Master thesis – GEO 511

Tree-ring response of three Mediterranean shrubs *Juniperus phoenicea* L., *Phillyrea angustifolia* L. and *Pistacia lentiscus* L. to different climatic parameters at Capo Caccia (Sardinia, Italy)

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Summary

For the Mediterranean area a dramatic change in climate is forecasted. According to several studies, an increase in temperature and a decrease in precipitation, and therefore an increase in drought frequency and severity, in this area are expected. It is assumed, that these changes will probably have an impact on the highly sensitive shrubland ecosystems in the Mediterranean. This thesis aims at enhancing the understanding of the behaviour of some species of the typical Mediterranean scrubland vegetation systems (hereafter called "macchia") with the help of dendroecological methods. Tree rings often have been used as a useful tool to see the influence of different climatic parameters on plant growth. For this thesis, tree disks of three typical macchia vegetation shrubs, *Juniperus phoenicea* L., *Phillyrea angustifolia* L. and *Pistacia lentiscus* L., were sampled in a coastal ecosystem in north-western Sardinia (Italy). Tree-ring growth was compared with mean monthly precipitation, mean monthly temperature, mean monthly maximum temperature and mean monthly minimum temperature since 1970. For a shorter period starting in 1990, mean monthly wind speed and mean monthly relative humidity data were analysed as well. Finally, net ecosystem exchange (CO_2 fluxes) data of eddy covariance measurements from 2004 until 2011 were compared with the tree-ring width. The results show that ring-width values of *J. phoenicea* were the highest among the species, followed by *P. lentiscus* and then *P. angustifolia*. The synchronicity of high-frequency growth patterns of the different species is not very high, which suggests different responses to climatic parameters or other environmental factors. *Juniperus phoenicea* seems to be more limited by precipitation than the other species, even though during strong droughts all the species showed limited growth. *Juniperus phoenicea* also seems to suffer most because of high maximum temperatures during summer, while the other species were not affected. The response signal to temperature was stronger and of higher significance than to precipitation, and may have in general a higher influence on these species. As it was expected, *J. phoenicea* showed the best correlation with net ecosystem exchange data, probably because of its strong dominance at the site. Tree-ring widths are a promising tool to be combined with data from eddy covariance measurements, to reconstruct ecosystem exchange data for the past. Considering the expected changes in precipitation and temperature it is likely that *J. phoenicea* at our site is the species which will suffer the most. *Pistacia lentiscus* and *P. angustifolia* on the contrary seem to be more adapted to dry

conditions, and might be able to cope with the expected, dramatic increase in drought frequency and severity in a better way.

1 Introduction

For the Mediterranean region an increase in temperature and a decrease in precipitation are expected for the future (IPCC, 2007). Some studies call the Mediterranean area a hot spot for climate change in the near future, which means the changes in temperature and precipitation might change disproportionally in comparison to other areas (Giorgi, 2006). These changes may lead to an increase in term of the drought periods as well as in the intensity of the droughts.

It can be assumed that a change in climatic conditions will also affect the behaviour of the ecosystems in the concerned areas, namely tree growth. Enhanced temperatures are predicted to benefit trees which grow where water is not a limiting factor, whereas the opposite should be expected for trees growing where water is the major limiting growth factor, like in the Mediterranean area (Gea-Izquierdo et al., 2011).

A common kind and widespread ecosystem in the Mediterranean area is the so called “macchia”. This vegetation community consists in the main part of evergreen shrubs and is mostly situated at the border between the Mediterranean Sea and the bigger forest ecosystems, which are found more inland. Sometimes a degraded state of the macchia, the so called “garigue”, lies between the macchia and the sea (Fares et al., 2009). The garigue is a form of degraded macchia, and the macchia can ecologically be seen as a degraded state of the originally existing Mediterranean forest ecosystems. This degradation has been caused by human activities like agriculture, grazing, wildfires for thousands of years or recently tourism (Meiggs, 1982; De Datto et al., 2008). In Italy the area covered by macchia is around 2-3% of the total area. Beside the high biodiversity in the macchia vegetation, many macchia species show similar ecological adaptions to environmental conditions. These species often have to adapt to circumstances like hot and dry summers or an enhanced exposure to salinity, due to sea breeze or a high salty groundwater table (Fares et al., 2009). Thus, "the typical woody vegetation in mediterranean regions is characterized by the predominance of hard-leaved evergreen shrubs and dwarf and short trees, with small, stiff, leathery and thick leaves” (Cherubini et al., 2003).

Main stress factors for trees and shrubs in the Mediterranean are summer drought and low temperature in the winter (Mitrakos, 1980). As mentioned, some species adapted to these stress factors caused through the Mediterranean climate and developed different strategies to avoid or minimize damage through drought (e.g., stomata closure to avoid transpiration to prevent a critical decrease in water potential). When these adaptions for the plants took a long time to develop (Fonti et al., 2013), it is questionable whether they will all be able to cope well with a relatively fast increase of temperature and drought as predicted.

Thus, understanding how different plant species have reacted to summer drought or low temperatures in winter, in the past, is important to predict their possible behaviour in the future. This knowledge can also be useful in practical forestry, e.g., in afforestation of sand dunes against erosion. The study of tree rings, i.e. dendrochronology, applied in ecology, i.e., dendroecology, can help to enhance this understanding. Dendroecological methods, comparing tree-ring width with climatic parameters, allow reconstructing how different tree species have reacted to a drought in the past, and therefore how they might do in the future (Schweingruber, 1996). Even though there is a great potential for understanding and predicting a possible impact of global change on ecological processes, studies of tree rings in the mediterranean region are rare (Martinelli, 2004). In contrary to temperate regions, tree rings in the Mediterranean sometimes do not show a clear seasonality, i.e., they are not annual, which complicates their dating and analysis (Cherubini et al., 2003).

This thesis aims at enhancing the knowledge about the reaction of typical Mediterranean species growing in coastal macchia to precipitation and temperature. Further reactions to other climatic parameters as wind speed and relative humidity will also be analysed and discussed. Additionally to the climatic parameters, data from eddy covariance (EC) measurements (net ecosystem exchange fluxes) were also taken for a comparison with plant growth. Three evergreen shrubs were studied: *Juniperus phoenicea* L., *Phillyrea angustifolia* L. and *Pistacia lentiscus* L., growing in a macchia vegetation system in north-western Sardinia. To my knowledge no dendroclimatological studies exist with these species. Furthermore, studies which include EC data in combination with ring-width measurement are in general rare, although could be of major importance in the future for predicting the development of such ecosystems under different climatic scenarios, and their carbon uptake and role in the global carbon cycle. I want to contribute with this thesis to a deepener understanding of these species in the Mediterranean.

Research questions and scientific hypotheses

H1: In the years where drought periods occur, plants show smaller ring width.

A dramatic decrease in ring width during years characterised by strong droughts is expected, because it is known that water supply is a main factor for tree growth in the mediterranean region (see literature in Cherubini et al., 2003). Furthermore, a general positive response to precipitation is expected, with an increase in ring-width growth in years with abundant precipitation.

H2: Winter low minimum temperature has a negative effect on ring-width growth.

Beside strong drought events, low temperature in winter is known as a major limiting factor for tree growth in the Mediterranean (Cherubini et al., 2003). Thus, in all the species a decrease in ring-width growth is expected during cold winters.

H3: Summer high maximum temperature has a negative effect on ring width.

High maximum temperatures during the summer, increasing evapotranspiration, have an effect similar to low precipitation (Cherubini et al., 2003). Thus, narrow rings are expected to be formed in years with extraordinary high maximum temperatures during summer.

H4: Higher wind speed leads to a decrease of growth.

Being the site where the samples were taken situated very close to the sea, it is exposed to strong wind, which might increase evapotranspiration and influence tree growth. Moreover, strong salty winds, such as those which may be expected at our site, are known to have an impact on vegetation, e.g., to reduce the size of trees or shrubs (Farris et al., 2013).

H5: High relative humidity values minimize the effect of summer drought.

High relative humidity decreases evapotranspiration, reducing plant water losses (Chaves et al., 2002). Thus, positive correlation with relative humidity during summer is expected, when water is the limiting growth factor.

2 Research site

2.1 Capo Caccia

All the samples have been taken at four different sites in Capo Caccia. Capo Caccia is a peninsula situated in the north-western part of Sardinia, close to Alghero. The research sites are part of the natural reserve which is called "Le Prigionette" and part of the peninsula (40° 36′ 18″N, 8° 9′7″E). The area is around 74 m above sea level and is to the north-western and western boundaries delimited by a cliff on the sea. The whole site has a surface area of about 1200 ha (Marras et al., 2011).

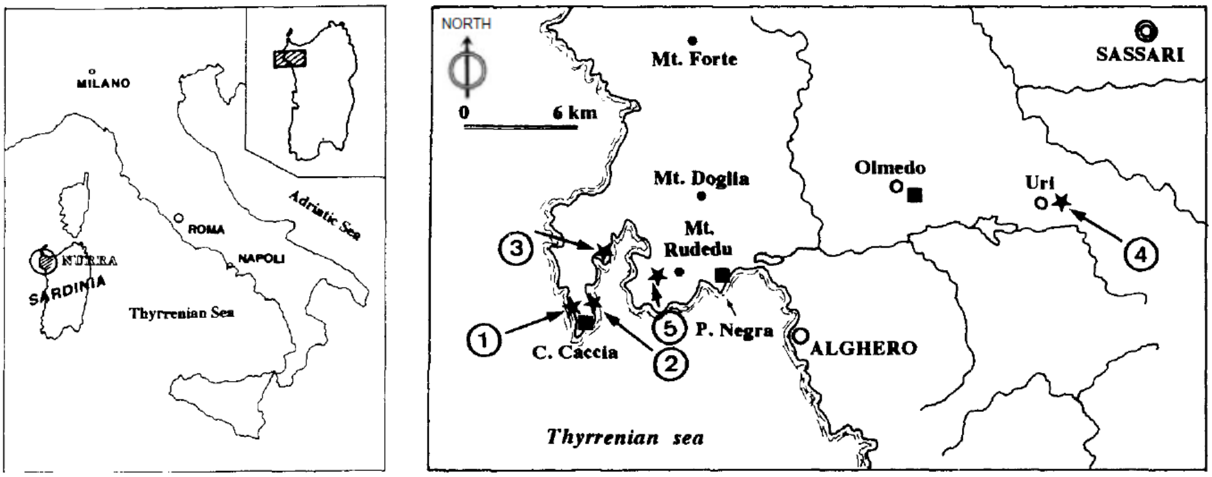


Figure 1: Localisation of Capo Caccia (1) in Sardinia. Source: Carannante et al., 1995, modified.

2.2 Climate

The climate at Capo Caccia is semi-arid with an annual rainfall of 495 mm. Most part of precipitation occurs from autumn to spring. From May to August there is a dry period with an average precipitation of around 70 mm. The mean annual temperature is 16.4°C. Mean of the minimum temperature in the coldest months (Dec - Feb) is 8.5°C. Mean of the maximum temperature in the hottest months (Jul - Aug) is 27°C (meteorological station at Capo Caccia, 40° 36′ 18′′N, 8° 9′7′′E, 1970 - 2012, University of Sassari).

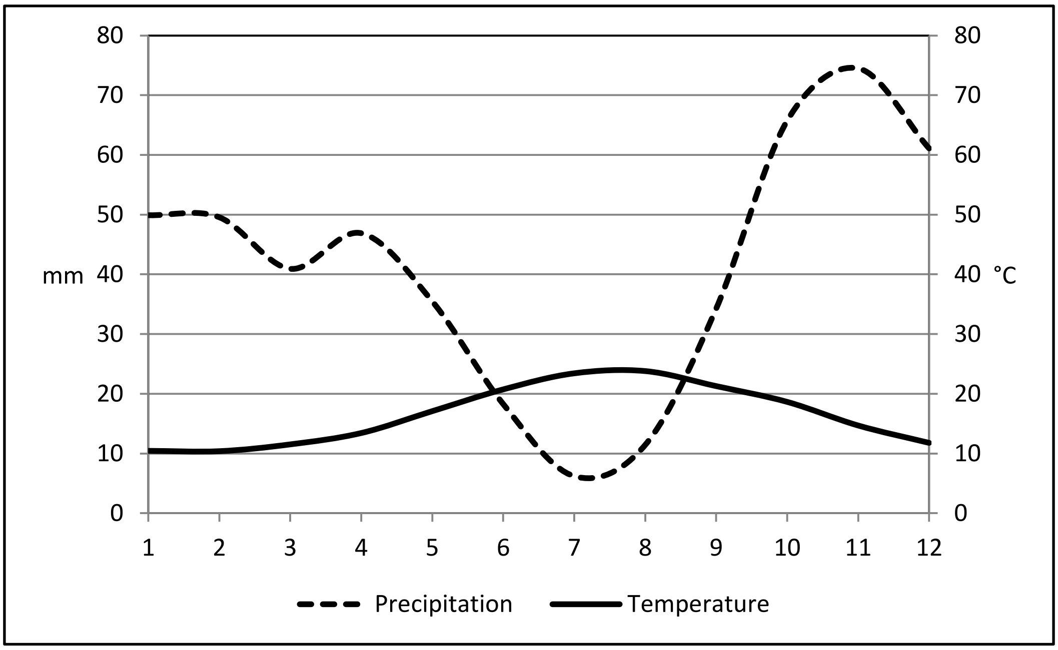


Figure 2: Climate diagram Capo Caccia. Mean annual temperature (°C) and mean annual precipitation (mm) at Capo Caccia. Measurements from 1970 to 2012, January to December.

2.3 Geology and soil

Geological substrate consists of Mesozoic limestone. The main soil type is Terra Rossa (Lithic Xerorthent and Typic Rhodoxeralfs), rocky and shallow with sandy loam texture in it. Depth of the soil is around 30 cm with a typical ABC profile and neutral pH-values (De Datto et al., 2009). Because of its consistency it is highly erodible (Spano et al., 2009).

2.4 Vegetation

In the research area the vegetation is typical Mediterranean macchia vegetation. Dominant species are *J. phoenicea, P. lentiscus, P. angustifolia* and *Chamaerops humilis* L. Out of these species *J. phoenicea* is the most competitive species (covers around 52% of the survey area) followed by *P. lentiscus* (covers around 22% of the survey area) (Baraldi et al., 2005; Rotondi et al., 2003). Other species which can be found in the research area are *Rosmarinus officinalis* L., *Genista corsica* (Loisel) DC., *Daphne gnidium* L., *Smilax aspera* L., *Euphorbia characias* L., *Helichrysum microphyllum* DC., *Asphodelus microcarpus* Salzm., and *Ferula communis* L. The macchia is a secondary succession which established to a great part after a big fire in 1963 and agricultural abandonment in 1970. Since these events the research area rarely has been exposed to human interference. Ground coverage is between 40% and 90% and the mean height of the macchia plants is around 1 m to 1.5 m (Marras et al., 2011). Beside the macchia, other vegetation types present in the Natural Reserve are an olm-oak forest and an afforested area with *Pinus halepensis* Mill., *Pinus pinea* L., *Cupressus sempervirens* L. and *Eucalyptus* spp. (De Datto et al., 2009). Nearest to the coast the vegetation type is called garigue, which is a degraded state of the macchia vegetation. It consists mostly of small shrubs situated between stones and calcareous rocks. Species found there are *Astragalus massiliensis* L, *Helichrysum italicum* (Roth) Don subsp. and *Microphyllum* (Willd) Nyman (Rotondi et al., 2003).

Figure 3: Overview of the vegetation types at Capo Caccia. View from the cliff to the hill, ecosystems in following order; garigue – macchia – pine forest - olm-oak forest.

3 Material and methods

3.1 Research species

3.1.1 *Juniperus phoenicea*

Juniperus phoenicea (English name: phoenicean Juniper) is a small evergreen conifer tree or shrub which belongs to the *Cupressaceae*. It is native all over coastal Mediterranean, Canary Islands, Portugal, Saudi Arabia and Sinai near to the Red Sea (Fig. 4). Its name was given by the region Phoenicia in Syria, where *J. phoenicea* still is distributed. In Sardinia *J. phoenicea* can be found all over the island. It is well adapted to wind-exposed sites characterised by high solar irradiance, with rocky soils and near to the sea. Being a pioneer "modest" species, it is often used in afforestation projects on sandy soils as preparation for more demanding species (Düll et al., 2007; Schönfelder et al., 2005). The wood of *J. phoenicea* traditionally often was used in construction and in production of distilled oil for veterinary medicine (Munoz-Reinoso, 2004).

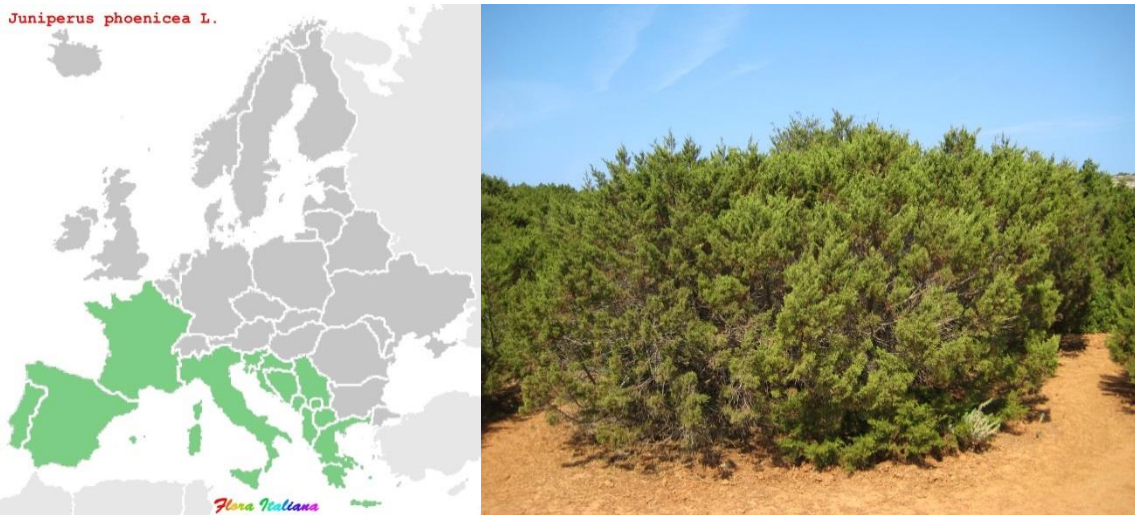


Figure 4: *Juniperus phoenicea* L. and its distribution map in Europe. Source: Flora Italiana online.

