(Kelsey, 2013)

Dendrochronological study of the structure and dynamics in a subalpine spruce-larch stand in Davos (Switzerland)

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2 Abstract

Mountain forests as found in Dischma (Davos, Switzerland) have important protective functions for the communities that live in the valleys. Thus, it is of great importance to understand ecological processes in these forests. But human impact influences forest dynamics to a degree that it becomes difficult to observe and understand the natural processes within a forest. In the last century, human impact on mountain forests has decreased because of urbanization and low profitability of poorly accessible stands. As a consequence, the natural dynamics slowly take over again in many mountain forests, making them interesting study objects.

In this dendrochronological study, I analysed age and size structures of Norway spruce and European larch within a part of a marteloscope in Dischma (Davos). Additionally, I calculated long-term growth trends for the last two centuries. Finally, I related competition to growth to better understand the dynamics within the stand.

The stand has an extremely high volume (1388 m^3/ha), which can be explained by extensive wood harvesting, little disturbances, high vigour and the projection of the steep slope into a plane. European larch is well represented in high age classes. This can be explained by past land use traditions and/or natural disturbances, showing that the forest has not regained its completely natural state yet. In a forest where growth is mainly limited by the short vegetation period, the recent positive growth trend could be related to increasing mean temperatures. The negative correlation between distance dependent, above-ground competition and recent growth also suggests that not only temperature but also light seems to be a limiting resource in this north-east facing steep slope.

3 Introduction

Mountain forests are important ecosystems as they have numerous ecological, hydrological, social and economic functions (Kulakowski *et al.*, 2016). In mountain forests, the social function is usually less important than in the lowland forests as fewer people live in mountain regions. However, these forests fulfil important protective functions that mainly involve processes of the hydrological cycle such as avalanches and landslides (Kulakowski *et al.*, 2016). The forests in Dischma (Davos, Switzerland) in particular have an important function in protecting the valley from avalanches and other natural hazards (Bebi, 1999).

Forests of the subalpine elevational zone are interesting study objects for different reasons. Mountain forests are situated on the ecological boundary of where forest growth is possible, making them the first communities to show growth changes caused by environmental changes (Tessier *et al.*, 1997). Additionally, where conditions are harsh and resources limited, competition between trees can have a major effect on tree growth (Biging and Dobbertin, 1992).

Age and size structures are influenced by the temporal variability of past regeneration and mortality (Johnson *et al.*, 1994). Understanding structures and dynamics of protective forests can be important for local forest authorities as a well-managed forest reduces the frequency of damage-causing avalanches and therefore increases security for the community (Bebi *et al.*, 2009). While small-scale mortality can be advantageous with regards to a forest's protective function, it should, for example, be avoided that the forest reaches a decaying stage on a large spatial scale as this reduces its protective function (Frehner *et al.*, 2005).

Human activities are reflected in a forest's structure and its dynamics. To understand natural forest structures and dynamics, it is essential to study a forest with as little human impact as possible (Motta and Lingua, 2005). While most mountain forests in Switzerland have been heavily logged for centuries (Bebi, 1999) and are therefore not suitable to study natural forest structures and dynamics, the forest stand chosen for the marteloscope (a permanent plot within the forest) hasn't been used intensively for a long time (Bebi, personal communication, 2016). Thus, the marteloscope can be seen as a near- natural forest and is, therefore, an interesting stand to study natural forest structures and dynamics.

Global warming will also have an effect on forests. It is predicted that higher temperatures will have a positive effect on forest growth in northern and western Europe in the short- to medium term (Lindner *et al.*, 2010). As growth of mountain forests is also restricted by low temperatures (Ott *et al.*, 1997), a positive growth trend in recent decades is likely to be observed in the subalpine forest in Dischma (Davos, Switzerland).

With the results of this study the following questions should be answered:

- What do size and age structures tell us about the stand's history?
- To what extent does above-ground competition influence the growth of trees?
- How did long-term growth trends develop in the last two centuries?

I hypothesize that:

- The stand has a large count of old trees compared to younger trees.
- Larch is mainly represented in the high age classes.
- Above-ground competition between trees has a major effect on secondary growth.
- Growth trends are positive on a stand level for the last decades.

4 Theoretical basics

4.1 Growth of trees

Trees increase in height (primary growth) and circumference (secondary growth) simultaneously. In temperate regions, trees usually produce early wood in spring to maximize water transport and late wood in autumn to provide the tree with enough stability for the additional weight gained throughout the year (Reece *et al.*, 2011). Late wood contains a higher portion of lignin than early wood, making its appearance darker than early wood (Cherubini *et al.*, 2004). This change in tissue adds one ring a year to the tree's stem (Reece *et al.*, 2011).

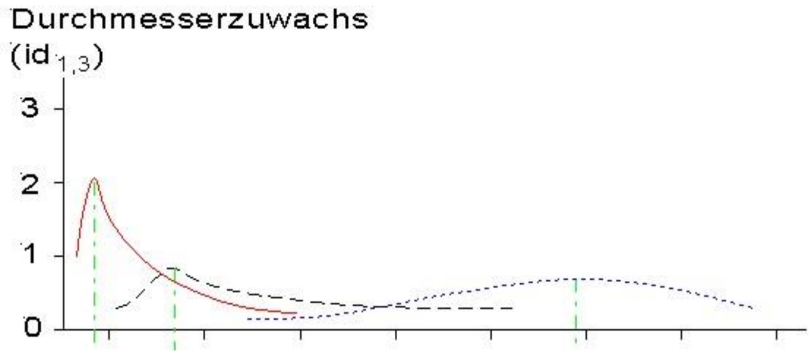

Fig. 1: Age-growth relationship in different tree species. The x-axis represents tree age. The y-axis represents increase in diameter per year. The different colours stand for different tree species (Bachmann, 1993).

Fig. 2: Tree rings become narrower, the further away they are from the pith (Kelsey, 2013).

Tree ring width is correlated with both age and circumference of a tree (Peters *et al.*, 2015). The diameter increase changes with the age of the tree (Fig. 1), reaching a peak after several decades (Bachmann, 1993). Tree ring width decreases with increasing tree circumference simply due to geometry (Fig. 2). A thick tree has to produce a thinner tree ring than a thin tree in order to have the same annual basal area increment (Peters *et al.*, 2015).

Tree ring widths are influenced by the annual climate variability resulting in a distinct tree-ring pattern, which allows to date the tree rings. Dendrochronology as a scientific discipline is based on crossdating to assign each tree ring to the correct year. This is secured by crossdating them with already existing chronologies (Cherubini *et al.*, 2004). Tree ring widths vary with changing site conditions. This makes tree rings integrators of both biotic and abiotic influences and reflects the growth history of a tree (Fritts, 1976). Trees can have very long lifespans, making them long-term recorders of their surrounding environment. This makes dendrochronology one of the most important environmental recording techniques for a variety of different processes and disturbances (Speer, 2010).

4.2 Growth of stands and forest succession

Without disturbance, forests usually go through different succession stages with varying ecological processes dominating (Korpel, 1995). The succession can be divided into three major phases. In the juvenile phase ("Verjüngungsphase" and "Jungwaldphase" in Fig. 3) both the number of stems and the volume increases. Trees from all size classes are present. Mortality rates are low while volume and basal area values are on an intermediate level (Korpel, 1995). When the volume and basal area have reached their peak, the forest is in its climax stage ("Optimalphase" in Fig. 3). Juvenile trees are suppressed while there are many trees in large height classes (Korpel, 1995). The last part of the succession is the decaying phase ("Zerfallsphase" in Fig. 3). The total biomass has reached its maximum and starts to decrease because the mortality of large trees is increasing. Patches of big trees alternate with patches of upcoming regeneration (Korpel, 1995). The regenerating trees are usually of the same species as the climax tree species. Pioneer species are often reluctant on catastrophic events in order to be exposed to enough light to out-compete shade-tolerant species (Korpel, 1995).

