concentration. An earlier study was carried out on detecting radial growth enhancement on Juniper trees under 'ecologically comparable' drought years at the beginning of the 20th century (1896 – 1949) where carbon dioxide (CO_2) was significantly lower than at the second study period of 1950 – 1996/97 (Knapp *et al.*, 2001). Knapp *et al.* (2001) noted that six out of seven study sites had showed a significant positive trend from their climate/growth residual models, suggesting the presence of a non-climatic factor causing the recent decades' growth increase (23% increase in the second study period). However, Knapp *et al.* (2001) also noted that in the latter 20th century, growth indices were 63% greater during matched drought years than within matched wet years (30%) when compared with the earlier 20th century.

These results agree with some other studies that discussed the effects of CO_2 elevated atmospheric levels on increasing plants' water use efficiency during drought years or conditions (Hogan *et al.*, 1991; Hattenschwiler *et al.*, 1997; Idso and Idso 1994; Tognetti *et al.*, 2000b). When Scots pine was studied within one of the Dolomitic straights to test the effect of soil water deficit on its radial growth, the results suggested that in order to prevent a substantial xylem embolism, mature Scots pine sufficiently closes its stomata (Oberhuber *et al.*, 1998), probably to reduce the evapotranspirtation rate through the stomatal control of it, preventing dramatic decline of needle water potential (Irvine *et al.*, 1998). Together with the plotted temperature and precipitation meteorological data, this finding suggests also that trees within the study area have acclimatized to the recent increase in temperature since the 1940s (Figure 5).

This can also explain the cambial activity of developing normal, wide rings following extraordinary dry events of the late period of the 20th century (Oberhuber *et al.*, 1998; Weber *et al.*, 2007) which was depicted in Scots pine chronologies after the hottest and relatively dry year of 2003 (Oberhuber et al, 2008) (Figure 3), and was absent after the year 1921.

Furthermore, a slight positive response to May-August temperatures of prior year and June's precipitation of the current year was also identified as well as a negative response to precipitation of May-August prior year and June's temperature of the current year (Figures 10, 11 and 12). Even if June's MCF results are not significantly influential on ring growth, they agree with July's prior year's temperature positive correlation, although a disagreement in the current year precipitation correlation was plotted. Oberhuber (1998) suggested that within the growing season (May – August) in this Alpine climate, trees react positively to early spring-summer precipitation and mid summer temperature, and so Scots pine trees still need the summer water to grow, which was clearly present in June’s precedent year’s results.

Moreover, as a typical pioneer tree species, Scots pine needs much light for regeneration and growth (Bigler *et al*., 2006; Eilmann *et al*., 2006), and as the typical Alpine summer rain is usually centralized above a certain area, this may have imposed an additional indirect stress on the light demanding Scots pine trees, leading to a significant reduction in the photosynthesis process, caused by the lack of sufficient solar radiation.

Chapter 5 : Conclusion

The Scots pine chronologies in this study were dated back to 1825, suggesting that they possibly survived or established in Col de Roa after the 1814 Antelao landslide (Guzzetti et al., 2005). Trees have managed to adapt to the water shortage and poor nutrient availability of the local Dolomitic soil, which led to the assumption that possible drought signals may be traced in the studied samples. The strongest and temporally significant climatic signal shown by Scots pine ring-width indices is a positive response to July's prior year's temperature and a negative response to its current year's precipitation, suggesting that July's precipitation is the most important factor influencing Scots pine tree-ring growth.

There is a possibility that Scots pine trees at Col de la Roa have developed a higher water use efficiency in the last few decades, and this may be associated with the enhancing fertilization effect of the recent elevated atmospheric carbon dioxide levels (Knapp *et al.*, 2001) as earlier suggested, which may be possible to detect during drought years or conditions. Furthermore, this finding suggests also that trees within the study area have acclimatized to the recent increase in temperature since the 1940s, probably by the stomatal control of evapotranspirtation rates, preventing dramatic decline of needle water potential (Irvine *et al.*, 1998).

This could also explain the cambial activity to develop normal, wide rings following extraordinary dry events from the late parts of the 20th century (Oberhuber *et al.*, 1998; Weber *et al.*, 2007) which was depicted in Scots pine after the hottest and relatively dry year of 2003 (Oberhuber *et al.*, 2008), and was not plotted after the year 1921.

Scots pine negative reaction to July's precipitation of the current year proposes the assumption that the typical Alpine summer rain may have imposed an additional indirect stress on the light demanding Scots pine trees, leading to a significant reduction in the photosynthesis process, caused by the lack of sufficient solar radiation. Nevertheless, Oberhuber (1998) suggested that within the growing season (May – August) in this Alpine climate, trees react positively to early spring-summer precipitation and mid summer temperature, and so Scots pine trees still need the summer water to grow, which was clearly present in June's precedent year's results.

This study provided some evidence of enhanced Scots pine growth in the last few decades, even if other environmental factors cannot be ignored in study area, such as the poor Dolomitic soil condition, trees recovery from landslides, or simply the recent undetected climate change. The current understanding of CO_2 fertilization effects on tree growth is consistent with the documented evidence of Scots pine trees. However, further dendrochronological studies within the Dolomites are highly recommended to give a better understanding of the effect from recent changes in climate, and to investigate the suggested positive fertilization effect of atmospheric CO_2.

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