Juniperus phoenicea reaches heights around 8 m. For this thesis samples were taken from shrubs with an average height of 3-4 m. Its needle-like leaves are green, white at the margin and around 2 cm long. It is flowering from March to early May. Its globular fruits of around 1 cm diameter change their colour from dark violet to dark brownish-red when mature (Düll et al., 2007). Its root system is reported to be shallow, with most of the horizontal roots in the first 50 cm of the soil profile, and not many caudal roots which reach deeper horizons into the soil (Castillo et al., 2002).

3.1.2 *Phillyrea angustifolia*

Phillyrea angustifolia (English name: narrow leaved Phillyrea) is a small evergreen shrub which belongs to the *Oleaceae* family. It is found all over the western Mediterranean region (Fig. 5), usually in macchia or garigue ecosystems, but rarely as a dominant species (Traveset, 1994; Vassiliadis et al., 2000). It prefers to grow on loamy and calcareous soil, best at covered sites. In frequently disturbed areas it can be found as a multi-stemmed shrub, since it possesses an underground lignotuber from which new branches sprout out after above ground damage (Pannell et al., 2000). It is considered a suitable plant for landscaping purposes due to its tolerance to occurring drought periods (DellaGreca et al., 2011).

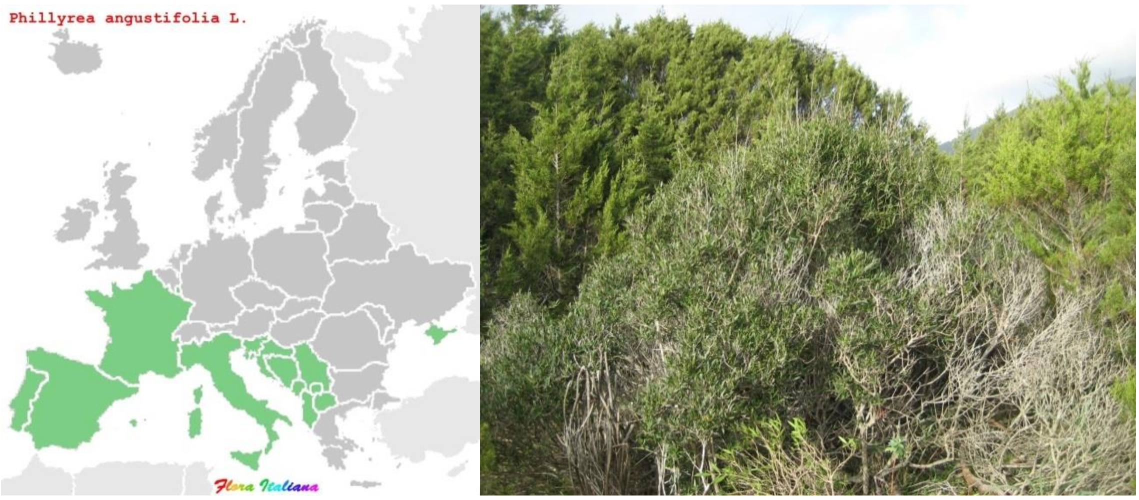


Figure 5: *Phillyrea angustifolia* L. and its distribution map in Europe. Source: Flora Italiana online.

Phillyrea angustifolia reaches heights up to 5 m. Samples for this thesis reached a height of around 2 m. This evergreen shrub has dark green leaves which reach normally lengths around 3-8 cm. Its white-yellowish flowers are blooming from March to May (Traveset, 1994). The fruits are of blue colour, have an oval to globular shape and are around 6-8 mm long (Schönfelder et al., 2005).

3.1.3 *Pistacia lentiscus*

Pistacia lentiscus (English name: mastic) is an evergreen shrub or small (seldom) tree which belongs to the *Anacardiaceae* botanical family. It is distributed around the whole Mediterranean area including Portugal, Canary Islands and the Mediterranean part of Turkey (Fig. 6). In these places it prefers to grow on sandy or rocky soil, mostly in garrigues or macchia ecosystems. It can be found up to 800 m a.s.l. (Schönfelder et al., 2005; Dogan et al., 2003). It counts to the most important woody species in the coastal Mediterannean areas, where it is a common part of the climax vegetation. Moreover *P. lentiscus* is known to be a suitable plant for restoration of semiarid areas, due to its adaptions to drought and resistance to disturbance (Cortina et al., 2008). Despite its good adaption to the Mediterraean climate, it is negatively affected by tourism, fire or deforestation for plantation. *Pistacia lentiscus* furthermore has economical value as source for the mastic gum, which is of use in pharmaceuticals or, e.g., as dental adhesives (Dogan et al., 2003).

Figure 6: *Pistacia lentiscus* L. and its distribution map in Europe. Source: Flora Italiana online.

It can reach a height of about 8 m. Examples in this thesis were shrubs with a maximum height of about 2 m. *Pistacia lentiscus* is known as a slowly growing plant (Ostos et al., 2008). Its leaves are dark green all year long in a par pinnate order and reaches lengths around 5 cm. From March to June its dioecious flowers are blooming. Its fruits are around 4 mm and turn from red into black colour later in the season (Schönfelder et al., 2005). It has a dimorphic root system with caudal roots, which can reach depths of about 5 m below ground (Armas et al., 2010).

3.2 Dendrochronological sampling

3.2.1 Site selection

The plants were all selected in the Nature Reserve at Capo Caccia. Samples of *J. phoenicea* and *P. angustifolia* were all taken at the same site (site 1). For *P. lentiscus* four different sites at Capo Caccia were chosen. The plants from site 4, which were the nearest to the sea, looked more damaged and seemed to have suffered more stress than the plants in the other sites. Plants at site 2 and site 3, which are close together, showed big differences in the size of their leaves. The size of the leaves at site 3 was almost twice as big as that at site 2. Some samples of *P. lentiscus* were taken at site 1 as well. In all these sites *J. phoenicea* is the dominant species.

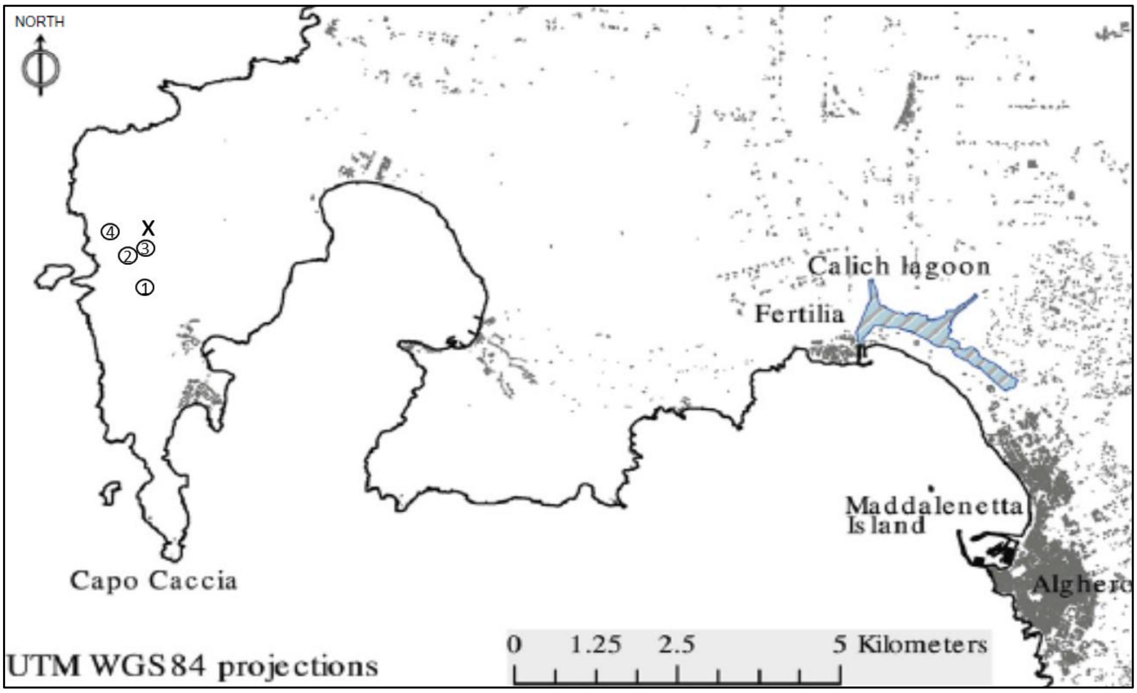


Figure 7: Position of the research sites (1-4) and meteorological station (X) at Capo Caccia. Source: Manca et al., 2013, modified.

3.2.2 Sampling

Sampling for tree-ring analyses, very young and small plants were purposely avoided. Sampling *J. phoenicea* big individuals were not sampled and left aside, because of the high ecological value of very old plants. The samples were taken avoiding small slopes, to avoid any influence from hang sliding events or a special water supply through growing in a small notch. Samples were also chosen in consideration to straight trunks. The plants were cut with a handsaw low at their base, to have as many tree rings in the samples as possible. Because of the small size of the plants it wasn't possible to take cores, so that we decided to take tree disks, which allows also a more detailed analysis, e.g., in case of very narrow rings it allows to count along another radius of the disk where rings are visible (Wilford et al., 2005). In total 41 plants were cut in four different sites (Fig. 7). After cutting, tree disks were labelled properly for further identification and analysis in the laboratory. Sampling was done on the 5th March 2013, thus, the plants might already have started to build new tree rings, which is important to know for the tree-ring measuring.

3.3 Laboratory methods

3.3.1 Sample preparation

Before samples were used for further analysis they had to be sanded to enhance the visibility of the tree rings. Sanding was done on a belt sander at the WSL institute in Birmensdorf. To optimise the result different gradients grit papers were used starting with the coarse one (100, 150, 280, 320, 400). Beside the enhancement of the visibility, sanding allowed also the surface of the disk be the exact transversal section, which is important for counting the tree rings afterwards. Care had to be taken so that sanding was not made with too much pressure to avoid burn marks on the tree disks.

3.3.2 Tree-ring measurement

Measurements had been taken at the WSL institute in Birmensdorf. Visual counting of the tree rings was not possible due to an often very narrow ring width. Thus, rings had to be counted with the help of a Leica MS5 stereoscope (Leica, Germany). Counting was done from bark to pith starting with the year of 2012. In some samples the wood which was grown in 2013 was already visible, thus, great care had to be taken there not to count this as the first ring of the chronology. To simplify the ring counting, every 10 and 50 year period dots had been made for identification. Furthermore, every year was marked and counted twice or more times until the same results were achieved. With the TSAP-WIN program (RinnTech, Heidelberg, Germany) the ring width was measured to the nearest 0.01 mm. To achieve a representative result two radii were chosen and measured on each tree disk. When possible due to structure of the tree disk, radii opposite each other were taken, to represent the tree disk as best as possible. Most serious problems were caused by very narrow ring width or intra-annual density fluctuations (IADF), which occurred in almost all the samples of all the species. IADF or false rings, as they also are called, are a widespread phenomenon in trees or shrubs in the Mediterranean. This changing in the wood density during the growing period often has been related to dry periods (De Micco et al., 2012). Samples which could not have been analysed due to very narrow ring width or identification problems caused by IADF were left aside.

3.3.3 Cross-dating

After measuring the ring width of the samples, they had to be compared. This comparison was done with the TSAP-WIN software at the WSL in Birmensdorf. First the curves of the two radii of each tree disk were plotted and visually analysed and checked for their *Gleichläufigkeit* (there is no English equivalent to this term). "*Gleichläufigkeit* is a measure of the year-to-year agreement between the interval trends of two chronologies based upon the sign of agreement, and Student's *t*-test, which determines the degree of correlation between the curves" (Cherubini et al., 2003). Comparing the two curves at 1-year interval, different correlation values for each position were given, and allowed it to find possible dating errors. When *Gleichläufigkeit* was significant ($p<0.05$) between the two radii, the average was taken and same analysis was done with the other averages from the tree disks of the same species. With this method, possible dating errors can be found and identified. Eventually, all the samples which showed statistically significant *Gleichläufigkeit* values with the mean chronology of a species were taken for further analysis. The ones which showed too low correlation were excluded. In another step the mean chronologies of the different species and sites were also analysed for *Gleichläufigkeit*. Apart of *Gleichläufigkeit*, the radii were all checked for their Cross Date Index (CDI), which is a combination of *t-test* and *Gleichläufigkeit*, and a powerful parameter for the matching of chronologies (Rinn, 2003).

3.3.4 Statistical analysis

"One of the main elements of dendrochronological standardization is removing the biological trend, i.e. the progressive decline of ring width along a cross-sectional radius that is caused by the corresponding increase in stem size and tree age over time" (Biondi et al., 2008). A common method used to deal with this "age trend" is to detrend the tree-ring chronology for their age effect. The problem with these methods is, that if the age trend coincides with the environmental trend to be found, this signal will also be removed (Biondi, 1999). Considering this, and also the fact that no distinct age trend was found in the tree-ring series, another method was applied. To minimize this biological effect on the tree-ring series, basal area increment (BAI) method was chosen, as used in other studies (e.g., Battipaglia et al., 2013), to compare with the raw ring-width chronology. For the comparison between tree-ring chronology and climatic data, another variable (size independent increment) was established to minimize the effect of stem size on the correlation. Both methods will be explained more detailed afterwards.

Being the plants young and the period of measurement relatively short, the use of dendroecological programs usually used, e.g., Dendroclim, was not possible. Statistical comparison between tree-ring data and climatic data were done using IBM SPSS Statistics 21 software. All of the data were tested for normal distribution using Kolmogorov-Smirnov test. Linear regression was used for analysing existing trends. Pearson's correlation coefficient (r) was used as the standard coefficient for normally distributed data, to check for correlation between ring with and the climatic parameters. The values of Pearson's correlation coefficient, ranges from -1 to 1. These maximum values represent the perfect negative and perfect positive correlation between the two variables. A negative value indicates that the value of one variable decreases, while the other one increases. A positive correlation value indicates that the value for both variables increases. All the tests were done for statistical significance at $p<0.01$(**) and $p<0.05$(*).

3.3.4.1 Basal area increment

Yearly BAI values were calculated in assumption of consistent growth around the stem, using Excel Microsoft software. To derive yearly BAI values following formula was used:

$$\boxed{BAI_t = \pi R_t^2 - \pi R_{t-1}^2}$$

Figure 9: Formula of basal area increment calculation. Source: Biondi et al., 2008.

Where t stands for a specific year, R_t is the stem radius at the end of the annual increment while R_{t-1} is the beginning of the annual increment (Fig. 8) (Biondi et al., 2008). Values of BAI typically are increasing since germination start because of the increasing radius of the stem. Thus, a size independent increment was created out of the BAI values.

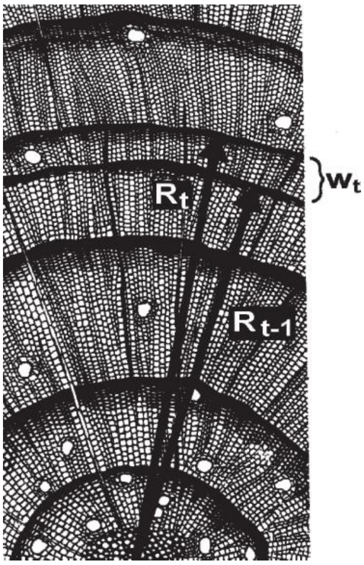


Figure 8: Visualisation of basal area increment. At each year ring width (w_t) is equal to the difference between the current tree radius (R_t) and the prior year radius (R_{t-1}). Source: Biondi et al., 2008.

3.3.4.2 Size independent increment

Yearly $\log_{10}$ BAI values were correlated with $\log_{10}$ BAI area values of the previous year to check for the size dependency. The correlation allows computing for the expected BAI from the size of the plant by the following equation:

$$Log_{10}\ ExBAI_t = a + b\log_{10}\ BAI_{t-1}$$

ExBAI is the expected BAI. The size independent growth then was calculated as BAI/ExBAI. A and b coefficients were calculated independently for each individual. Out of these calculations, variables with the averages for all the species were created (Size 2 JP, Size PHA, Size 1 PL), and for *J. phoenicea* and *P. lentiscus,* additionally variables with the best correlating individuals were created as well (Size 1 JP and Size 2 PL).

3.4 Climatic data

3.4.1 Meteorological station

Climatic data used in this thesis are all taken at a meteorological station at Capo Caccia, which is managed by the University of Sassari. The station is situated in the research area, near to our sites, around 20-100 m far from the sites (Fig. 7). Hence, no corrections on the data had to be done, as it would have been necessary if the meteorological station was on a higher altitude than the research site.

3.4.2 Climatic parameters

Available data over the period from 1970 to 2012 were: total monthly precipitation (PREC), mean monthly temperature (TEMP), mean maximum monthly temperature (TMAX), mean minimum monthly temperature (TMIN).

Available data over the period from 1990 to 2010 were: mean monthly wind speed (WIND) and mean monthly relative humidity (RH).Yearly values were calculated using the monthly values, in order of the Italian hydrological year (Nov-Oct).

For a shorter period from 2004 to 2011 yearly net ecosystem exchange (NEE) values were available.

The different temperature and precipitation data were analysed with a linear regression model to establish the trend of the last 40 years.

3.4.2.1 Drought definition for Capo Caccia

To analyse the impact of drought on tree-ring growth, three drought thresholds were set, for annual, summer and winter drought. To define the annual drought threshold, the average precipitation of the hydrological years from 1970 to 2012 was calculated. From this average, the standard deviation of the mean annual precipitation between the hydrological years from 1970 to 2012 was subtracted to generate the threshold. Hydrological years with precipitation below this threshold, were considered as years with drought anomalies. The thresholds for summer (JJA) and winter (DJF) drought was set three times below the average of each of them. As with annual drought, all values below these thresholds were considered as drought anomalies.

3.4.2.2 Net ecosystem exchange data

The net ecosystem exchange is a measurement of CO_2 fluxes between an ecosystem and the atmosphere. Thus, it is a measurement of the net photosynthesis of an ecosystem (the difference between gross photosynthesis and respiration). Carbon therefore is assimilated in an ecosystem when the photosynthesis range is higher than ecosystem respiration. NEE values were measured by eddy covariance method near to the meteorological station by the University of Sassari. The measurement of carbon dioxide, water vapour and energy exchange was done by a sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) and an open gas analyser (LiCOR 7500, Lincoln, NE, USA) which were placed at 3.5 m above ground (Marras et al., 2011). Values were measured every 30 minutes and added to annual values, whereas carbon assimilation in the ecosystem was counted as negative and carbon loss to the atmosphere as positive for the calculation.

4 Results

4.1 Climate

Temperature variability over the last 40 years have been analysed with a linear regression model. A clear trend exists in TMAX where the values during the last 40 years show an increase of about 2.5°C. TMEAN and TMIN do not show clear temporal trends (Fig. 10).