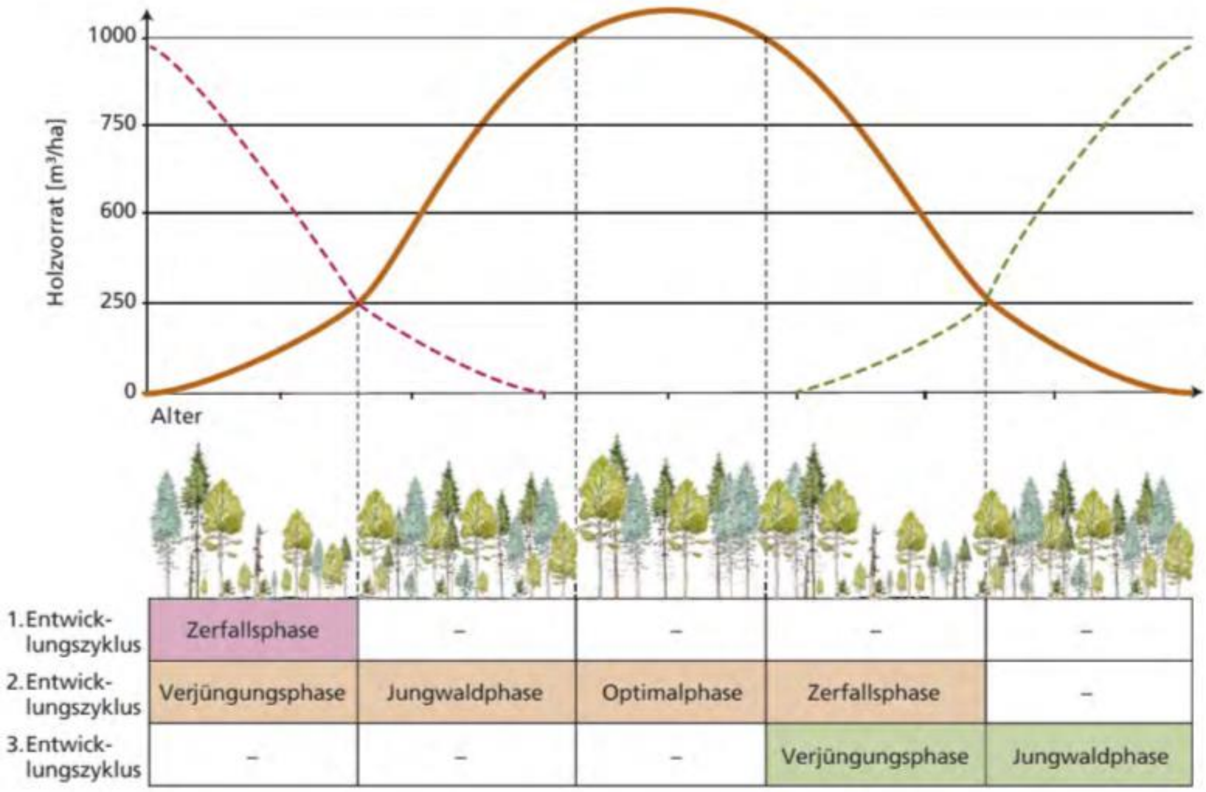

Fig. 3: Schematic representation of different forest succession stages in a natural forest and how the volume changes with time (Korpel, 1995), edited by Bugmann, 2016.

4.3 Ecology of sampled tree species

4.3.1 Norway spruce (*Picea abies*)

Norway spruce is a coniferous tree that is home to montane and subalpine areas in Switzerland. It is a species that can tolerate shade and low average temperatures relatively well and is not dependent on a nutrient-rich substrate. This gives Norway spruce the ability to endure unfavourable growing conditions and then excel in growth when conditions change for the better, making it a possibly dominant tree species within a stand (Aas *et al.*, 2002). Extremely dry sites, heavy snow load, decay and strong winds are the main threats Norway spruce has to face in Switzerland. Where these conditions occur, Norway spruce can lose its dominance in the stand and partially be substituted by European larch (*Larix decidua*) or Swiss stone pine (*Pinus cembra*) (Aas *et al.*, 2002).

4.3.2 European larch (*Larix decidua*)

European larch is a deciduous coniferous tree species found in a variety of elevational zones ranging from colline to subalpine in Switzerland. It is mainly found on acidic substrates in areas with a rather continental climate (compared to the generally temperate climate in Switzerland) (Aas *et al.*, 2002). In comparison to Norway spruce, European larch is very light-demanding, especially in its juvenile phase, and not as competitive as Norway spruce. The lacking ability to compete against other tree species leads to individual larch trees being rather scattered than widespread. European larch is therefore reluctant on natural hazards or otherwise unsuitable growing conditions for Norway spruce in order to coexist (Aas *et al.*, 2002).

4.4 Competition among trees

Competition between trees exists when a resource availability lies below the requirement of the population for optimal growth (Biging and Dobbertin, 1992). It can either take place above-ground or below-ground. In the forest, the limiting resources are usually either light, nutrients or space (Yokozawa *et al.*, 1999). Competition is one of the major factors that can have an influence on long-term growth trends (Biging and Dobbertin, 1992). For this reason, reduced growth can be interpreted as a response to decreasing resource availability possibly caused by increased competition (Waring and Pitman, 1985).

4.5 Specific characteristics of mountain forests

Mountain forests face different challenges than lowland forests. Due to the harsher environmental conditions, they are pushed to the limits of where trees can survive (Ott *et al.*, 1997). Low mean annual temperatures slow down physiological processes in trees, ultimately making it impossible for trees to survive if the mean annual temperature drops below a required minimum. The trees are not the only organisms affected by the cold climate in the mountains. The activity of litter-decomposing microorganisms is also reduced due to the low temperatures. As a consequence, an organic layer of poorly decomposed litter accumulates (Ott *et al.*, 1997). This organic layer has a low water retention capability and the nutrients are poorly available for the trees. Besides the sometimes low nutrient content of the substrate, the trees face another challenge when growing up. Ground vegetation can be extremely lush in the mountains, making it difficult for seedlings to get enough light. A consequence can be that tree regeneration is mainly found on decomposing wood (Ott *et al.*, 1997). Once a tree has managed to survive the juvenile phase, it faces other challenges like snow pressure and sometimes avalanches. Depending on the frequency of avalanches, these disturbances can become a major factor in the dynamics of forests (Bebi *et al.*, 2009).

5 Methods

5.1 Study area

The study site is located in a subalpine valley called *Dischma* close to Davos, Switzerland (Fig. 4). The site is located at 46°46'15.417'' N and 9°52'37.796'' E. A marteloscope with a size of 0.9 ha was set up by Peter Bebi[1] and Frank Krumm[2] at an average altitude of 1830 m a.s.l. A total of 489 trees were marked, adding up to 525 trees/ha, a basal area of 100.7 m^2/ha and a volume of 1388.5 m^3/ha (Bebi and Krumm, 2015) (Fig. 5).