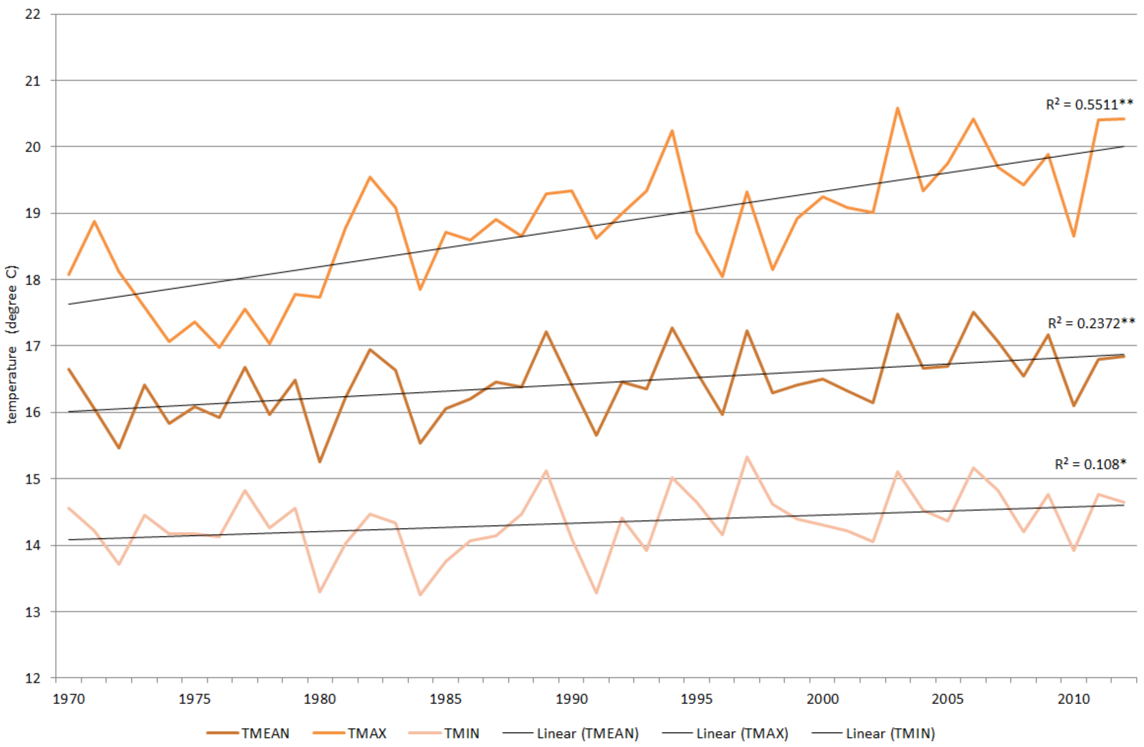


Figure 10: Annual temperatures of the last 40 years at Capo Caccia. Annual values of mean temperature, maximum temperature and minimum temperature from 1970 to 2012 at the meteorological station at Capo Caccia, including linear trend lines. Significance $p<0.01$ (**) and $p<0.05$ (*).

Over the last 40 years the annual precipitation seems to decrease slightly ($R^2=0.094^*$). If the last 5 years of the measuring period were not taken into account, the signal of decrease would even have been stronger (Fig. 11).

Precipitation correlates negatively with all the temperature variables (TMEAN, r=-0.414**; TMAX, r=-0.353*; TMIN, r=-0.445**). Also wind speed and relative humidity correlate negatively with each other (r=-0.479*).

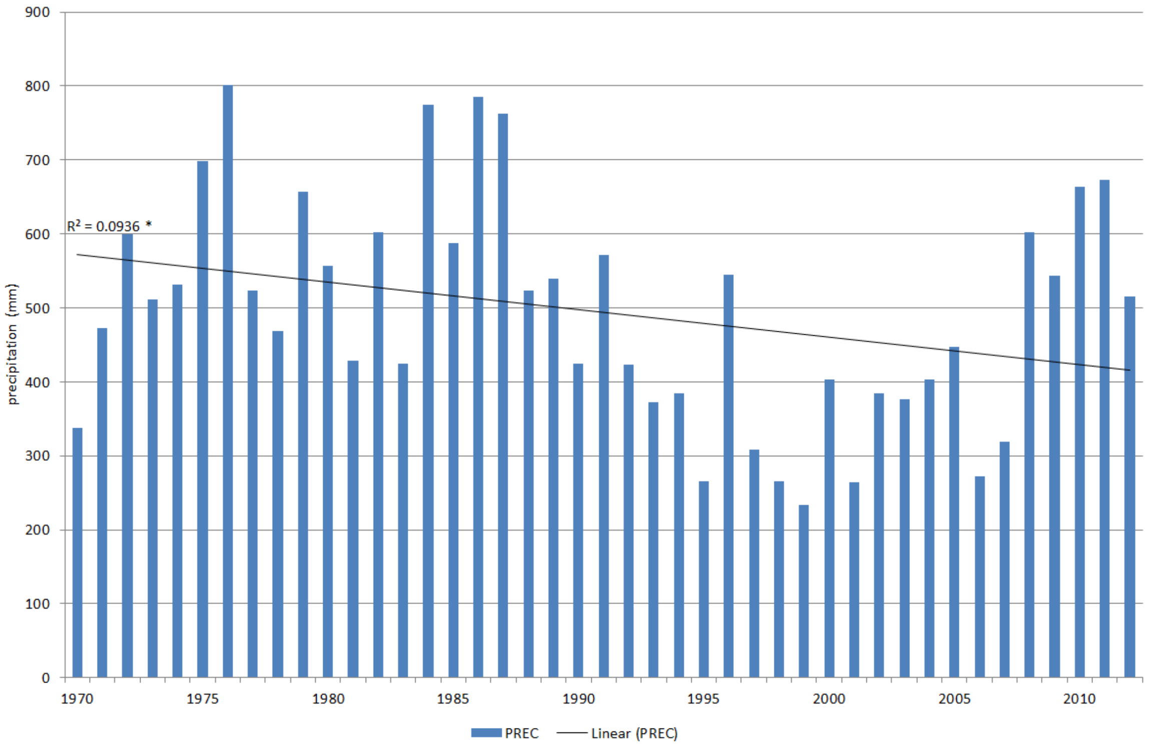


Figure 11: Annual precipitation from the meteorological station at Capo Caccia from 1970 to 2012, including linear trend line. Significance p<0.01 (**) and p<0.05 (*).

4.2 Sample overview

Out of the 41 disks collected, 10 were discarded because exact dating of the tree rings was not possible being, sometimes, rings extremely narrow or IADF which confounded dating procedure. Hence, only 31 disks were used for further analysis: 11 out of 13 for *J. phoenicea*; 15 out of 22 for *P. lentiscus*; 5 out of 6 for *P. angustifolia.*

The average age of the plants varied considerably among the three different species. The average age of *J. phoenicea* is the highest (56 years) followed by *P. angustifolia* (39 years) and *P. lentiscus* (33 years). *Pistacia lentiscus* at different sites has different ages. The oldest plants were found at site 4 with an average age of 40 years. The plants at site 1 and site 3 have almost the same average ages (31 respectively 30 years). A large difference in age was found at site 2 (average age of 19 years). The age distribution of the collected samples does not reflect the age structure at the site, as samples were not collected randomly but the largest-diameters of *J. phoenicea* and smallest individuals purposely excluding. However, the age of the selected plants provides an indication on plant age at the sites.

Figure 12 illustrates the distribution of the germination date of the samples. *Juniperus phoenicea* seems very regularly distributed. We see also that the *J. phoenicea* samples are almost all older than the samples from the other species. The *P. lentiscus* samples are, apart of three samples, all younger than the youngest *J. phoenicea*. The oldest individuals are *J. phoenicea* - the oldest plant germinated before 1948, the oldest *P. angustifolia* 1958, and the oldest *P. lentiscus* 1964.

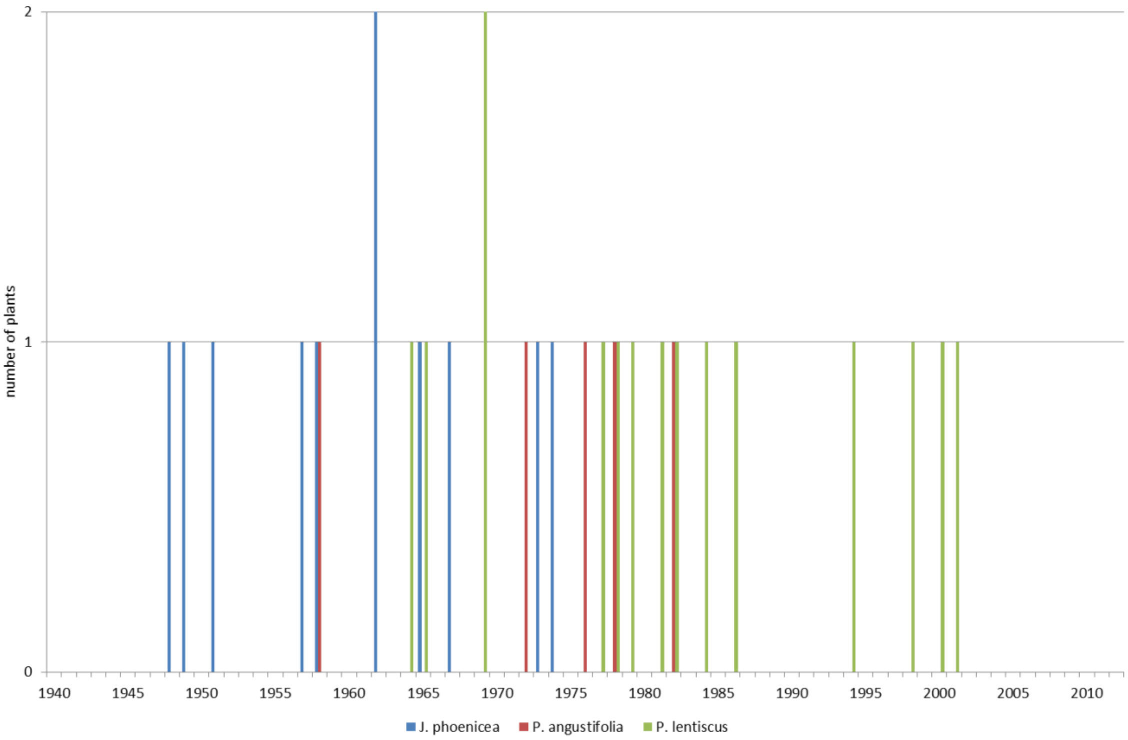


Figure 12: Germination distribution. Illustration of how the germination of the single samples of *J. phoenicea, P. angustifolia* and *P. lentiscus* are distributed.

4.3 Ring-width chronologies

4.3.1 Species comparison

4.3.1.1 Basal area increment values all sites

In this section the mean basal area increment of the three different species is analysed, which means that for *P. lentiscus* samples from all the sites are included. Pearson's correlation coefficient (r) between BAI series for *J. phoenicea* and *P. lentiscus* showed the highest value (r=0.818**, 1964 – 2012). Very similar values were found for *P. angustifolia* compared with *P. lentiscus* (r=0.811**, 1964 – 2012). The lowest correlation, although still highly significant, was found between *J. phoenicea* and *P. angustifolia* (r=0.697**, 1958 – 2012).

There is a positive age trend in *J. phoenicea*, with values rising until around 1984. Afterwards the values are stable with the exception of the peak in 2010, when a very high value was recorded. In *P. angustifolia* a period of positive growth from 1985 until 1996 was found. After 1996 the growth has been very stable. The mean BAI of *P. lentiscus* are constantly increasing since the start of the series until a very high peak in 2010. In 2010, all species showed a positive peak but *J. phoenicea* and *P. lentiscus* showed the highest growth rates. Beside this very clear peak in 2010, there are also positive peaks in the years 1993 and 1996 for all the three species. In 1990, a very negative BAI peak is clear in the chronologies of all the three species, particularly evident in J. *phoenicea*. Also in 1981 and 2012 all the species show a decrease in growth, most evidently *J. phoenicea* and *P. lentiscus* (Fig. 13).

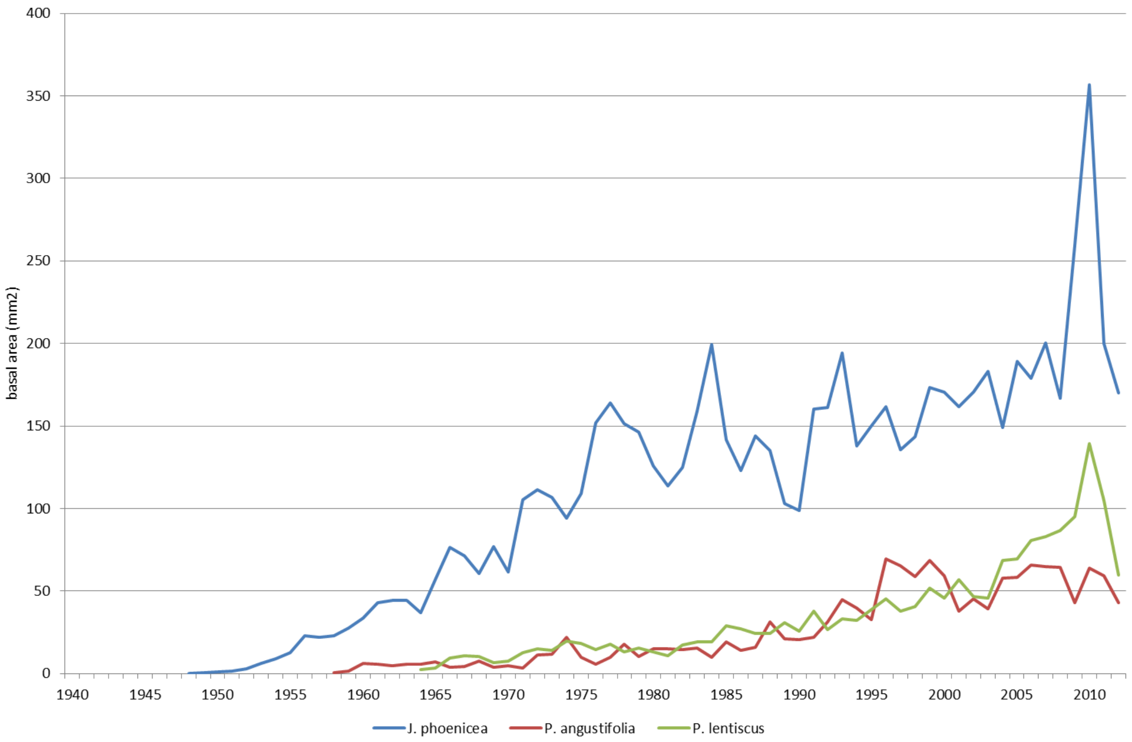


Figure 13: Mean basal area increment chronology of *J. phoenicea, P. angustifolia* and *P. lentiscus* from all sites.

4.3.1.2 Basal area increment values site 1

Having been all three species sampled only at site 1, a comparison between the BAI series of all species is only at this site possible. The mean BAI of *P. lentiscus* at this site was higher than the mean values at the other three sites, probably due to the fact that from 1998 until 2010 there was an increase in growth rates. At site 1, Pearson's correlation coefficient (r) between BAI of *P. lentiscus* and the other species is lower than comparing all the *P. lentiscus* at different sites (r=0.785** for *J. phoenicea* and r=0.731** for *P. angustifolia*). In *P. lentiscus* at site 1, positive and negative peaks in BAI are the same as in the chronology all sites including, but they are more distinct (Fig. 14).

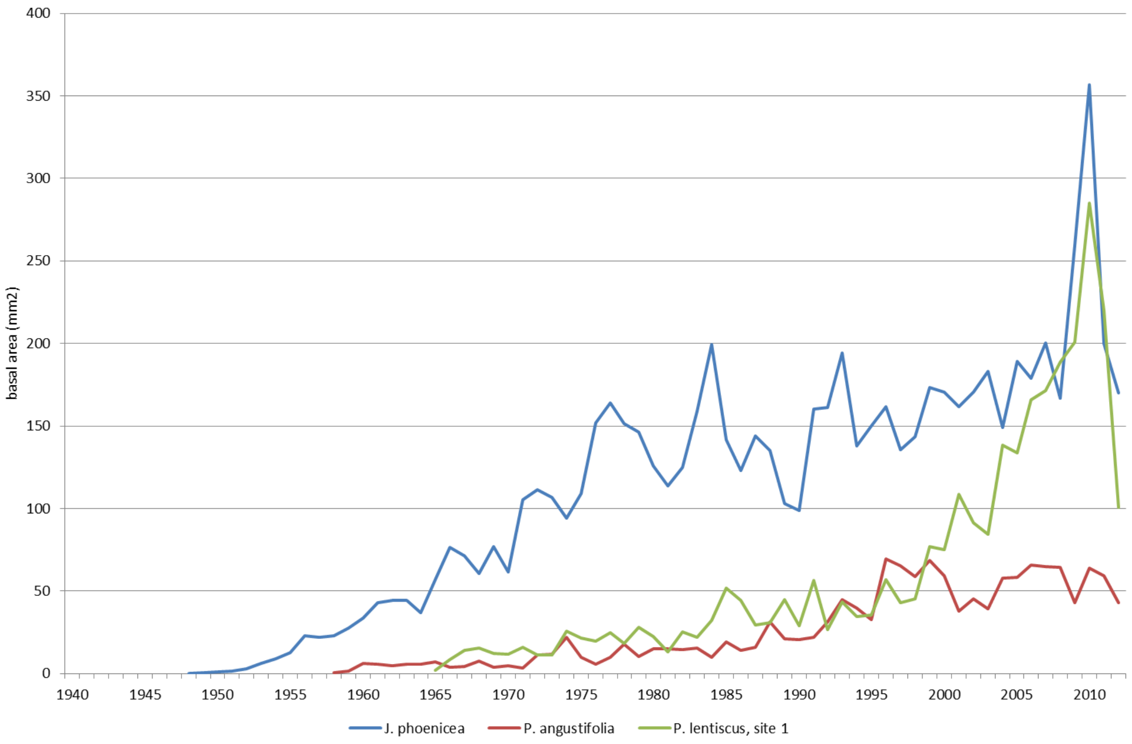


Figure 14: Mean basal area increment chronology of *J. phoenicea, P. angustifolia* and *P. lentiscus* from site 1.

4.3.1.3 Ring-width values

No negative age trend was observed in any tree-ring width chronology of the three species, which means that, at these sites, considering our species, younger plants do not grow faster than older ones, as usually elsewhere observed (Biondi et al., 2008). Correlation analysis of the ring width of the three species yielded very low values. Similarly, also *Gleichläufigkeit* and CDI didn't show a good match between the chronologies (Tab. 1).