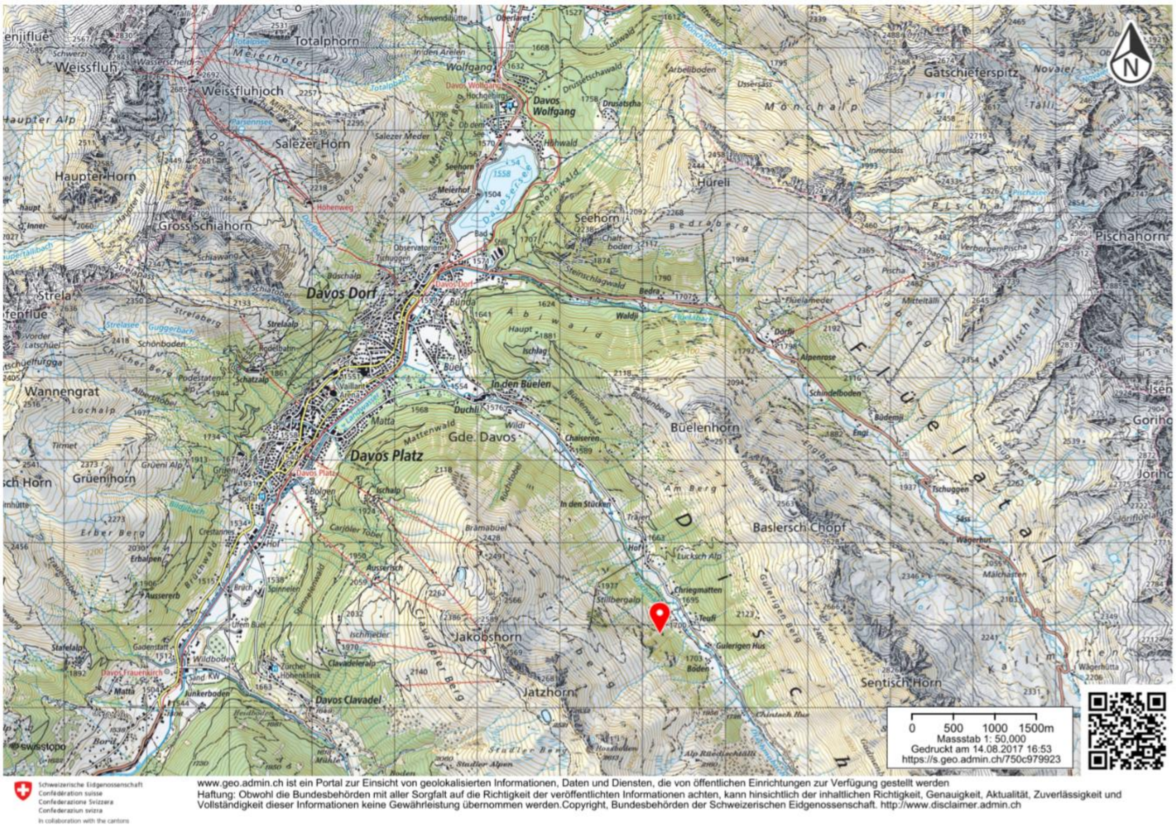

Fig. 4: Map of Davos and its surroundings. The red mark shows the location of the marteloscope site in the Dischma valley, Davos (map.geo.admin.ch).

The site is relatively steep (35 °-40 °) and north-east facing. The climate can be described by the mean annual temperature of 3.9 °C and a mean annual precipitation of 1060 mm (Fig. 5)(SLF, 2015). GPS-position, height and diameter at breast height (DBH) were recorded for each tree in 2015. Additionally, volume and basal area were calculated from the measured data (Bebi and Krumm, 2015).

The majority of the trees in the stand are Norway spruce, with some European larch and few rowans completing the species mix (Fig. 5). The marteloscope can be related to the *Adenostylo alliariae-Piceetum typicum* forest community, a spruce forest type with tall and lush ground vegetation found in Swiss subalpine regions (Ott *et al.*, 1997).

[1] WSL Institute for Snow and Avalanche Research, SLF Davos (Switzerland)
[2] Swiss Federal Institute for Forest, Snow and Landscape Research WSL (Switzerland)

The forest of the marteloscope has remained almost untouched by humans since World War II and was not logged intensively before then due to its steepness and poor accessibility (Bebi, personal communication, 2016).

State/ Region	Owner	Year of establishment	Size
Davos, Grison	Private	2015	0.9 ha
Altitude [m.a.s.l.]	**Mean annual precipitation [mm]**	**Mean annual temperature [°C]**	**Natural forest community**
1 830	1060	3.9	Larici-Piceetum
Number of trees [N/ha]	**Basal area [m²/ha]**	**Volume [m³/ha]**	**Habitat value [points]**
525	100.7	1388.5	5 841

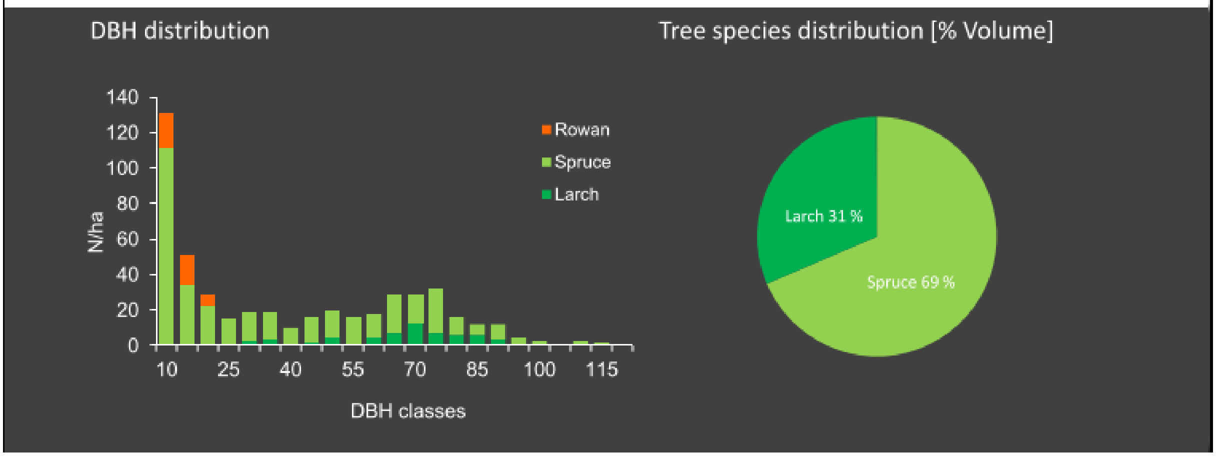

Fig. 5: Key figures of the marteloscope in Davos (Bebi and Krumm, 2015).

5.2 Selection of study plots

A total of 488 trees with a diameter at breast height (DBH) of ≥ 8 cm are located within the marteloscope in Davos. Because of time restriction, not all of the trees could be sampled. Two trees that were at least 50 m apart and not too close to the edge of the marteloscope were selected. Around these trees circles with a radius of 25 m were drawn in the GIS program (Fig. 6). All trees within those two circles were attempted to be sampled with an increment borer. Of the 143 trees that are in the two selected circles, 112 were ultimately used for the chronology. The remaining increment cores were either too decayed to process (10 cores), damaged too much to date (11 cores) or the correlation of the increment core with the reference chronology was too low due to missing tree rings or supressed individuals (10 cores) (Table 1). The two circles cover an area of 0.39 ha and contain 140 trees combined.

5.3 Field sampling

Increment borers were used to extract one increment core from each living tree. The cores were taken as close to the ground as possible, at a maximum height of 1.3 m (breast height). All cores were taken from the up-slope half of the trees to avoid reaction wood.

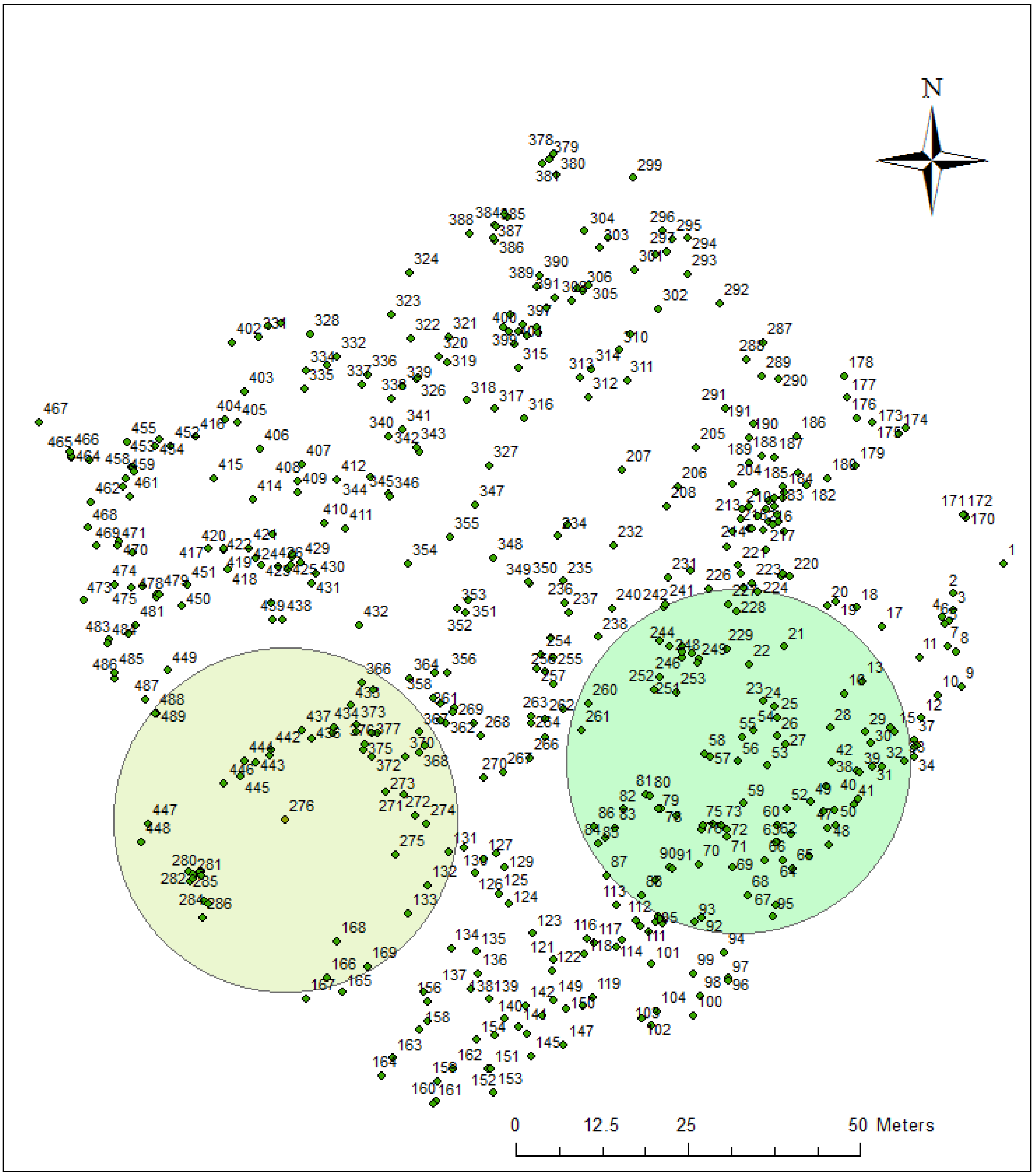

Fig. 6: Overview of the marteloscope in Davos with the trees labelled with numbers. The two green circles enclose the trees that were drilled with the increment borer.

The biggest challenge during the field sampling was the high amount of Norway spruce affected by butt rot. Nine Norway spruce and one rowan were too decayed to extract a useable core (Table 1). This is no surprise, as 15-20 % of Norway spruce are affected by butt rot in Switzerland (Graber, 1995). Following the extraction of increment cores, the drilled hole could act as an entry for fungi. However, removing increment cores does not affect the mortality of the sampled trees (Wunder *et al.*, 2011). There is no preferable season to extract the increment cores with regards to tree health as both the vegetation period and winter have their advantages and disadvantages. During the vegetation period, the tree is capable of forming a callous margin (i.e. covering the hole) quickly whereas in winter the repairing takes longer but the tree is less exposed to pathogens (Cherubini *et al.*, 2004).

Table 1: Summary of number of trees used in different stages of the study

	Marteloscope	Study plots	Successful core extraction	Core datable	Used for chronology
Number of trees	488	143	133	122	112
% of total tree number	100	29.3	27.3	25	23
% of extracted cores			100	91.7	84.2

The extracted cores were stored in plastic straws and labelled with the tree number to allow assigning the measured values in the lab to the correct tree and protecting the cores from any damage while transporting them to the laboratory.

5.4 Laboratory methods

5.4.1 Processing and measurement of the cores

First, the cores were glued onto core mounts to enable further handling. A second core mount was attached with a clamp for a day to make sure the glue dried properly to fix the core on the mount. The fibres of the increment cores were aligned vertically as a horizontal alignment would complicate recognising the tree rings. Next, the cores were sanded on a belt sander with increasing grit from 60 to 240 to ameliorate the visibility of the tree rings.

Tree ring widths were measured from bark to pith at a resolution of 0.01 mm with a LINTAB 5 measurement bench and the TSAP-Win software (both from Rinntech, Heidelberg, Germany).

5.4.2 Crossdating

Tree rings were visually compared using the TSAP-Win tree ring program (Rinn and Jäkel, 1996) with chronologies from the International Tree-Ring Data Bank (ITRDB; chronologies SWIT179 for Norway spruce, SWIT185 for European larch) as references. The increment cores from the reference chronology for Norway spruce were taken from the same valley as the cores from the research site (Dischma, Davos).

The cores for the European larch reference chronology were taken from Bergün (Switzerland), with a similar elevation as the study site. So the reference chronologies should be a valid comparison to test the quality of my own tree ring series.

In addition to the visual crossdating, the tree ring measurements were also quantitatively checked using COFECHA (Holmes, 1983). COFECHA is a computer program that helps the dendrochronologist assess the quality of crossdating and the accuracy of the measurements. However, the program should not be used as a substitute to visual crossdating with e.g. TSAP-Win as COFECHA cannot decide for the researcher whether the tree ring series has been dated correctly (Grissino-Mayer, 2001). It is, however, a useful tool to help the dendrochronologist identify possible problems within a tree ring series.

5.5 Data analysis

5.5.1 Tree age correction

Three problems arise when the age of a tree is determined using increment cores. Firstly, increment cores often miss the pith of the tree. These missing rings were extrapolated using a geometrical method from Duncan 1989 (Fig. 7). Usually, the increment cores were taken close enough to the pith to see the arcs of the inner rings (Fig. 7). This method assumes that the growth from the pith to the increment core was concentric (Duncan, 1989).

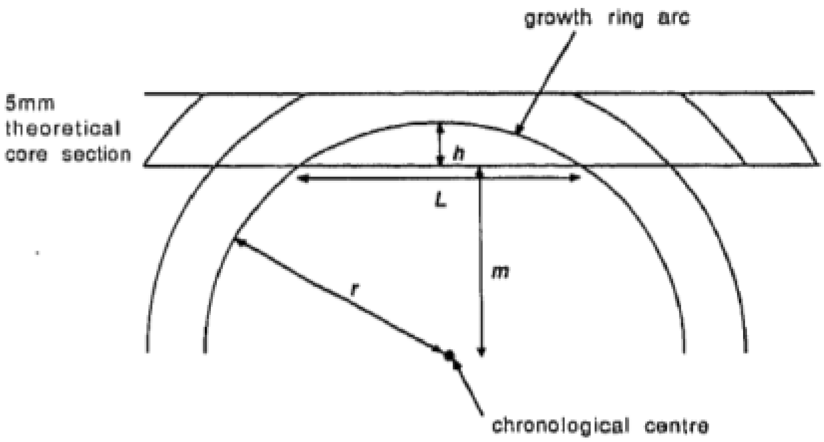

Fig. 7: Plan of how to estimate the number of missing tree rings to the pith with Equation 1 (Duncan, 1989).

Equation 1 $$r = \frac{L^2}{8h} + \frac{h}{2} \qquad K = \frac{r}{\bar{\bar{X}}}$$

The length of the missing radius (r) can be related to the height (h) and the length (L) of a measured arc close to the pith. The calculated length of the missing radius (r) can then be used to calculate the number of missing rings (K) by dividing r by the mean of the last 5 rings measured ($\bar{X}$) (Equation 1)(Duncan, 1989).

Secondly, rings can be missing in the portion of the circumference where the increment core was taken (Duncan, 1989). If the visual and quantitative crossdating showed obvious missing rings, these were inserted with a standard width of 0.1 mm. From the 112 trees included in the chronology, 5 have inserted missing rings.

And thirdly, increment cores are usually not taken at ground level. To calculate the age of the tree, the time the tree took to grow up to the sampling height has to be estimated too (Duncan, 1989). In this paper, a derived Bertalanffy (1957) equation (Equation 2),

Equation 2
$$t = \ln\left(1 - \left(\frac{H(t)}{H_{\max}}\right)^{1/3}\right) \Big/ -g$$

as proposed in the paper by Rammig et al (2007), was used to estimate the actual age of the tree at ground level. To calculate the current age *t*, the following calculations were done. For the current height *H(t)*, the drilling height of the increment borer was inserted. The values for the maximum height H_{max} were set to the maximum height of each species within the stand (41.407m for European larch, 40.5 m for Norway spruce). The growth factor *g* was adopted from Rammig et al (2007) (0.037 for European larch, 0.03 for Norway spruce).