Table 1: Results of cross-dating between the different species. Mtime (overlapping years), CDI (Cross Date Index), TV (*t*-test), GSL (level of *Gleichläufigkeit*), Glk (*Gleichläufigkeit* between the different species), r (Pearson's correlation coefficient). Significance p<0.001(***), p<0.01 (**) and p<0.05 (*).

Species	Mtime	CDI	TV	GSL	Glk %	r
J. phoenicea *P. angustifolia*	1958-2012	2	4	-	48	-0.056
J. phoenicea *P. lentiscus*	1964-2012	13	0.3	-	57	0.045
P. angustifolia *P. lentiscus*	1964-2012	1	0.1	-	47	-0.02

For the period from 1966 to 1972 there is a very good correlation between *J. phoenicea* and *P. lentiscus*. Similarly to the BAI comparison, there are positive and negative peaks occurring synchronously in the three species. The positive peaks in 1993 and 1996 are not as clear as in the BAI series. The most clear positive peak is in 2010, like in the BAI chronologies. *Juniperus phoenicea* and *P. lentiscus* show almost the same amplitude in ring width, while the values of *P. angustifolia* are lower (Tab. 2). Four main negative peaks can be seen in the ring-width chronologies, namely in 1975, 1981, 1990, and 2012, even though they are not as pronounced as the positive peak in 2010. The negative peak for ring width in 1975 cannot be seen in the BAI chronology.

Overall, the values of the ring-width averages are stable over the measuring period, with a slight increasing trend for *J. phoenicea* and *P. angustifolia* (Fig. 15).

Table 2: Ring-width properties all Species. Mean RW (Mean ring width of all samples), min RW (minimum ring width of all samples), St.D (Standard deviation) (1/100 mm).

	J. phoenicea	*P. angustifolia*	*P. lentiscus*
mean RW	83	48	63
min. RW	29	12	37
St.D	21.6	18.4	13.8

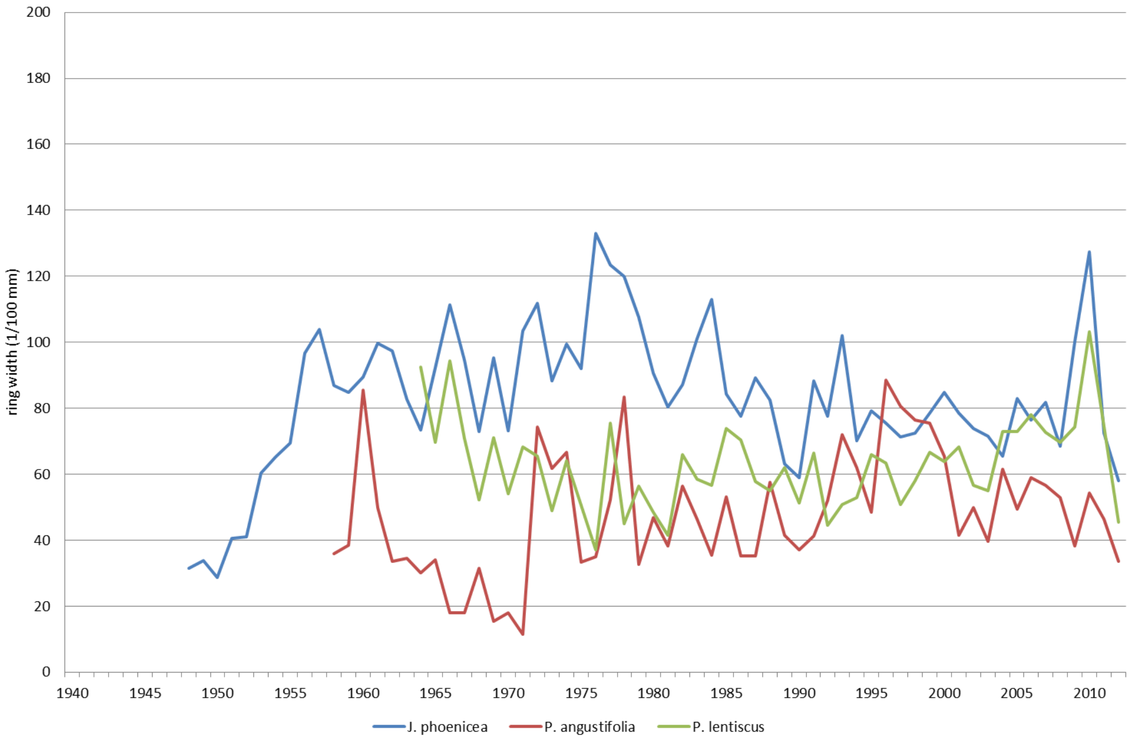


Figure 15: Mean ring-width chronology of *J. phoenicea, P. angustifolia* and *P. lentiscus* from all sites.

4.3.2 *Juniperus phoenicea*

4.3.2.1 Basal area increment values

During the first three decades (1950-1980), the plants do not show any similar growth peaks. In 1984 there is a first positive peak when 8 out of 11 samples show positive BAI values. More recently, similar growth trends and synchronous peaks in 1991, 1993 and 2010 were found. The peak in 2010 is particularly evident in all samples with the exception of JP4, which reached a maximum value one year before. One very low peak year occurred in 1990, where all the samples show low BAI values, except JP9.

The BAI values of the sample JP2 are always higher than the others, with peaks two or even three times as high as the values in the other samples (Fig. 16). In JP2 there is cycle-like regularity in the positive and negative peak years, which starts in 1977. The highest and lowest values in this period are similar in both their negative and positive peaks (maybe with the exception of the positive 2010), and show no age trend after 1977.

Comparing different plants, JP2 reaches its highest values in 1992 and not in 1991 and 1993 (Fig. 16).

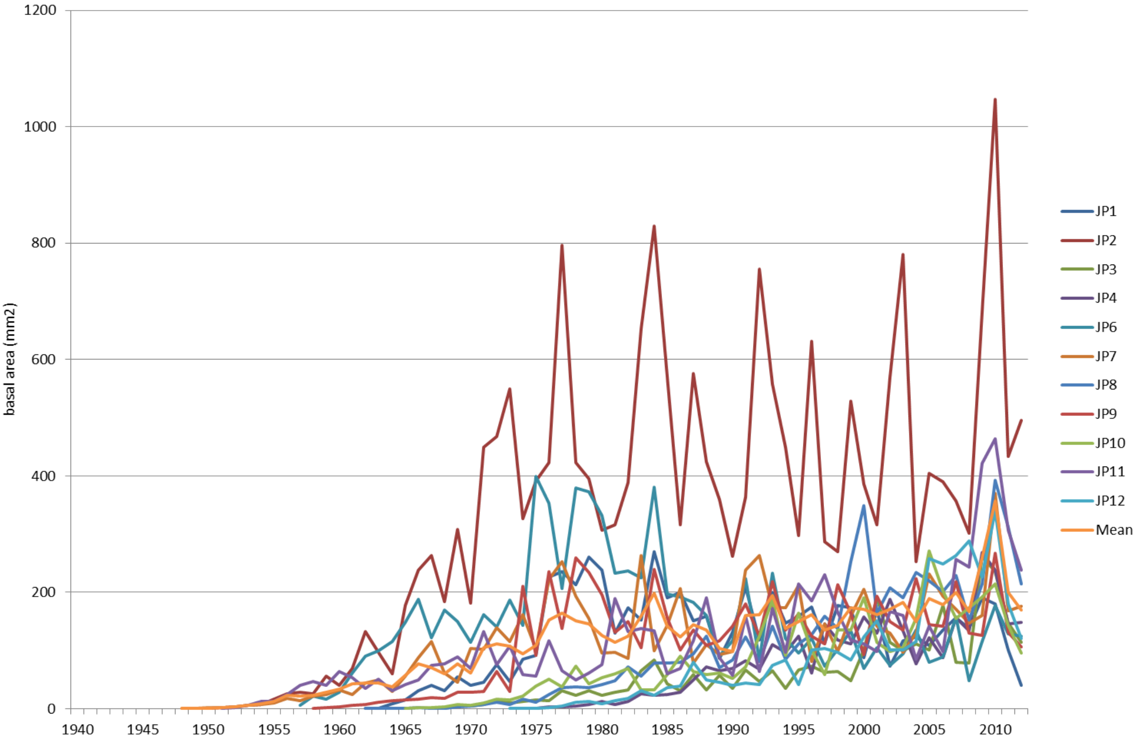


Figure 16: Basal area increment chronology of all samples of *J. phoenicea*.

4.3.2.2 Ring-width values

In Appendix 1 the ring-width values of *J. phoenicea* are shown. A first positive peak in 1972 in more than the half of the samples is evident. The next positive peaks are very similar to them in the BAI chronology of *J. phoenicea*. There are positive peaks in 1984, 1991, 1993 and 2010. Highest synchronicity was again found in 2010, where only two radii do not show high values. First negative peaks can be seen in 1964, 1968 and 1970, even though they are not as pronounced as in the positive peak years. The lowest peaks follow in 1992 and 1994. The next following negative peak is less evident, in the year 2008. The positive peaks in the ring-width chronology are very synchronous with the BAI chronology, whereas the negative are more frequent in the ring-width chronology. In total 6 negative peaks were found in the ring-width chronology, whereas only one was found in the BAI series.

From 1970 to 1980, JP2a and JP9a show very high ring-width values. JP9a values decrease after 1980, JP2a has high values until the peak in 2010 (Appendix 1).

4.3.2.3 Comparing basal area increment and ring-width values

Figure 17 shows the comparison between the mean values of BAI and ring width of all samples. The positive age trend in the BAI chronology is very pronounced, whereas the typical negative age trend in the ring-width chronology is surprisingly absent. The Pearson's correlation analysis shows significant coefficients between the two graphs (r=0.43**, 1948 – 2012). Synchronicity seems especially high after 1964.

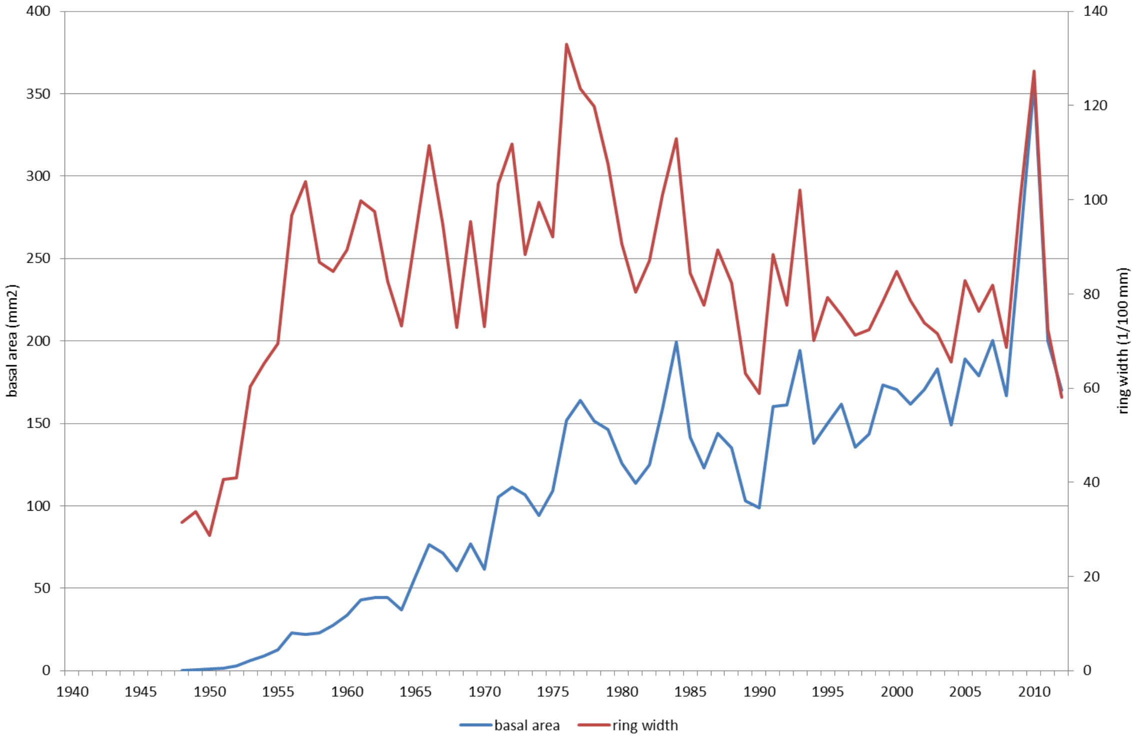


Figure 17: Chronologies of mean basal area increment and ring width of *J. phoenicea* in comparison.

4.3.3 *Phillyrea angustifolia*

4.3.3.1 Basal area increment values

A first positive peak occurs in 1978, where all the already existing plants have high BAI values. Further positive peaks are found in 1996 and 2010, where at least 3 out of the 5 samples show high BAI values. Negative peaks seem to occur more often than the positive ones, and were found in 1979, 1984, 1995, 2001 and 2009. In these years, at least 3 out of the 5 samples show a distinct negative peak in growth. During the period from 1989 to 1992 the samples show not only a one-year negative peak, but also a period with general very low BAI values. PHA5 shows overall the highest BAI values. Especially during the period from 1984 to 1998 the BAI values of PHA5 are high above the BAI values from the other samples. Afterwards the values decrease and become more similar to the values of the other samples (Fig. 18).

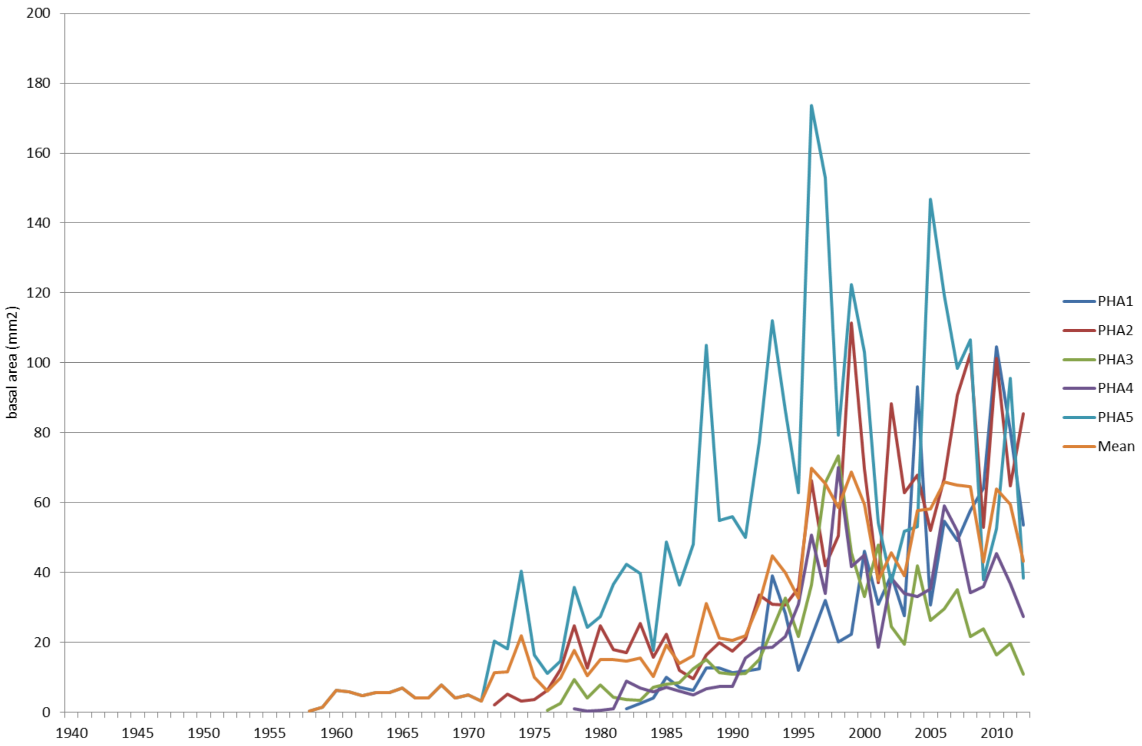


Figure 18: Basal area increment chronology of all samples of *P. angustifolia*.

4.3.3.2 Ring-width values

Seemingly to the BAI values, the first positive peak in the ring-width series can be seen in 1978, where all the radii show high values. Other positive peaks are later found in 1988 and 1996. In 2010, some of the measured radii show an increase in growth, but this peak is not as high as seen in the ring-width chronology of *J. phoenicea*. Similarly to the BAI values, more negative than positive peaks were found (1979, 1986-1987, 1995 and 2001), along with a period from 1989 to 1992, where almost all the radii have narrow rings. The radii of the different plants are generally similar in width (Appendix 2).

4.3.3.3 Comparing basal area increment and ring-width values

Figure 19 shows the mean values of BAI and ring width in comparison. Ring widths do not show any negative age trend, whereas BAI values show a positive age trend at least until 1996. After this peak in 1996, the values stay stable around the same values without a clear trend. Pearson's correlation coefficient is r=0.56** (the whole period).

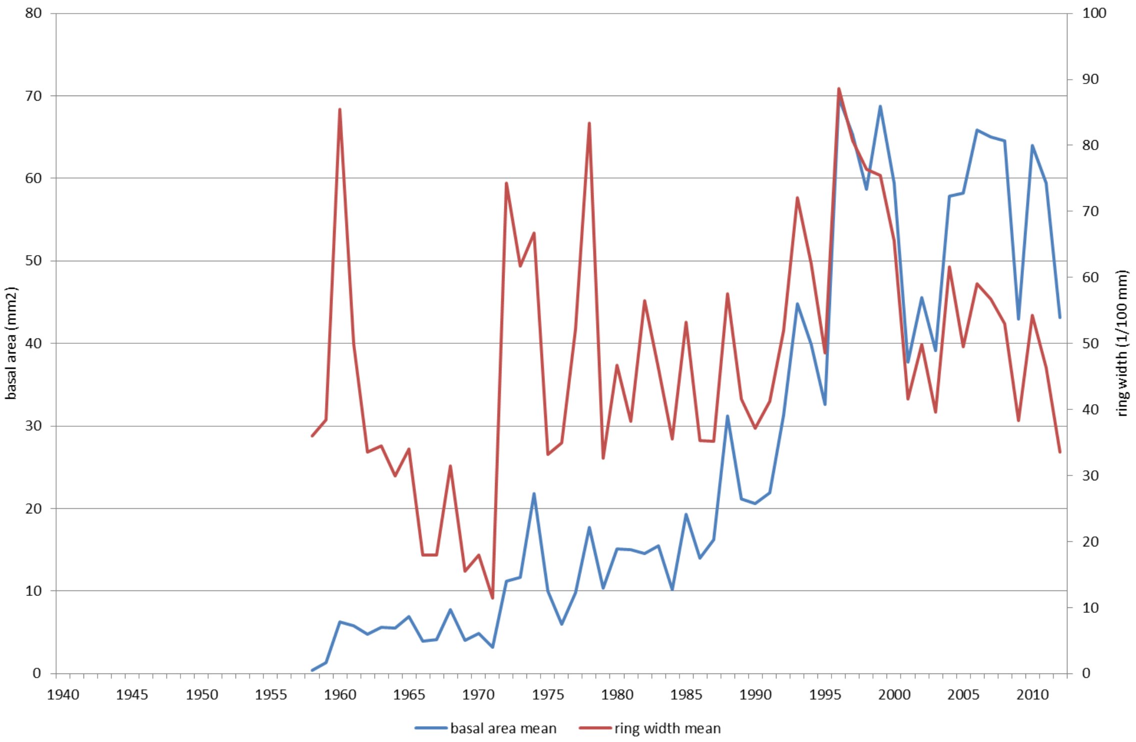


Figure 19: Chronologies of mean basal area increment and ring width of *P. angustifolia* in comparison.