5.5.2 Growth trends

5.5.2.1 Basal area increment

Tree growth can, for example, be evaluated by measuring the basal area increment of a tree (Peters *et al.*, 2015). The *bai.out* function of the dplR package (Bunn, 2008) in R (R Core Team, 2013) was used to convert tree ring widths to basal area increments. Some trees were not successfully sampled because of strong decay of the cores. From other trees, an increment core was taken but the analysis in the lab was not possible because it was either missing too many pieces or was not analyzable because of other reasons. To get a correct value for the estimated basal area increment (BAI) per ha, the percentage of the basal area from the missing samples was calculated in relation to the total basal area of the two circles. The area of the two study plots (Fig. 6) was then reduced by 21.4 % (percentage of the basal area of missing trees sampled) before the BAI was upscaled to 1 ha.

5.5.2.2 Regional Curve Standardization

I used regional curve standardization (RCS) as a growth-trend detection method (Briffa and Melvin, 2011). One first calculates growth rates for the different cambial ages of the trees, resulting in the regional growth curve. A mathematical smoothing function is fitted to show the relationship between age and growth. The individual tree ring series are then divided by the expected growth for each cambial age to calculate the residual growth rate, which is related to each calendar year to show long-term growth trends (Peters *et al.*, 2015).

5.5.3 Calculation of competition index

A number of different methods have been devised to assess the competition between plants and trees. Based on the available GPS-coordinates, a distance dependent index was chosen to assess competition (Fig. 8). The values depend on the DBH of both the tree looked at and the competing trees and the distances between the different trees (Biging and Dobbertin, 1992). The search radius was set to 10 m and a buffer of 10 m was used to exclude all trees too close to the edge of the marteloscope as these values might be biased due to missing trees on the map.

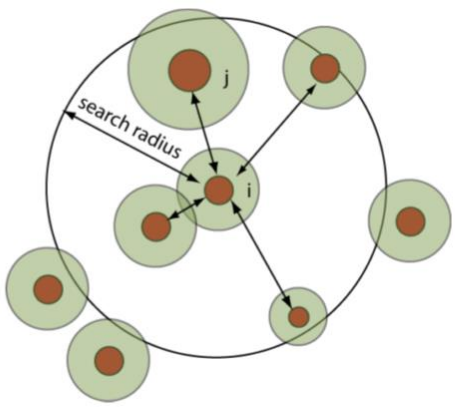

Fig. 8: Scheme for calculating the competition index (CI). The index *i* stands for the tree one is calculating the competition index CI for, *j* represents all the surrounding trees within the search radius (Bigler, 2016).

The competition index is calculated by dividing the quotient of the squared DBH of the surrounding trees (j) and the tree of interest (i) by the distance (DIST) between the two trees and then summing up all these values for a tree within a defined search radius (Equation 3)(Biging and Dobbertin, 1992).

Equation 3

$$CI = \sum_{j=1}^{n} \frac{DBH_j^2 / DBH_i^2}{DIST_{ij}}$$

5.6 Tree ring chronology

COFECHA is a useful tool for validating the quality of a tree ring chronology. The following values were all calculated using the default 50-year segment length and 25 years lag in COFECHA. The cubic smoothing spline was set to 32 years and the critical correlation to 0.3281 (Grissino-Mayer, 2001).

The Norway spruce tree ring chronology consists of 100 trees (Table 3). The time span of the master dating series is 310 years long (1707-2016). The series intercorrelation is satisfyingly high with 0.597. In 15 tree ring series, a total of 17 flags were detected (Table 3,Table 4), meaning that statistically, 17 segments would fit better in another place in the chronology. All flags were checked by visually and quantitatively crossdating the series again. 10 out of the 17 flags were found in series that were only 1 segment long (i.e. these trees were 50 years old or younger). This could be explained by the low sensitivity of the 50 years segments for short series (Table 3).

12 tree ring series make up the European larch chronology. The tree ring series used for the master dating series covers a time span of 262 years (1755-2016). The series intercorrelation is 0.627 and therefore even higher than the intercorrelation of the Norway spruce chronology. From the 12 tree ring series, COFECHA only flagged 1 segment that would fit better somewhere else. But once again this flagged segment is the only segment this tree ring series has, making the 50-years segment not sensitive enough. The flagged segment was double checked and declared as correct, despite its low correlation with the master series (Table 4).

6 Results

6.1 Static stand characteristics

The age distribution (Fig. 9A) can more or less be described by an inverse J-shape up to the age of about 200 years. In the older age classes, it is eye-catching that the counts are very high compared to middle age classes. Therefore, the stand could also be referred to as two-aged. Also noticeable is that most of European larch can be found

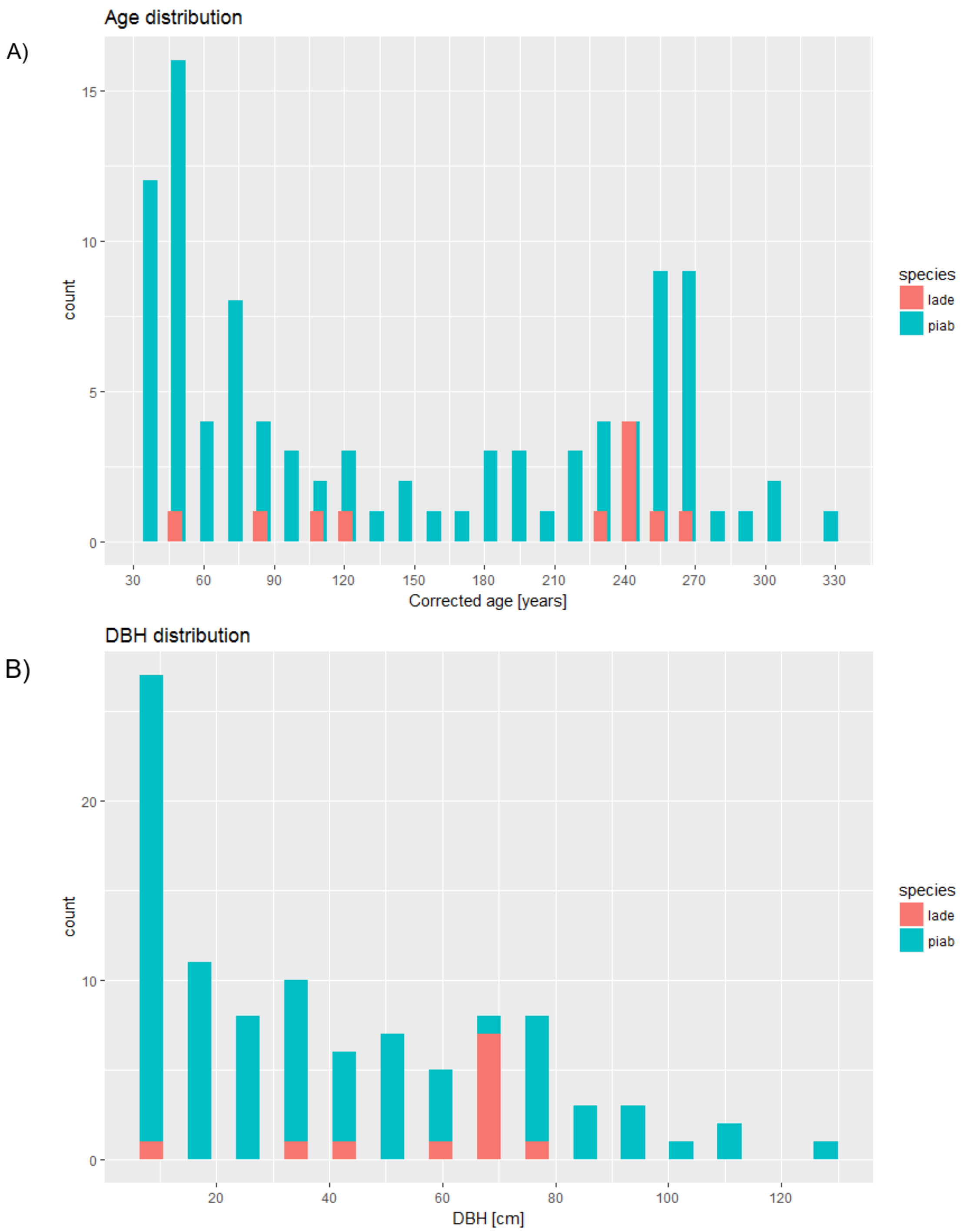

Fig. 9: A) Age distribution of 100 Norway spruce (=piab, green) and 12 European larch (=lade, red). To increase visibility, the bars of larch were slightly shifted to the left. B) DBH distribution of 100 Norway spruce (green) and 12 European larch (red).

in the higher age classes above 200 years with trees missing completely for a whole century (between 120 and 220 years of age).