4.3.4 *Pistacia lentiscus*

Pistacia lentiscus was the most difficult species to be analysed, thus, only 15 out of the 22 samples were prepared for further analyses. Especially samples taken at the sites 2, 3 and 4 were particularly difficult to be dated and measured, because of very narrow and unclear (e.g., density fluctuations) rings. Despite the smaller size, the oldest plants of *P. lentiscus* are at site 4.

4.3.4.1 Mean basal area increment values at the different sites

Figure 20 shows the mean BAI chronologies at the different sites. As mentioned before, the values at site 1 are by far the highest. The large difference in values between the different sites starts at around 1998. BAI values at site 1 increase dramatically around 1998, whereas the values at the other sites stay on a similar level as before. Until 1998 at all sites similar BAI values can be seen. The chronologies of the different sites do not correlate well with each other. In 2010, a strong positive peak was found at site 1 and site 3, but was absent at site 2 and site 4.

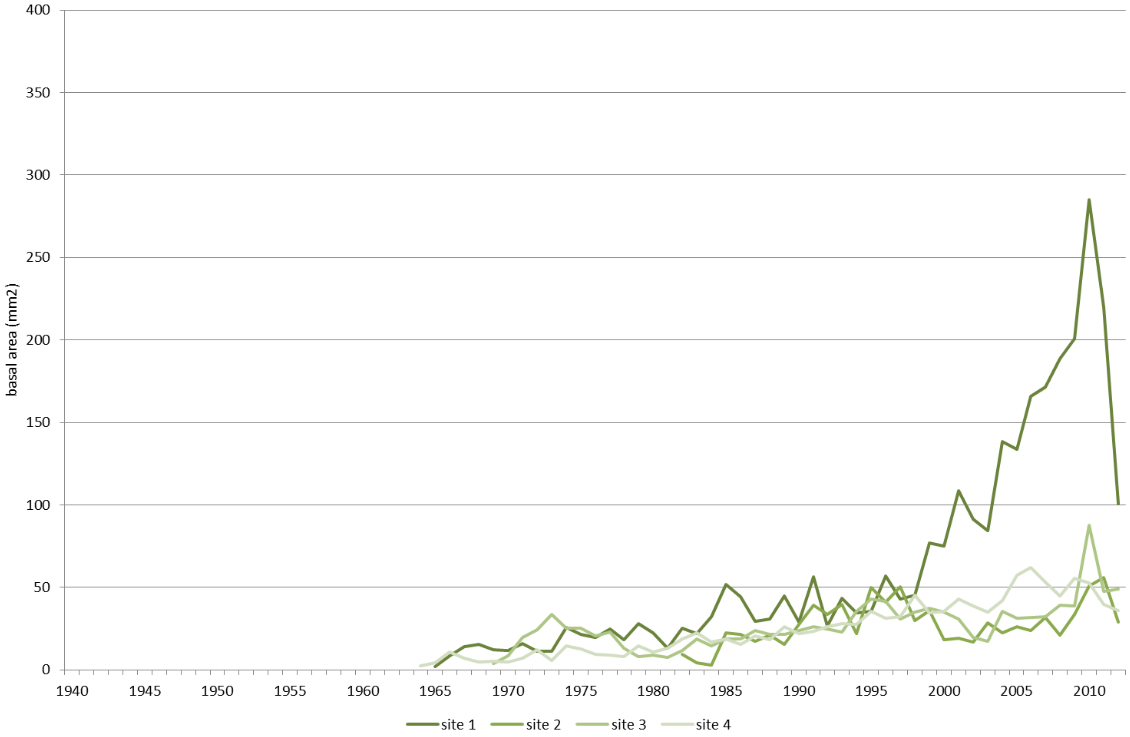


Figure 20: Mean basal area increment chronology of *P. lentiscus* from the four different sites.

4.3.4.2 Mean ring-width values at the different sites

Trends in the mean ring-width chronology were generally different from the BAI chronology. Similarly to the BAI values, ring-width values at site 1 start to increase around 1998 until 2010. Plants at site 2 show a negative age trend. Mean ring widths at sites 3 and 4 decrease after the first years and stay stable until the end with the exception of the positive peak at site 3 in 2010, which is absent at site 4 (Fig. 21).

Table 3: Ring-width properties *P. lentiscus*, all sites. Mean RW (Mean ring width of all samples), min. RW (minimum ring width of all samples), St.D (Standard deviation) (1/100 mm).

	site 1	site 2	site 3	site 4
mean RW	79	64	57	47
min. RW	33	21	34	23
St.D	28.8	28	21.3	14

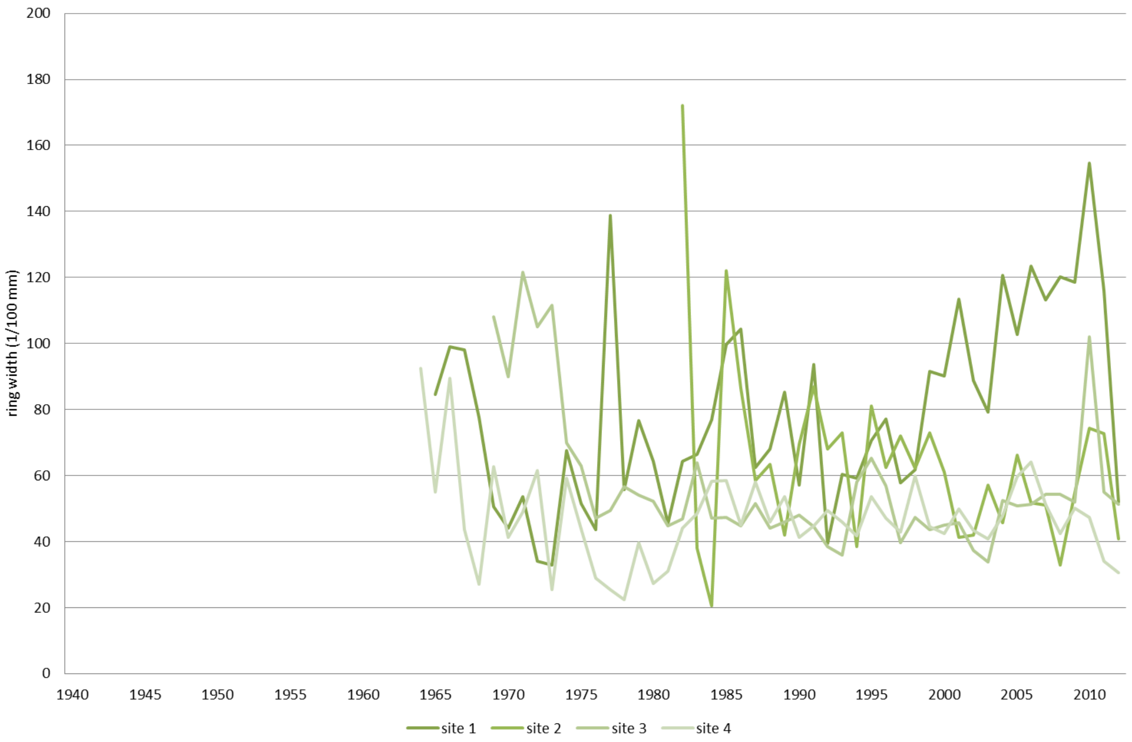


Figure 21: Mean ring-width chronology of *P. lentiscus* from the four different sites.

Similarly to the mean ring-width comparison between the different species, also the comparison between the mean ring widths at the different sites of *P. lentiscus* does not show very good correlation nor *Gleichläufigkeit* values. Only between site 1 and site 4 *Gleichläufigkeit* is significant (Tab. 4).

Table 4: Results of cross-dating within *P. lentiscus* between sites. Mtime (overlapping years), CDI (Cross Date Index), TV (*t*-test), GSL (level of *Gleichläufigkeit*), Glk (*Gleichläufigkeit* between sites), r (Pearson's correlation coefficient). Significance p<0.001(***), p<0.01 (**) and p<0.05 (*).

P. lentiscus	Mtime	CDI	TV	GSL	Glk %	r
Site 1 / 2	1982 - 2012	7	0.5	-	47	-0.08
Site 1 / 3	1969 - 2012	8	1.4	-	62	-0.216
Site 1 / 4	1965 - 2012	6	1.1	**	67	0.165
Site 2 / 3	1982 - 2012	1	0.2	-	35	-0.037
Site 2 / 4	1982 - 2012	1	0.1	-	42	-0.023
Site 3 / 4	1969 - 2012	6	0.8	-	58	0.111

4.3.4.3 Basal area increment values all sites

Positive peaks were found in 1991, 2001 and 2010. Especially in 2010 the BAI values were very high. As seen above, the highest BAI values are of plants at site 1. One negative peak can be seen in 1992 (Fig. 22).

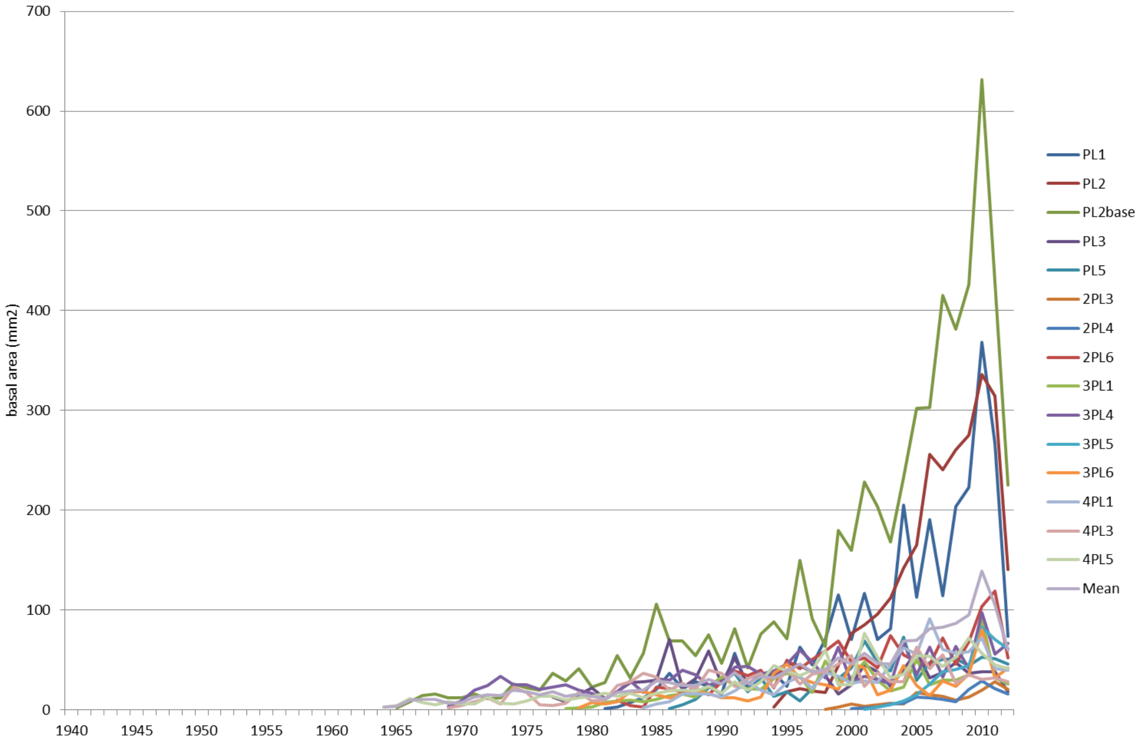


Figure 22 : Basal area increment chronology of all samples of *P. lentiscus*.

4.3.4.4 Ring-width values all sites

Positive peaks in ring width occur in the same years as seen in the BAI series (1991, 2001 and 2010). Very distinct is again the positive peak in 2010, where 11 out of 15 samples show high ring-width values. Almost all the plants reach their highest ring-width values in 2010. The values of the radii reach their highest peaks in the time between 1998 until 2010. Samples of site 1 are mainly responsible for this trend. In the years of 1990, 1992, 2003 and 2009, ring-width values for many samples are very low (Appendix 3).

4.3.4.5 Comparing basal area increment and ring-width values all sites

Figure 23 shows the mean values of BAI and ring width in comparison. There is a positive age trend in the BAI values, which starts from the beginning of the chronology until the high peak in 2010 (low to very low values were found in 2011 and 2012). In the ring-width chronology, no clear negative age trend is visible. Pearson's correlation coefficient between the two series is high (r=0.68**).

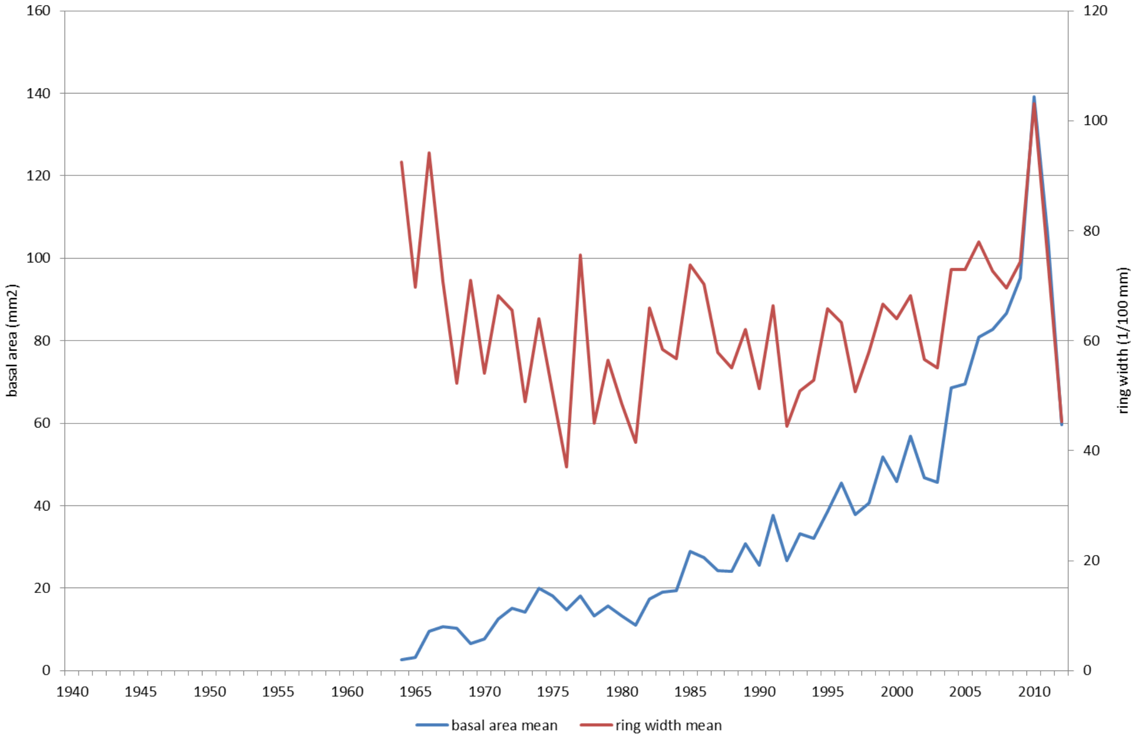


Figure 23: Chronologies of mean basal area increment and ring width of *P. lentiscus* in comparison.

4.4 Tree-ring response to climatic parameters

Beside the RW (ring width) and BAI (basal area increment) variables as mentioned in chapter 3.3.4, size independent variables were calculated to compare with the climatic data. Additionally, for *P. lentiscus* a variable was created using only the values from site 1 and site 4, since the mean ring-width values from these sites correlated well witch each other. For the next tables in chapter 4.4, following abbreviations for these variables were used:

RW 1/4 – Ring-width values only from site 1 and site 4.

BAI 1/4 – Basal area increment values only from site 1 and site 4.

Size 1 JP – Average of the best correlating size independent increments of *J. phoenicea*.

Size 2 JP – Average of the size independent increments of all samples of *J. phoenicea*.

Size PHA – Average of the size independent increment of all samples of *P. angustifolia*.

Size 1 PL – Average of the size independent increment of all samples of *P. lentiscus*.

Size 2 PL – Average of the best correlating size independent increments of *P. lentiscus*.

4.4.1 Precipitation

4.4.1.1 *Juniperus phoenicea*

There is significant correlation between annual precipitation and ring width or the size independent variables. Significant correlation for these variables can also be seen in June and August. Basal area increment values are not significantly correlated with precipitations (Tab. 5).

Table 5: Pearson's correlation coefficient between PREC and *J. phoenicea* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

PREC	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	0.386*	-0.050	0.103	0.271	0.186	0.376*	-0.008	0.269	0.473**	0.174	0.485**	-0.054	0.130
BAI	-0.021	0.140	0.037	-0.110	-0.204	0.022	-0.154	0.094	0.186	-0.094	0.018	0.067	-0.068
Size 1 JP	0.344*	-0.094	0.067	0.255	0.218	0.347*	0.040	0.221	0.381*	0.166	0.4**	-0.035	0.127
Size 2 JP	0.323*	-0.094	0.076	0.318*	0.229	0.314*	0.003	0.206	0.365*	0.154	0.373*	-0.050	0.071

4.4.1.2 *Phillyrea angustifolia*

All three growth variables correlate significantly with annual and in some case monthly precipitations, but, differently form *J. phoenicea*, the correlation is negative (Tab. 6).