The DBH distribution can also be roughly explained by an inverse J-shape. The DBH classes of 70 and 80 cm seem to have a disproportionately high count for both Norway spruce and European larch while for the latter, DBH classes seem to be rare, reaching counts of only 1 each in most DBH classes (Fig. 9B).

An age-DBH relationship and an age-height relationship seem to be existing with R^2 values of 0.645 (age-DBH) and 0.735 (age-height) and p-values of 2.2×10^{-10} (both relationships). But looking at the two graphs, outliers are frequent (Fig. 10).

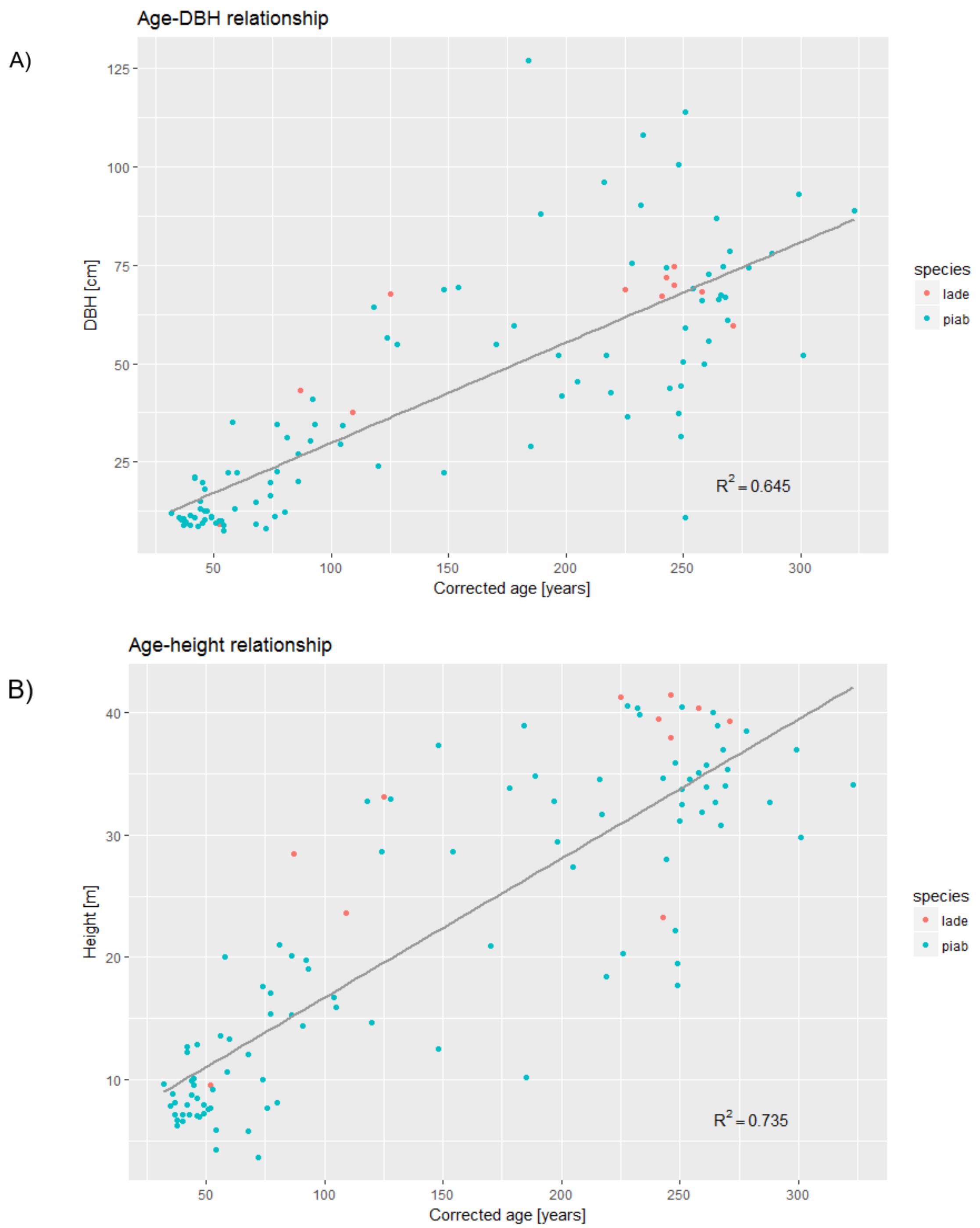

Fig. 10: A) Relationship between the corrected age and the DBH for Norway spruce (=piab, green) and European larch (=lade, red). B): Relationship between the corrected age and tree height for Norway spruce (green) and European larch (red). A linear regression model was applied to both relationships. How well this model explains the variation is displayed by the R^2 values.