Table 6: Pearson's correlation coefficient between PREC and *P. angustifolia* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

PREC	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.36*	-0.149	-0.31*	-0.114	-0.155	-0.271	-0.092	-0.047	0.052	-0.177	-0.234	-0.003	-0.239
BAI	-0.51**	0.030	-0.244	-0.375*	-0.402**	-0.384*	-0.203	-0.171	-0.147	-0.220	-0.358*	0.072	-0.264
Size PHA	-0.449**	-0.335*	-0.287	-0.030	-0.222	-0.237	-0.151	-0.078	-0.068	-0.175	-0.222	0.032	-0.275

4.4.1.3 *Pistacia lentiscus*

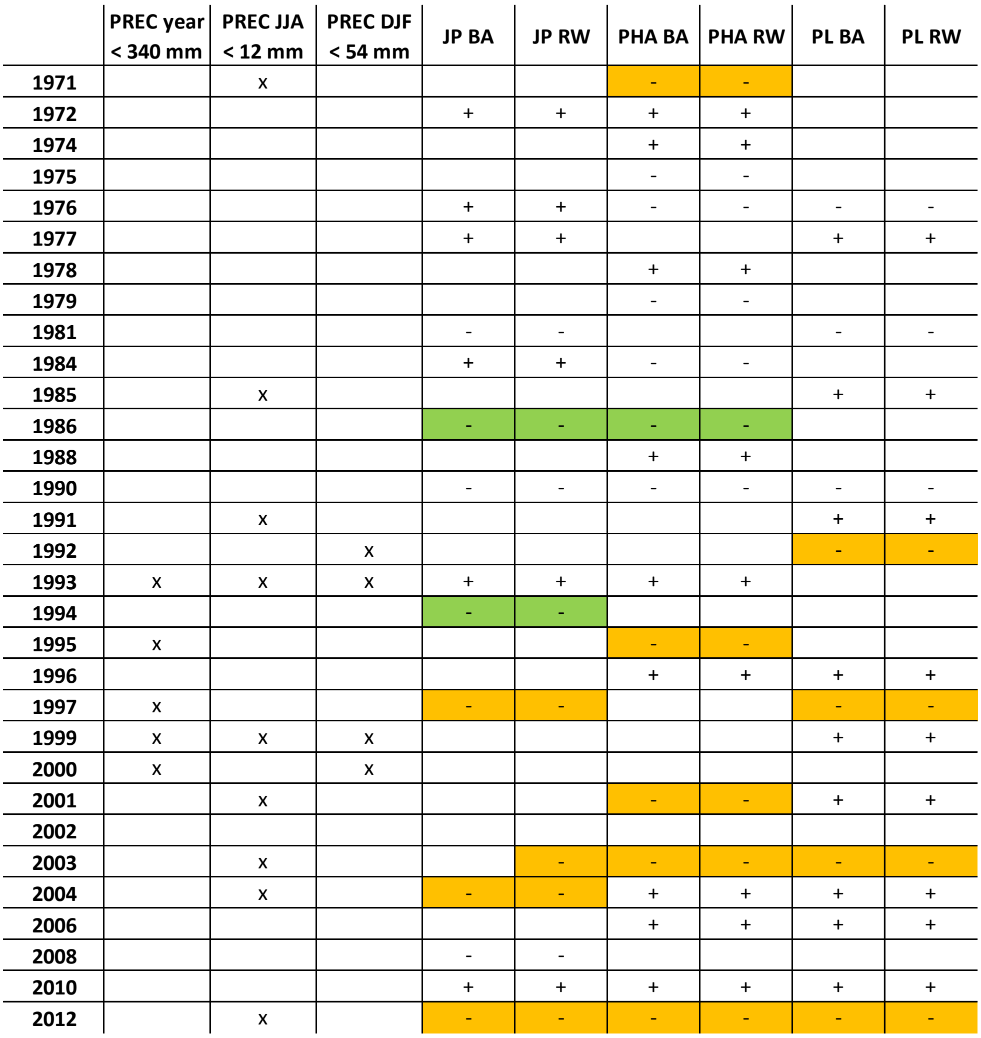
Growth variables of *P. lentiscus* only poorly correlate with the precipitations in October of the current year and, as for *P. angustifolia,* the correlation is negative (Tab. 7).

Table 7: Pearson's correlation coefficient between PREC and *P. lentiscus* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

PREC	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.068	-0.028	0.142	0.152	0.054	0.061	-0.125	0.058	-0.013	-0.204	-0.132	0.039	-0.395**
RW 1/4	-0.146	0.062	0.063	-0.043	-0.043	-0.035	-0.129	0.005	-0.093	-0.182	-0.125	0.056	-0.36*
BAI	-0.170	0.153	0.010	-0.114	-0.201	-0.075	-0.150	-0.062	-0.010	-0.200	-0.239	0.091	-0.218
BAI 1/4	-0.156	0.147	0.033	-0.104	-0.193	-0.066	-0.165	-0.042	-0.035	-0.187	-0.206	0.081	-0.205
Size 1 PL	-0.108	-0.051	0.057	-0.067	0.149	0.090	-0.046	0.080	-0.285	-0.118	-0.181	-0.004	-0.314*
Size 2 PL	-0.158	-0.064	-0.029	-0.030	0.127	0.110	-0.118	-0.007	-0.240	-0.100	-0.187	0.054	-0.378*

4.4.1.4 Drought analysis

Drought occurrence seems to have increased in the last 20 years of the analysis. Narrow ring width and low BAI values matched with summer droughts more often than with the winter or spring drought periods (Fig. 24).



	PREC year < 340 mm	PREC JJA < 12 mm	PREC DJF < 54 mm	JP BA	JP RW	PHA BA	PHA RW	PL BA	PL RW
1971		x				-	-		
1972				+	+	+	+		
1974						+	+		
1975						-	-		
1976				+	+	-	-	-	-
1977				+	+			+	+
1978						+	+		
1979						-	-		
1981				-	-			-	-
1984				+	+	-	-		
1985		x						+	+
1986				-	-	-	-		
1988						+	+		
1990				-	-	-	-	-	-
1991		x						+	+
1992			x					-	-
1993	x	x	x	+	+	+	+		
1994				-	-				
1995	x					-	-		
1996						+	+	+	+
1997	x			-	-			-	-
1999	x	x	x					+	+
2000	x		x						
2001		x				-	-	+	+
2002									
2003		x			-	-	-	-	-
2004		x		-	-	+	+	+	+
2006						+	+	+	+
2008				-	-				
2010				+	+	+	+	+	+
2012		x		-	-	-	-	-	-

Figure 24: Years with exceptional wide (+) or narrow (-) BAI or RW values compared with drought occurrence during year, summer (JJA) and winter (DJF). Yellow fields show matches between drought occurrence and narrow BAI or RW values in the current year. Green fields show matches between drought occurrence and narrow RW and BAI values in the following year.

4.4.2 Temperature

4.4.2.1 *Juniperus phoenicea*

Ring width and the size independent increment of *J. phoenicea* are negatively correlated with temperatures. The highest correlation coefficients are found for TMAX (Tab. 9), lower for TMEAN (Tab. 8) and even lower but still significant for TMIN (Tab. 10). Growth variables correlate with annual mean values whereas temperatures during winter and early spring do not seem to be relevant. BAI values are positively correlated but only with the temperatures recorded in the month of April.

Table 8: Pearson's correlation coefficient between TMEAN and *J. phoenicea* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

TMEAN	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.442**	-0.034	0.024	-0.059	0.071	-0.185	-0.235	-0.314*	-0.373*	-0.154	-0.402**	-0.354*	-0.349*
BAI	0.156	0.221	-0.136	-0.051	-0.235	0.072	0.35*	0.224	0.175	0.274	0.056	-0.046	-0.069
Size 1 JP	-0.516**	-0.110	-0.015	-0.100	0.071	-0.203	-0.285	-0.358*	-0.421**	-0.206	-0.379*	-0.34*	-0.428**
Size 2 JP	-0.476**	-0.084	-0.003	-0.093	0.079	-0.210	-0.261	-0.332*	-0.397**	-0.167	-0.383*	-0.342*	-0.37*

Table 9: Pearson's correlation coefficient between TMAX and *J. phoenicea* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

TMAX	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.632**	-0.309*	-0.262	-0.402**	-0.248	-0.399**	-0.382*	-0.493**	-0.475**	-0.268	-0.456**	-0.472**	-0.441**
BAI	0.291	0.317*	0.019	0.028	-0.052	0.201	0.478**	0.255	0.283	0.270	0.076	0.034	0.117
Size 1 JP	-0.665**	-0.356*	-0.318*	-0.444**	-0.237	-0.394**	-0.453**	-0.532**	-0.538**	-0.267	-0.402**	-0.431**	-0.525**
Size 2 JP	-0.633**	-0.319*	-0.289	-0.436**	-0.235	-0.408**	-0.423**	-0.5**	-0.505**	-0.239	-0.412**	-0.437**	-0.464**

Table 10: Pearson's correlation coefficient between TMIN and *J. phoenicea* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

TMIN	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.357*	-0.275	-0.057	-0.107	0.024	-0.185	-0.217	-0.216	-0.384*	0.107	-0.149	0.026	-0.468**
BAI	0.010	0.213	-0.093	-0.047	-0.269	-0.030	0.220	0.191	0.128	0.094	-0.120	-0.204	-0.057
Size 1 JP	-0.404**	-0.318*	-0.10827	-0.142	0.033	-0.193	-0.227	-0.248	-0.389*	0.076	-0.130	0.060	-0.548**
Size 2 JP	-0.379*	-0.287	-0.097	-0.141	0.038	-0.199	-0.207	-0.232	-0.372*	0.093	-0.163	0.040	-0.489**

4.4.2.2 *Phillyrea angustifolia*

Only the BAI values of *P. angustifolia* are correlated significantly with temperatures and, as for *J. phoenicea*, the highest correlation coefficients were found with TMAX (Tab. 12), lower for TMEAN (Tab. 11), and even lower with TMIN (Tab. 13) but still significant. Ring width is significantly, and positively, correlated only with the temperatures of January.

Table 11: Pearson's correlation coefficient between TMEAN and *P. angustifolia* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

TMEAN	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.014	-0.011	-0.008	0.318*	0.112	0.118	-0.111	0.051	0.039	-0.114	-0.088	-0.032	-0.221
BAI	0.408**	0.184	-0.127	0.238	-0.135	0.199	0.447**	0.471**	0.391*	0.158	0.236	0.121	0.098
Size PHA	-0.033	0.055	0.041	0.244	0.167	-0.097	-0.167	0.032	-0.124	-0.150	0.004	0.081	-0.238

Table 12: Pearson's correlation coefficient between TMAX and *P. angustifolia* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

TMAX	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.144	-0.027	-0.051	0.183	0.119	0.076	-0.133	0.007	0.007	-0.234	-0.246	-0.227	-0.228
BAI	0.53**	0.383*	0.100	0.405**	0.177	0.395**	0.55**	0.526**	0.508**	0.199	0.232	0.205	0.261
Size PHA	-0.256	-0.067	-0.058	0.064	0.091	-0.143	-0.264	-0.072	-0.173	-0.318*	-0.229	-0.238	-0.279

Table 13: Pearson's correlation coefficient between TMIN and *P. angustifolia* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

TMIN	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	0.114	0.075	0.068	0.345*	0.138	0.156	0.007	0.090	0.110	-0.102	-0.080	0.022	-0.124
BAI	0.358*	0.349*	-0.022	0.284	-0.106	0.140	0.458**	0.468**	0.394**	-0.064	-0.014	-0.160	0.220
Size PHA	0.102	0.094	0.073	0.260	0.192	-0.028	-0.036	0.095	-0.034	-0.127	0.053	0.157	-0.143

4.4.2.3 *Pistacia lentiscus*

As for the other two species, the growth variables of *P. lentiscus* are highly correlated with TMAX (Tab. 15) and poorly with TMIN (Tab. 16). Differently form the other two species, all growth variables considered are positively correlated with temperatures. Annual mean temperatures are significantly correlated with BAI values (Tab. 14). At the seasonal scale, significant values are found for all the growth variables in the spring and summer.

Table 14: Pearson's correlation coefficient between TMEAN and *P. lentiscus* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

TMEAN	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	0.157	0.141	-0.079	-0.005	0.046	0.086	0.296	0.104	-0.028	0.35*	-0.050	-0.062	0.108
RW 1/4	0.251	0.151	-0.205	-0.030	-0.029	0.232	0.365*	0.211	0.123	0.375*	0.031	-0.005	0.208
BAI	0.364*	0.245	-0.150	0.057	-0.146	0.195	0.511**	0.372*	0.296	0.296	0.149	0.076	0.128
BAI 1/4	0.367*	0.250	-0.161	0.043	-0.152	0.200	0.521**	0.376*	0.323*	0.308*	0.123	0.073	0.142
Size 1 PL	0.043	-0.005	-0.206	-0.115	0.013	0.027	0.126	0.002	-0.023	0.35*	-0.003	0.018	0.038
Size 2 PL	0.097	0.044	-0.221	-0.079	-0.098	-0.050	0.214	0.104	0.043	0.416**	0.053	0.027	0.020

Table 15: Pearson's correlation coefficient between TMAX and *P. lentiscus* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

TMAX	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	0.254	0.290	-0.023	-0.022	0.144	0.116	0.327*	0.147	0.074	0.405**	0.002	0.078	0.256
RW 1/4	0.383*	0.357*	-0.035	0.068	0.175	0.323*	0.49**	0.312*	0.267	0.358*	0.011	0.070	0.395**
BAI	0.554**	0.448**	0.078	0.213	0.146	0.343*	0.601**	0.452**	0.418**	0.411**	0.256	0.288	0.317*
BAI 1/4	0.561**	0.458**	0.065	0.196	0.142	0.341*	0.623**	0.462**	0.448**	0.417**	0.240	0.285	0.329*
Size 1 PL	0.243	0.267	-0.032	0.034	0.189	0.187	0.275	0.128	0.123	0.36*	-0.048	0.064	0.251
Size 2 PL	0.277	0.327*	-0.038	0.017	0.054	0.106	0.361*	0.209	0.198	0.398**	-0.021	0.079	0.231

Table 16: Pearson's correlation coefficient between TMIN and *P. lentiscus* (1971 – 2012). Significance p<0.01 (**) and p<0.05 (*).

TMIN	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	0.080	0.247	-0.113	-0.007	0.022	0.018	0.266	0.102	0.034	0.171	-0.248	-0.202	0.109
RW 1/4	0.110	0.267	-0.180	-0.016	-0.051	0.129	0.290	0.187	0.116	0.102	-0.223	-0.275	0.237
BAI	0.246	0.343*	-0.101	0.072	-0.164	0.095	0.442**	0.311*	0.291	0.099	-0.080	-0.165	0.171
BAI 1/4	0.230	0.342*	-0.124	0.051	-0.175	0.093	0.429**	0.303	0.300	0.100	-0.100	-0.173	0.179
Size 1 PL	-0.083	0.199	-0.223	-0.098	0.002	-0.044	0.080	0.033	0.002	0.029	-0.303	-0.257	0.094
Size 2 PL	-0.026	0.229	-0.237	-0.070	-0.105	-0.116	0.175	0.125	0.063	0.133	-0.269	-0.207	0.085

4.4.3 Wind speed

4.4.3.1 *Juniperus phoenicea*

The only response to wind speed was found in April, where all three growth variables show significant negative correlation with wind speed. Beside this, correlation is low for the whole year and all the other months (Tab. 17).

Table 17: Pearson's correlation coefficient between WIND and *J. phoenicea* (1991 – 2010). Significance p<0.01 (**) and p<0.05 (*).

WIND	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.106	0.008	0.164	0.060	0.264	0.056	-0.511*	-0.153	-0.156	-0.096	-0.303	-0.080	0.008
BAI	-0.201	-0.083	0.136	0.098	0.243	0.021	-0.582**	-0.049	-0.255	-0.179	-0.171	-0.183	-0.110
Size 1 JP	-0.135	0.085	0.046	0.021	0.233	0.077	-0.445*	-0.243	-0.198	-0.130	-0.405	-0.064	0.066
Size 2 JP	-0.103	0.064	0.130	0.003	0.241	0.047	-0.469*	-0.198	-0.133	-0.059	-0.316	-0.066	0.032

4.4.3.2 *Phillyrea angustifolia*

No significant correlation was found for wind speed (Tab. 18).

Table 18*:* Pearson's correlation coefficient between WIND and *P. angustifolia* (1991 – 2010). Significance p<0.01 (**) and p<0.05 (*).

WIND	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.118	-0.037	-0.069	-0.364	-0.139	-0.283	-0.021	-0.325	0.231	0.405	0.022	0.101	0.196
BAI	-0.295	-0.188	-0.103	-0.411	-0.174	-0.235	-0.344	-0.019	0.148	0.411	0.320	-0.131	-0.153
Size PHA	0.035	-0.037	-0.044	-0.284	-0.081	-0.240	0.132	-0.296	0.340	0.398	0.062	0.148	0.312

4.4.3.3 *Pistacia lentiscus*

Similarly to *J. phoenicea* BAI variables and ring width show a significant negative correlation with wind speed in April. However, in this species, a negative correlation is also present in the month of October (Tab. 19).

Table 19: Pearson's correlation coefficient between WIND and *P. lentiscus* (1991 – 2010). Significance p<0.01 (**) and p<0.05 (*).

WIND	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.253	-0.370	0.191	0.135	0.073	0.149	-0.589**	0.339	-0.266	-0.130	0.103	-0.144	-0.525**
RW 1/4	-0.167	-0.341	0.184	0.067	-0.033	0.185	-0.47*	0.415	-0.130	-0.033	0.230	-0.123	-0.488*
BAI	-0.207	-0.218	0.189	0.069	0.041	0.121	-0.535*	0.257	-0.202	-0.127	0.103	-0.211	-0.375
BAI 1/4	-0.169	-0.222	0.185	0.044	0.001	0.129	-0.489*	0.302	-0.154	-0.084	0.180	-0.203	-0.353
Size 1 PL	-0.064	-0.274	0.231	-0.060	-0.135	0.318	-0.329	0.499*	-0.081	0.035	0.176	0.007	-0.435
Size 2 PL	-0.152	-0.467*	0.110	0.048	0.070	0.226	-0.455*	0.396	-0.098	0.033	0.303	-0.033	-0.506*

4.4.4 Relative humidity

4.4.4.1 *Juniperus phoenicea*

Positive correlations were found in December for all the growth variables. Annual correlation with RH is low overall. Further positive correlation with RH was found in January and September for BAI values (Tab. 20).

Table 20: Pearson's correlation coefficient between RH and *J. phoenicea* (1991 – 2010). Significance p<0.01 (**) and p<0.05 (*).

RH	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	0.201	0.134	0.495*	0.312	-0.044	-0.099	0.150	0.054	0.252	-0.031	0.053	0.313	0.006
BAI	0.361	0.178	0.472*	0.467*	0.102	0.047	0.135	0.145	0.344	0.269	0.170	0.448*	0.090
Size 1 JP	0.089	0.206	0.476*	0.177	-0.050	-0.268	0.105	-0.019	0.175	-0.190	-0.028	0.155	-0.062
Size 2 JP	0.138	0.143	0.483*	0.219	-0.036	-0.166	0.134	-0.010	0.193	-0.140	0.018	0.249	-0.003

4.4.4.2 *Phillyrea angustifolia*

Only for the size independent increment values a significant negative correlation was found (Tab. 21).

Table 21: Pearson's correlation coefficient between RH and *P. angustifolia* (1991 – 2010). Significance p<0.01 (**) and p<0.05 (*).

RH	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	-0.301	-0.437	-0.380	-0.314	-0.177	-0.141	0.146	-0.043	-0.329	-0.216	-0.242	-0.236	0.018
BAI	0.044	-0.257	-0.191	-0.061	0.010	0.069	0.150	0.094	-0.100	0.225	0.051	0.183	0.170
Size PHA	-0.435	-0.478*	-0.454*	-0.447*	-0.189	-0.162	0.027	-0.150	-0.343	-0.335	-0.351	-0.385	-0.130

4.4.4.3 *Pistacia lentiscus*

For ring width and BAI positive correlation was found for the summer period (JJA) and the annual comparison. Values for the size independent increment are only significant for August (Size 1 PL) and September (Size 2 PL) (Tab. 22).

Table 22: Pearson's correlation coefficient between RH and *P. lentiscus* (1991 – 2010). Significance p<0.01 (**) and p<0.05 (*).

RH	Annual	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT
RW	0.461*	0.242	0.406	0.293	0.134	0.123	0.153	0.320	0.348	0.430	0.414	0.56*	0.119
RW 1/4	0.47*	0.224	0.327	0.307	0.112	0.277	0.180	0.366	0.293	0.45*	0.452*	0.517*	0.125
BAI	0.456*	0.155	0.334	0.416	0.115	0.191	0.159	0.201	0.371	0.499*	0.403	0.533*	0.173
BAI 1/4	0.456*	0.163	0.301	0.420	0.121	0.260	0.153	0.213	0.351	0.495*	0.405	0.516*	0.165
Size 1 PL	0.298	0.210	0.245	0.109	-0.115	0.169	0.169	0.360	0.060	0.141	0.45*	0.380	0.059
Size 2 PL	0.371	0.216	0.328	0.137	0.019	0.142	0.233	0.360	0.152	0.293	0.391	0.492*	0.058

4.4.5 Net ecosystem exchange

Juniperus phoenicea shows high correlation values with all the growth variables and, despite the short measuring period, they all are significant. The correlation between NEE and *P. lentiscus* is less strong and only significant for ring width. Correlation with the BAI values and the size independent increment is visibly lower and of no significance. Differently from the other species, *P. angustifolia* shows no correlation with NEE (Tab. 23).

Table 23: Pearson's correlation coefficient between annual NEE and *J. phoenicea, P. angustifolia* and *P. lentiscus* (2004 – 2011). Significance $p<0.01$ (**) and $p<0.05$ (*).

J. phoenicea		*P. angustifolia*		*P. lentiscus*	
RW	0.842**	**RW**	-0.222	**RW**	0.709*
BAI	0.8*	**BAI**	-0.368	**RW 1/4**	0.702
Size 1 JP	0.819*	**Size PHA**	-0.452	**BAI**	0.572
Size 2 JP	0.808*			**BAI 1/4**	0.566
				Size 1 PL	0.406
				Size 2 PL	0.437

Figure 25 shows the comparison between NEE and the ring-width values of all the species. Good to see that when NEE values reach their highest values, ring width of *J. phoenicea* and of *P. lentiscus* are higher. This cannot be said for *P. angustifolia*, where ring width does not seem to follow the same NEE trend.

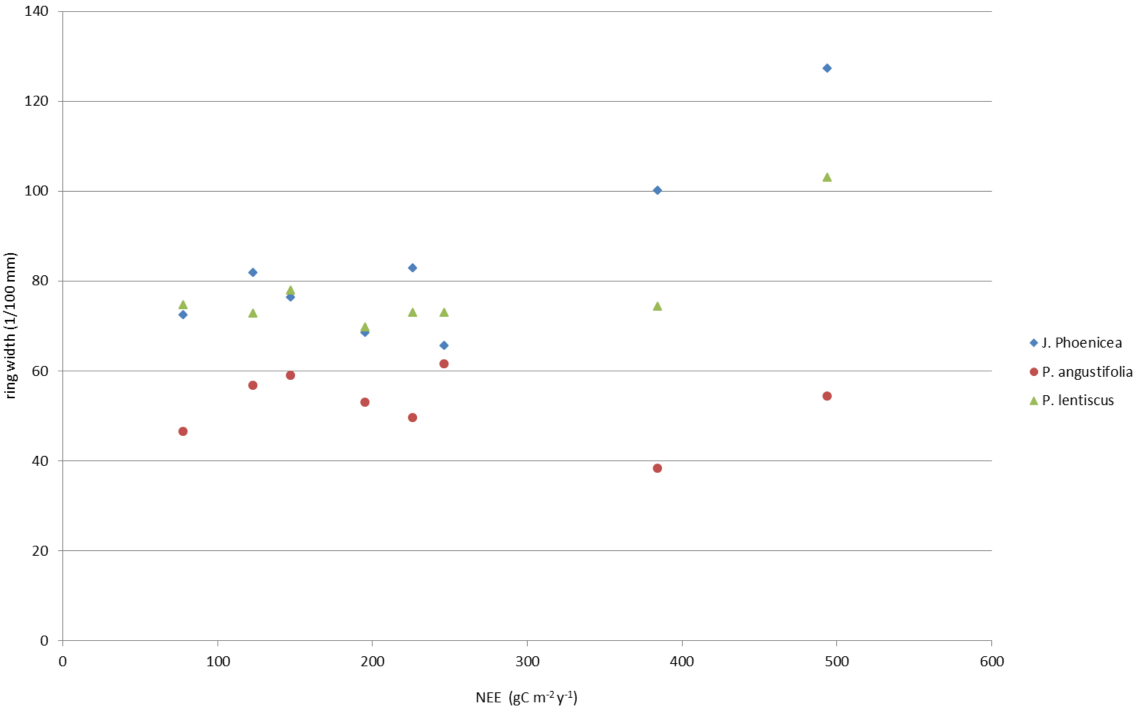


Figure 25: Influence of NEE data on mean ring width of *J. phoenicea, P. angustifolia* and *P. lentiscus*.

5 Discussion

5.1 Methods

As described earlier in this thesis, measuring tree rings of Mediterranean species is often confronted with the problem of false ring formation (IADF) (De Micco et al., 2007; De Micco et al., 2012; Battipaglia et al., 2010; Battipaglia et al., 2014; see for a review Cherubini et al., 2003), which could influence the results of the tree-ring analysis. Aware of this occurrence, lot of time was invested to clearly identify and exclude them from the measurement. Working with tree disks enhanced the correctness of the results, since analyses with cores imply a higher uncertainty in case of missing rings or IADF identification problems (Cherubini et al., 2003). Overall, the cross-dating methods were successful, and the ring-width chronologies can be considered correct. Additionally, the good correlation of the three growth variables with NEE confirms that the measurements are correctly reflecting the yearly growth.

Another point which can influence the outcome of the survey is the decision of the statistical methods to standardize the measurements, for removing age trends. The age trend is generally more pronounced in very old trees (Biondi et al., 2008), while the samples we collected were of younger age and no clear age trend was visible in the ring-width chronologies. Moreover, it should be considered that removing the age trend, other trends, which might be of interest for the thesis, can be removed as well (Biondi, 1999). Thus, I did not use common dendrochronological standardization programs. In order to verify my results and minimize the age – size dependency, I worked with the basal area increment to compare the results with the raw ring-with data. However, the strong and positive correlation on a logarithmic scale between BAI and basal area, suggests a size-age dependency of growth and so, for the correlation with climatic data, size independent increments of basal area were also calculated, to have also a parameter of tree-ring data which should minimize the effect of plant size. Although the r coefficient and its sign are different depending on which growth variable is used, often all three growth variables correlate similarly to the meteorological driver. Thus, the most robust analysis should be seen as that that yields the same information irrespectively of the growth variable.

Furthermore, the rather young age when working with shrubs can be considered as a general source of uncertainty in climatic studies, given the short period of comparable data, in comparison with species with a longer life span.

5.2 Ring-width chronologies

When looking at the chronologies of the ring width values, they do not show a strong *Gleichläufigkeit*. The correlation between the different plants of the same species was significant for the most of the samples, but the species really differ in their growth patterns. Considering the results of the climate correlation this is not surprising, because they respond differently to the climatic parameters. However there are years in which all the species show an increase or decrease in growth in the same year, which leads to the assumption that the same meteorological driver is affecting all the species. Comparing these positive (1993, 1996, 2010) or negative (1975, 1981, 1990, 2012) peak years with the climatic data, no clear connection was found. Thus, other factors than the climatic parameters have influenced the plant growth as well.

The mean values of ring width of the three species showed no very clear trend. For *J. phoenicea* and *P. angustifolia* a slight increasing trend in mean ring width was found over the measuring period. Comparing this with the established climate trends for Capo Caccia, it seems that until now, plant growth as a whole is not negatively affected through enhanced temperatures.

5.3 Tree-ring response to climatic parameters

Correlation with meteorological variables was in general weak although significant, suggesting a great ability by the species to adapt to annual meteorological variability. This ability is a well-known ecological trait of Mediterranean species and is achieved thorough a multitude of strategies that can differ among species (Garcia-Estringana et al., 2010). Complex dynamics controlling for the amount of annually stored reserves are likely to be mostly responsible for buffering low resource years (Mereu, pers. comm.). Overall it can be said that the species reacted differently to the meteorological variables, when there was a response at all, suggesting a different species-specific ecology.

5.3.1 Precipitation – drought periods

The precipitation signal in the three species is very different from each other and not very strong overall. *Juniperus phoenicea* showed a positive response to water availability whereas the response of *P. angustifolia* was negative and that of *P. lentiscus* was absent. This suggests that *J. phoenicea* is the most sensitive species to drought, in terms of growth, whereas the two other species are more resistant. This difference in correlation possibly reflects the different rooting depth of the species: shallow for *J. phoenicea* and deeper for the other two (Armas et al., 2010; Castillo et al., 2002). The different rooting depth would also explain the significant correlation of all three growth variables of *J. phoenicea* with summer precipitations, as plants with superficial roots often have a greater ability in taking up water immediately after unpredictable rain events (Cherubini et al., 2003). The strategy of plants with superficial roots is to use even those small amounts of water (including water from condensation) that only wet the superficial soil layers. This occurs often in the Mediterranean, where the drought period rain events of few mm wet the top soil without reaching the lower layers (Castillo et al., 2002). One other possible explanation could be that *P. lentiscus* is better suited for taking up salty groundwater than *J. phoenicea*, as it is mentioned in other studies (Armas et al., 2010). Furthermore, *P. lentiscus* is reported by Armas et al. (2010) to have roots which reach deeper soil layers. This and the advantage in dealing with salty groundwater contributes maybe to be less dependent on precipitation. *Phillyrea angustifolia* is known to have a low water requirement, which can be a reason for not showing a great dependency on precipitation (Fernandez et al., 2006) and it should be also noted that differently from the other two species, *P. angustifolia* is grazed by different mammals and so has a reduced leaf area index. Furthermore, for *P. angustifolia* and *P. lentiscus* it is reported that the plant activates several photo- and antioxidant protection, which helps to withstand summer drought (Penuelas et al., 2004; Mereu, pers. comm.).

Beside the correlation with annual and monthly precipitation data as well as looking at the seasons, response to specific drought periods was observed. Three thresholds for each observed period, which were year, summer and winter, were set according to their precipitation values. These drought periods were then compared with ring width and BAI extreme values of each species in the same year or a year after drought occurrence. Drought occurrence increased during the last 40 years. Since 1990, every second year a drought occurred, while in the same time frame from 1970 to 1990, a drought occurred only two times. These observations are similar with what is in general said about the future occurrence of summer drought in the Mediterranean, that their occurrence probably will rise (e.g., Giorgi, 2006; Nicault et al., 2008).

In comparison with the ring width and BAI values, several years were found where a possible connection between narrow ring width and low BAI values exists. *Juniperus phoenicea* seems to be mostly affected by summer drought. Three times, years with narrow ring width matched the years where a summer drought occurred. Drought in winter however, does not seem to have an impact, which is not a surprising result. Also the response to low mean annual precipitation is not very strong, as already observed in the past at different sites in different species (Cherubini et al., 2003). Results for *P. angustifolia* and *P. lentiscus* are very similar, and also for these species response to drought during summer is the highest.

5.3.2 Temperature

The response of the three studied species to temperatures was very different. For *J. phoenicea* it seems that temperature has an influence on its growth, since some significant correlation was found. The clearest signals were found for TMAX and TMEAN, while response to TMIN seems not to be very strong. The correlation values between ring width and basal area increment variables are very different and show negative values for ring width and the size independent variable, and positive correlation for BAI. The positive correlation with BAI values is probably due to the fact that the temperature in general has risen during the last 40 years, as well as the BAI values, and the correlation therefore is influenced by this synchronicity. The negative correlation with temperature of *J. Phoenicea* as compared with the other two species confirms that this species is not as termophyllous as the other two. Additionally, the negative correlation with summer temperatures, being aggravated by the concomitant drought, suggests that the two factors combined together can have a strong effect on growth (Llorens et al., 2003). This additive effect suggests that it is not only a direct effect of temperature on plant metabolism but an increased potential evapotranspiration that aggravates the drought period. Additionally, higher temperatures increase the direct evaporation of water from the top soil layers, thereby depleting a resource that is possibly used by *J. phoenicea* (Mereu, pers. comm.). It seems overall that *J. phoenicea* is more influenced by temperature than precipitation. Although cold stress is often found to be a limiting factor for Mediterranean species (Cherubini et al., 2003), *J. phoenicea* showed no correlation with TMIN in agreement with its presence also in relatively cold stations. Although there can be seen an influence for TMAX and TMEAN on plant growth, correlation with TMIN did not show a clear trend in the way we expected. It seems that growth of *J. phoenicea* is not affected by low minimum temperatures during the winter, or in any time of the year. If the predicted increase in temperature for the Mediterranean especially in combination with drought periods (Giorgi, F., 2006) will occur, *J. phoenicea* possibly will show a decrease in growth.

The comparison of *J. phoenicea* data with temperature clearly differ from the results of the other two species. Also for the other two species there is a positive correlation with BAI values but, as mentioned above, they tend to correlate with a general increase in temperature and therefore are to be looked at carefully. For *P. angustifolia* no clear signal can be seen when regarding ring width, and a low significant correlation was found with July only.

In contrary to the other two species, *P. lentiscus* responds positively to TMEAN and TMAX. A strong influence seems to occur mainly in spring during the main growing period. Considering that temperatures are not already that high in spring, it seems explainable that higher temperatures enhance plant growth. Surprisingly also the correlation in July was positive for TMAX and TMEAN. Even though this result seems to suggest that high summer temperatures are supporting growth of *P. lentiscus*, it is maybe showing that *P. lentiscus* is more resistant to high summer temperatures than the other two species. *Pistacia lentiscus* is not usually found at cold sites, and, at our site, a frequent complete leaf loss was observed during the winter months (Mereu, pers. comm.). Because of this, it is somehow surprising that growth of *P. lentiscus* seems not to be influenced by low minimum winter temperatures.

Nevertheless, in another study, carried out under comparable climatic conditions, *P. lentiscus* showed a large tolerance to low winter temperatures (Gratani et al., 2013).

Generally response to the different temperature parameters is higher than for precipitation. Furthermore it can be considered that high TMAX and TMEAN influence on the growth of the shrubs is higher than TMIN. In no case low temperatures during winter seem to have a strong impact on plant growth. This is probably due to the fact, that average winter TMIN values in Capo Caccia are around 9°C and frost days are rare. The results might look different for the same species growing further north or at higher altitude.

While the response for precipitation and temperature in the correlation analysis for *P. angustifolia* and *P. lentiscus* was rather low, it seems that a combination of summer drought and very high maximum temperatures have an influence on their growth, as also seen for *J. Phoenicea*. In the years 2003 and 2012 all species show narrow ring width and BAI values. In these years the average TMAX for summer (JJA) were exceptionally high, with 30°C in 2003 and 29.9°C in 2012 (TMAX average 1970 - 2012 = 25.7°C). This may indicate that plants are mostly stressed when there is a lack of water supply, combined with extremely high maximum temperatures in the summer. For *J. phoenicea* similar results were reported in other study (Rubio-Casal et al., 2010), where also summer drought occurrence and high maximum temperatures, as a key factor to growth decrease, were established.

5.3.3 Wind speed

Potential evapotranspiration is enhanced by wind speed as wind disrupts the canopy and leaf boundary layers and thus increases the exchange rates of energy and gasses. Wind speed could have enhanced the drought effects and consequently reduce plant growth (Mereu, pers. comm.). However, a negative correlation was found only for the month of April for *J. phoenicea* and *P. lentiscus*, suggesting that the negative impact on growth could be occurring as a consequence of a mechanical damage on the new spring shoots (Grace, 1988). So influence of wind is best visible while plants are in their main resprouting period. Results in May and March, the other months where the plants usually show strong growth (Cherubini et al., 2003), which are worse especially for *J. phoenicea,* may be explained by the fact that in

March temperatures are not already high enough to initiate the main growth period, and therefore wind influence is less visible. In the month of May, new leaves have completed their development and are more resistant to mechanical stresses (Read et al., 2006). Additionally, mean monthly wind speed is too low (in average 4 kmph less than in April, 1990 - 2010) to have an impact on the growth of the plants.

For *P. lentiscus* the results look a bit different. As mentioned above wind also seems to have an impact mostly in April. But, foremost compared with the ring-width values, also some response to wind speed is visible in October and a bit less in November. As the relation is negative it also seems that stronger autumn wind reduces growth. It should be noted that often in autumn-winter a strong defoliation of non-senescent leaves was observed in the site. Completely, or nearly completely, defoliated plants recover their leaf biomass only the following spring, thereby remaining the whole winter without the possibility to photosynthesis and thus store reserves for the coming spring (Mereu, pers. comm.). The sensitivity to wind speed is not explained by leaf size, as wind speed had no effect on *P. angustifolia,* which is similar in size and taken from the same places. However, the canopy of *P. angustifolia* is much more compacted than that of *P. lentiscus,* also as a consequence of grazing. Possibly the compactness of the canopy strongly increases the aerodynamic resistance and partially protects the species from mechanical damages or excess transpiration (Read et al., 2006).