6.2 Stand dynamics

6.2.1 Spatial development

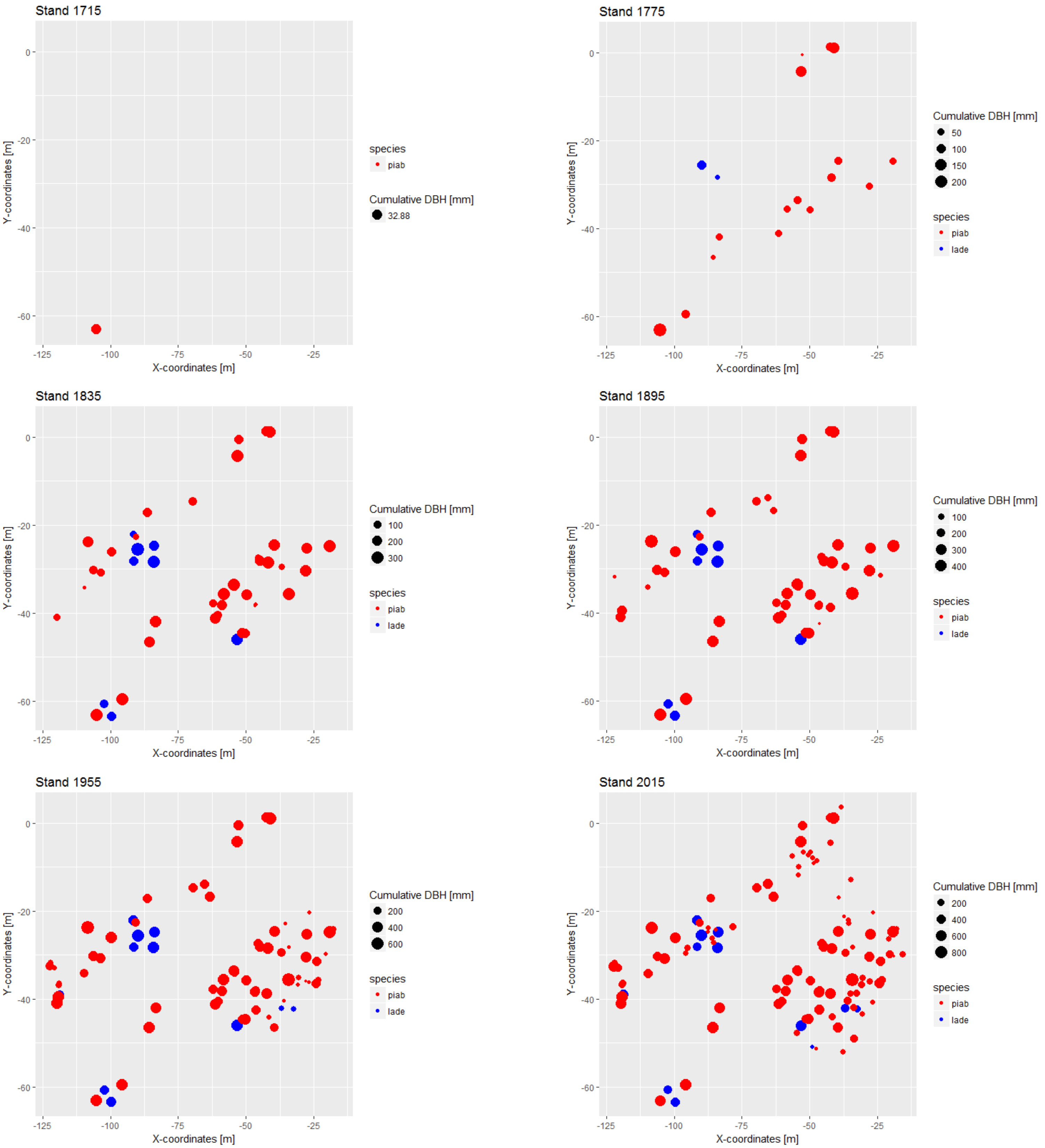

Fig. 11: Reconstruction of the growth of trees that were still alive in 2016, starting in 1715, ending in 2015 with 60-year intervals. Norway spruce (=piab) are represented by red dots, European larch (=lade) by blue ones. The size of the dots shows the accumulated diameter (=2x accumulated tree ring width at sampling height) up to that year as an approximation to the diameter of the tree in that year. The x-and y-axis stand for the coordinates of the trees.

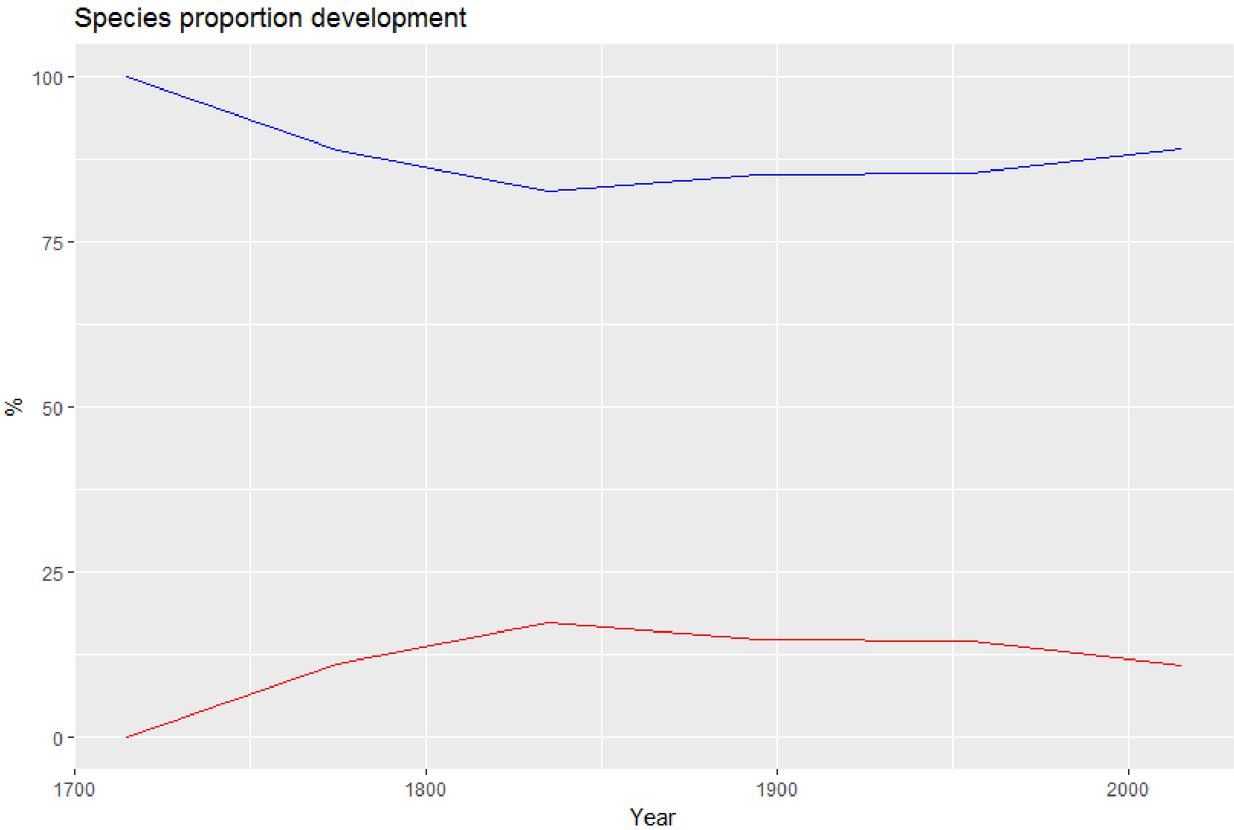

Fig. 12: The graph shows how the proportion of European larch (red line) and Norway spruce (blue line) changes with time.

Spatial distribution of trees and species proportion within a stand can change over time. This approximated reconstruction of the spatial development and the species proportion is based solely on a retrospective view of the trees alive in 2016. This means that trees that died between 1715 and 2016 are not shown in this spatial development and species proportion development.

Both the spatial development (Fig. 11) and the species proportion development (Fig. 12) show that regeneration of Norway spruce is coming along much better than the one of European larch. The regeneration is not distributed homogeneously but rather concentrated in some patches. Some areas were, at least in 2015, completely free from trees.

The species proportion development (Fig. 12) shows some changes. Until the first half of the 19th century, the proportion of European larch increased at expense of Norway spruce. Since about 1850, the proportion of European larch has reduced successively.

6.2.2 Growth development of stand

The basal area increment starts off with very low values, because from the sampled trees, very few were alive then. The BAI rises with peaks at about 1725, 1830 and 1950 with the latter reaching a value of about 0.3 m^2/ha. After a temporary low in about 1990, the trend seems to be positive again with no peak reached yet (Fig. 13).