5.3.4 Relative humidity

It was considered that a high RH would help the plants to minimize drought stress, especially during the summer time (Chaves et al., 2002). The hypothesis was partially confirmed for *P. lentiscus,* where significant positive correlation was found in the summer period (including September) for ring width and BAI values. This correlation with high RH values during the summer might be a factor amongst others (see 5.2.1), that *P. lentiscus* does not seem to be influenced negatively by dry conditions.

5.3.5 Net ecosystem exchange

The results show a significant correlation for *J. phoenicea* in ring width, BAI as well as in the size independent increment. *Pistacia lentiscus* shows some lower correlation but just significant for ring width, whereas for *P. angustifolia* no response was found. As mentioned before, *J. phoenicea* is by far the most dominant and also abundant species in the area (Baraldi et al., 2005). Thus, CO_2 fluxes are mostly influenced by this species and depend on the biggest part on their photosynthesis rate. It seems feasible that *P. lentiscus* which follows in dominance and abundance as second species, still can be considered to have a visible influence on CO_2 fluxes, whereas this is not the case for *P. angustifolia*.

While tree-ring growth is a proxy of plant growth, it should be kept in mind that in this thesis the correlation between plant-stem diameter and plant biomass is unknown. It is likely that the three species differ in carbon allocation (e.g., allocation to roots, branches and leaves) or and investment (root and leaf turnover). These allometric relationships would be necessary to compare annual growth from tree rings with NEE. Additionally, to perform a proper up scaling, the size distribution and the basal area of each species in the stand would also be needed (Mereu, pers. comm.). On the other hand, EC systems measure the net accumulation of carbon in the ecosystem, which includes soil respiration and all the photosynthesized CO_2 not used for growth but stored as a reserve in plant tissues. All these differences do not allow for a direct comparison of the two measures: large carbon storage pools are considered as a main problem in linking tree-ring growth with contemporaneous EC measurements of CO_2 exchange (Rocha et al., 2006). Hence, the good correlation found between NEE and ring width suggests the possibility, that studied species do not invest much in reserves. This is not likely, as an ability to store reserves is an essential trait for survival in highly variable climates like the Mediterranean, instead it is likely that reserves are either fairly constant among years or directly proportional to growth (Cruz et al., 2001).

5.4 Evaluation of the research questions and hypotheses

H1: In the years where drought periods occur, plants show smaller ring width.

The results confirm this hypothesis only for *J. phoenicea*, whereas *P. angustifolia* and *P. lentiscus* did not show a correlation with annual precipitation. However they were influenced by strong drought periods during the summer. So this hypothesis can be partly confirmed and it can be said that *J. phoenicea* seems to be the species which is mostly influenced by the lack of water supply, and that there is a response to precipitation, but not always, and other factors seem to influence the response of the plants as well.

H2: Winter low minimum temperature has a detrimental effect of ring width.

The results show no clear trend. Low minimum temperature has not a decreasing effect on growth of any of these species.

H3: Summer high maximum temperature has a decreasing effect of ring width.

Results show a significant negative correlation between TMAX and *J. phoenicea* during summer. So it can be assumed that high TMAX in summer has a decreasing effect on ring width of *J. phoenicea*. For the other two species no proof was found.

H4: Higher wind speed leads to a decrease of growth.

There is a connection between wind speed and growth. *Juniperus phoenicea* and *P. lentiscus* both showed in the correlation analysis a negative correlation with wind speed in April. No response on growth in connection with wind speed was found for *P. angustifolia*. For *J. phoenicea* and *P. lentiscus* wind speed seems to have a negative influence on growth during their main growth period.

H5: High relative humidity values minimize the effect of summer drought.

The results show a positive significant correlation during the summer for *P. lentiscus*. The other two species did not seem to be influenced by high RH values during summer.

6 Conclusions

This thesis aims at deepening the knowledge about the response of three typical macchia shrubs to different climatic parameters, using dendrochronological methods. The observed response was not always very strong, but some significant tendencies could be found. The signal of precipitation in general was not very high and significant for *J. phoenicea* only. It seems that *J. phoenicea* is more sensitive to precipitation than the other two species. However, the results are different, when additionally to the correlation analysis with precipitation also severe drought events are considered. In years when severe drought periods during summer occurred, also *P. lentiscus* and *P. angustifolia* responded in some years with narrow ring width, mainly when very high summer maximum temperatures were measured for the same period. It overall looks like temperature has a higher impact on the growth of these species. *Juniperus phoenicea* suffers the most from high temperatures, especially high maximum temperatures during the summer seem to have a negative influence on growth. In *P. lentiscus* and *P. angustifolia* the correlation analysis found no negative impact of high temperatures on their growth, it is rather the opposite, particularly for *P. lentiscus*. However, it is likely that very high maximum temperatures in summer, as occurred in 2003 and 2012, combined with drought, lead to a decrease in growth also for *P. lentiscus* and *P. angustifolia*.

The main conclusion of this thesis is that *J. phoenicea* will probably be the first species to suffer from less precipitation and especially from higher temperatures. In addition, I conclude that the probably most serious threat to all of these species, are severe drought events combined with very high maximum temperatures during the summer season (JJA).

As presented in the thesis, it is most likely that years with very high maximum temperatures will not be an exception in the near future, since observed high maximum temperatures have risen significantly of about 2.5°C for the last 40 years. In the opposite, low minimum temperature and drought during the winter seem not to affect plant growth negatively in these species. To achieve more knowledge about these species, it certainly would be interesting to do similar research in other areas, e.g., further north or at higher altitude, to analyse the impact of low minimum temperature in these areas. In another attempt it would be interesting to include pedological and hydrological data of the research site into the study, which would allow being more specific in relation to the influence of precipitation.

Furthermore, this thesis showed that combining NEE data with dendrochronological methods can be an important tool in future studies, concerning global carbon cycle. But as discussed, limitations with this method are that only information about the dominant or most abundant species in an ecosystem can be generated, since NEE are mostly influenced by these species.

Main achievements

- Drought occurrence at Capo Caccia increased during the last 40 years.
- *Juniperus phoenicea* is the most sensitive species to drought, in terms of growth, whereas the two other species are more resistant.
- *Juniperus phoenicea* is the species which suffers the most from high temperatures during the summer season (JJA).
- In all the three species, the general influence on growth of high maximum temperatures in summer is higher, than the influence of low minimum temperatures in winter.
- The probably biggest threat, for all the three species, are severe drought events, combined with very high maximum temperatures during the summer season (JJA).

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8 Literature

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9 List of tables

10 List of figures

11 List of abbreviations

BAI – Basal area increment

CDI – Cross Date Index

DJF – December of the previous year, January and February of the current year

EC – Eddy covariance

IADF – Intra-annual density fluctuations

JJA – June, July and August of the current year

NEE – Net ecosystem exchange

PREC – Mean monthly precipitation

RH – Mean monthly relative humidity

RW – Ring width

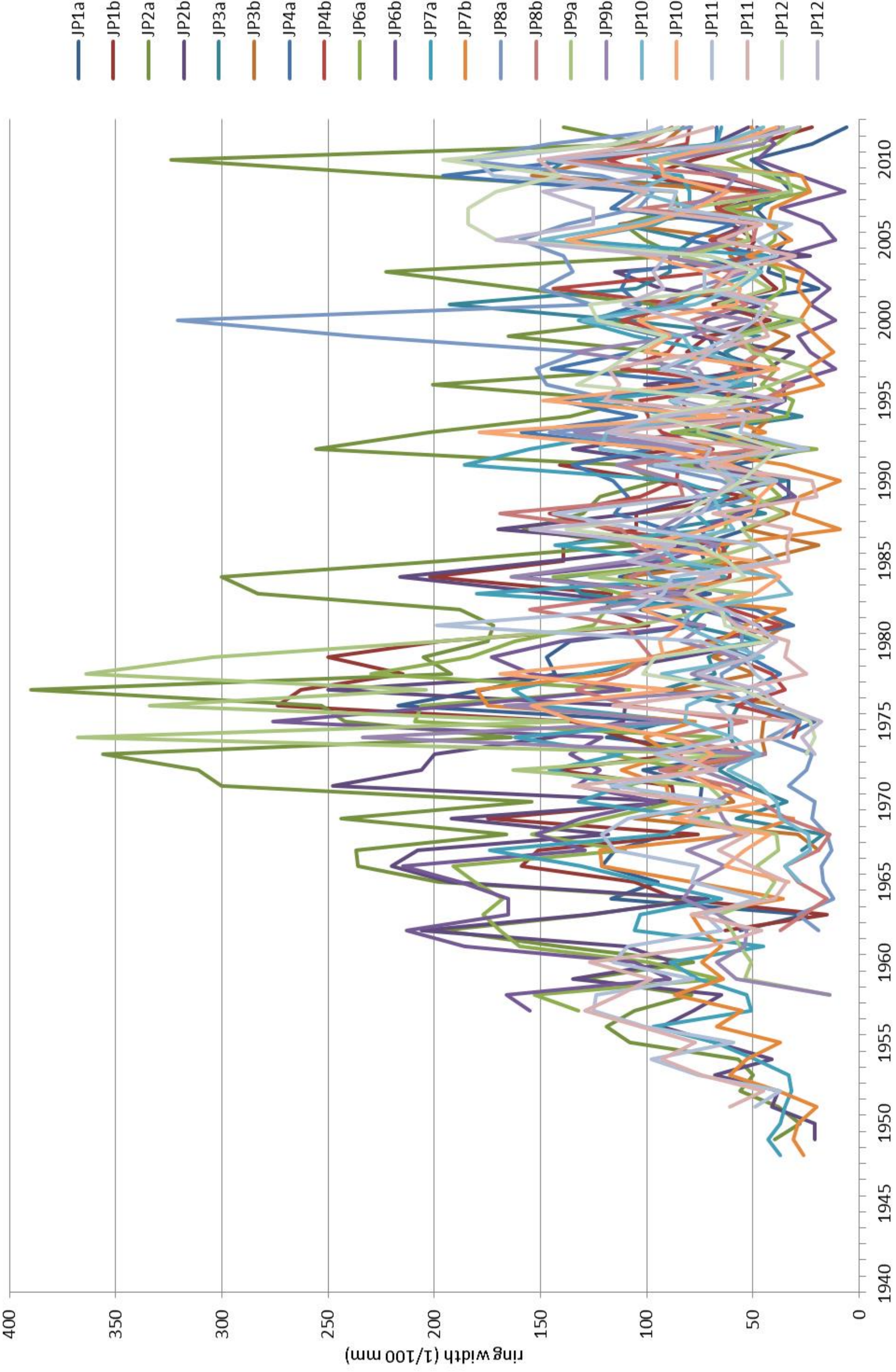
TMAX – Mean monthly maximum temperatures

TMEAN – Mean monthly temperatures

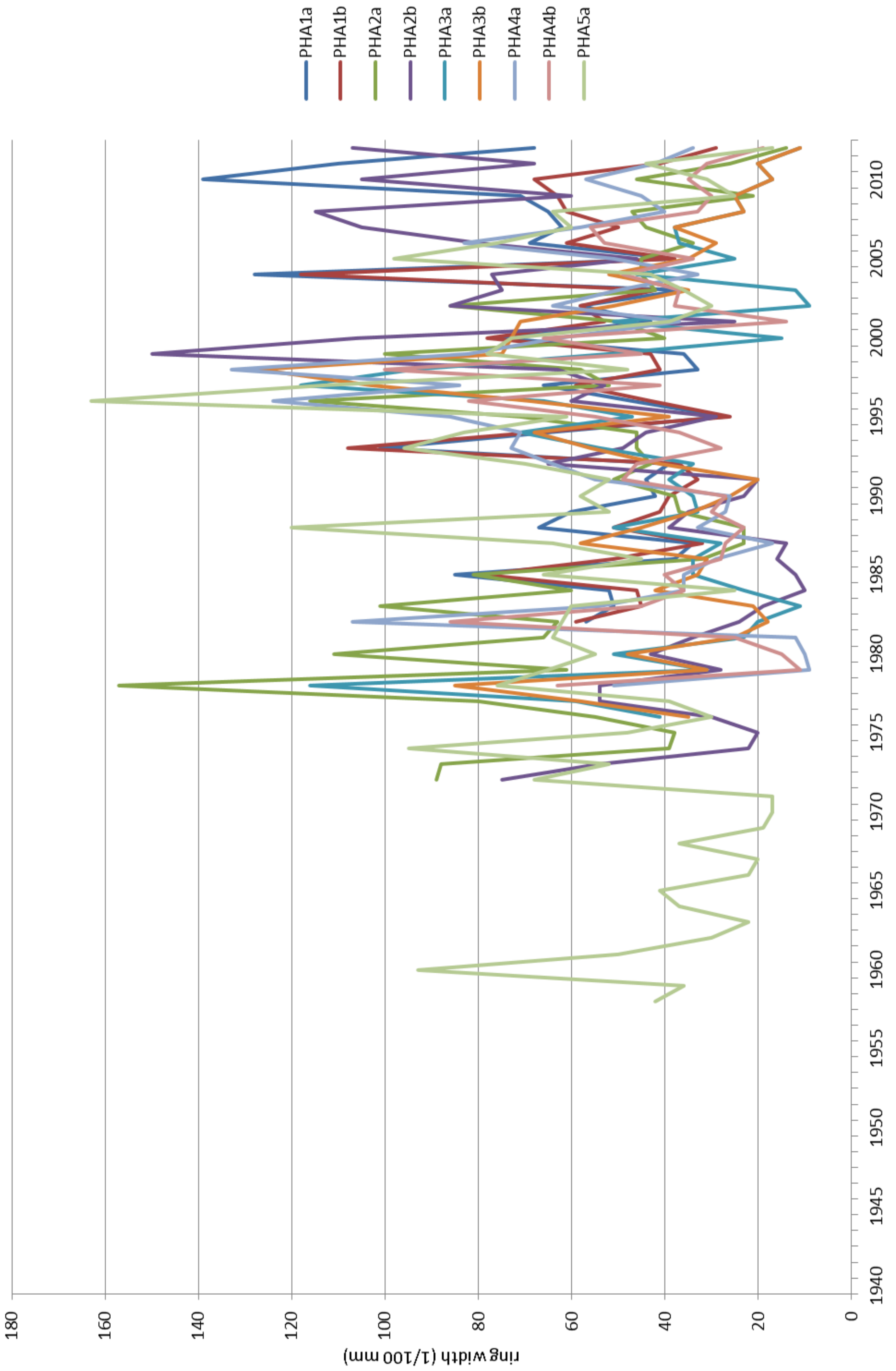
TMIN – Mean monthly minimum temperatures

WIND – Mean monthly wind speed

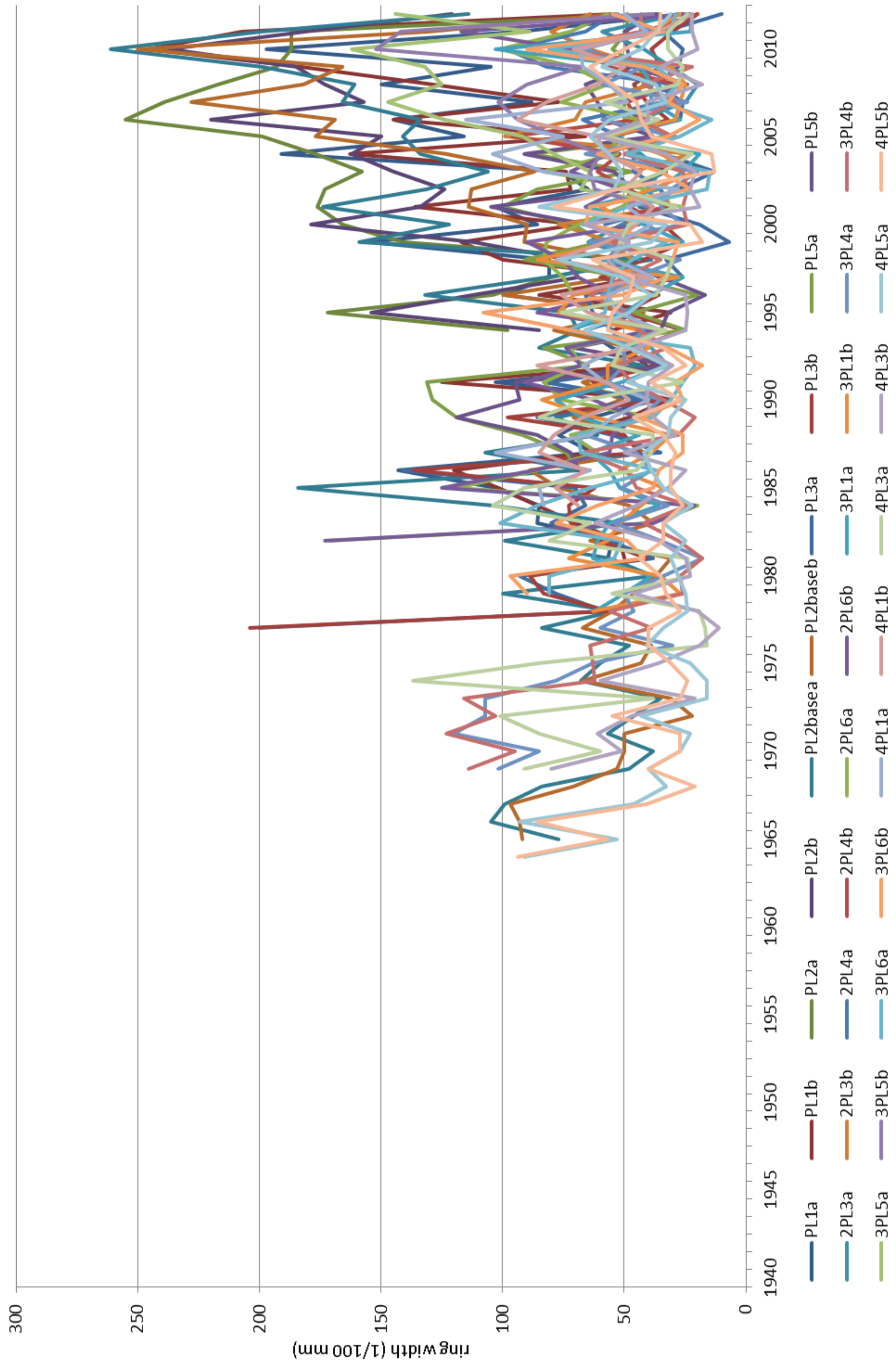
A Appendix



Appendix 1: Ring-width chronology of all measured radii of *J. phoenicea*.



Appendix 2: Ring-width chronology of all measured radii of *P. angustifolia*.



Appendix 3: Ring-width chronology of all measured radii of *P. lentiscus*.

Personal declaration

I hereby declare that the submitted thesis is the result of my own, independent, work. All external sources are explicitly acknowledged in the thesis.

Simon Vollenweider