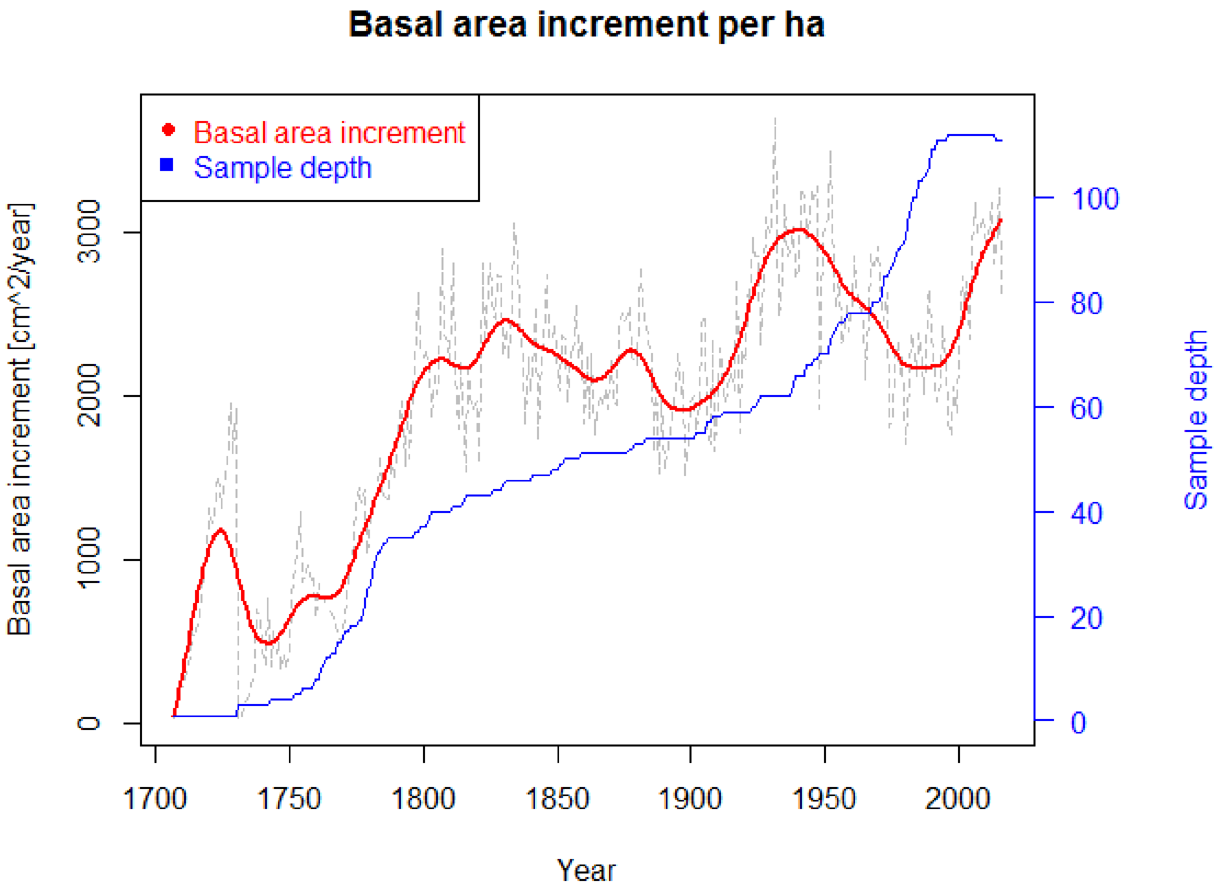

Fig. 13: Development of the basal area increment that was upscaled to 1 ha. The red line is a smoothing function of the BAI that facilitates recognising long-term trends. The blue line shows how many of the currently living trees were already present in a given year.

The mean curve of the RCS (Fig. 14, red line) reveals the age trend of the site. It shows that with higher cambial age, tree ring widths are expected to decrease (see 4.1 Growth of trees). To get a growth trend, each tree ring series is divided by the age trend, resulting in a ring width index with mean 1. This index is then related to calendar years to reveal long-term growth trends.

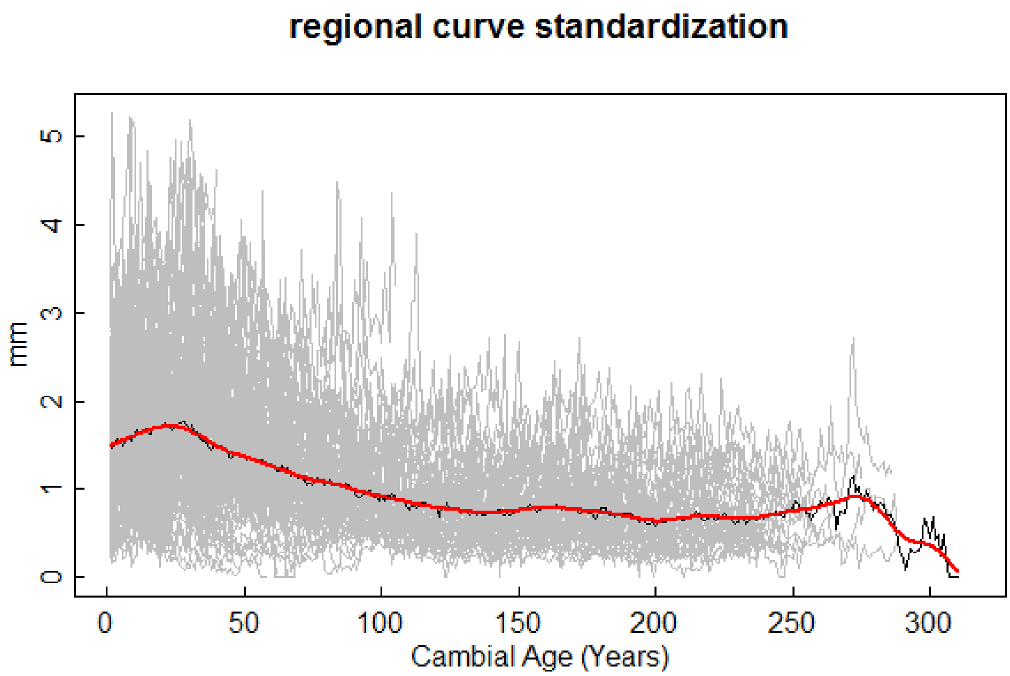

Fig. 14: The regional curve standardization plots tree ring width in relation to the cambial age of the trees. The red line shows the mean of all tree ring series.

Long-term growth trends become visible when the standardized ring widths are related to the calendar year. Both European larch and Norway spruce have fluctuating ring width indices below and above the mean index of 1. A positive growth trend can be seen for both species in the last 20-30 years (Fig. 15).

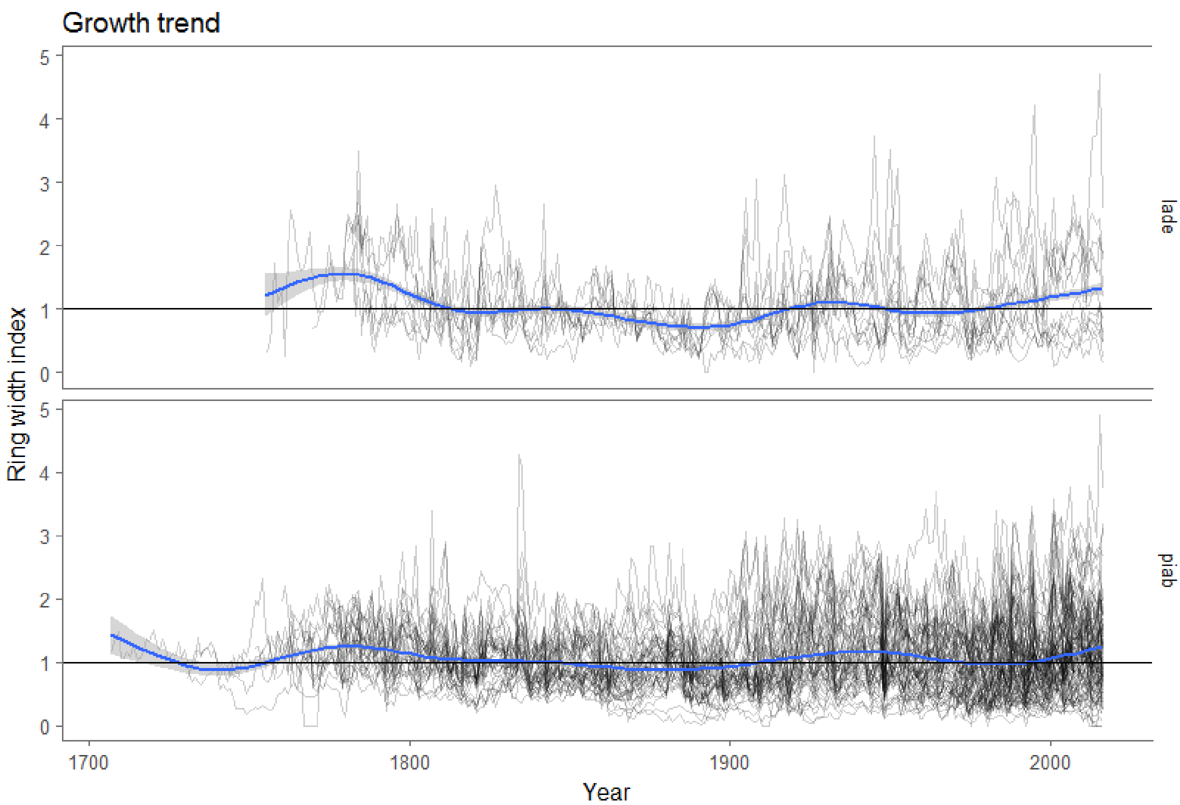

Fig. 15: Long-term growth trends of European larch (=lade, top) and Norway spruce (=piab, bottom). The horizontal black line shows the mean value of the ring with index, making it easier to recognize both positive and negative deviations from the mean and therefore possibly interesting trends.

6.3 Competition

Competition has a negative effect on tree growth (p-value of 4.7×10^{-10}). The intercept of the regression line is at 2.33 and the $logBAI_{10}$ (mean logarithmic basal area increment of the years 1997-2016) decreases by 0.03 with each additional competition index value (Fig. 16). Standard errors are 0.094 for the intercept and 0.004 for the slope. With an R^2 of 0.301, a linear regression model explains roughly a third of the variability.

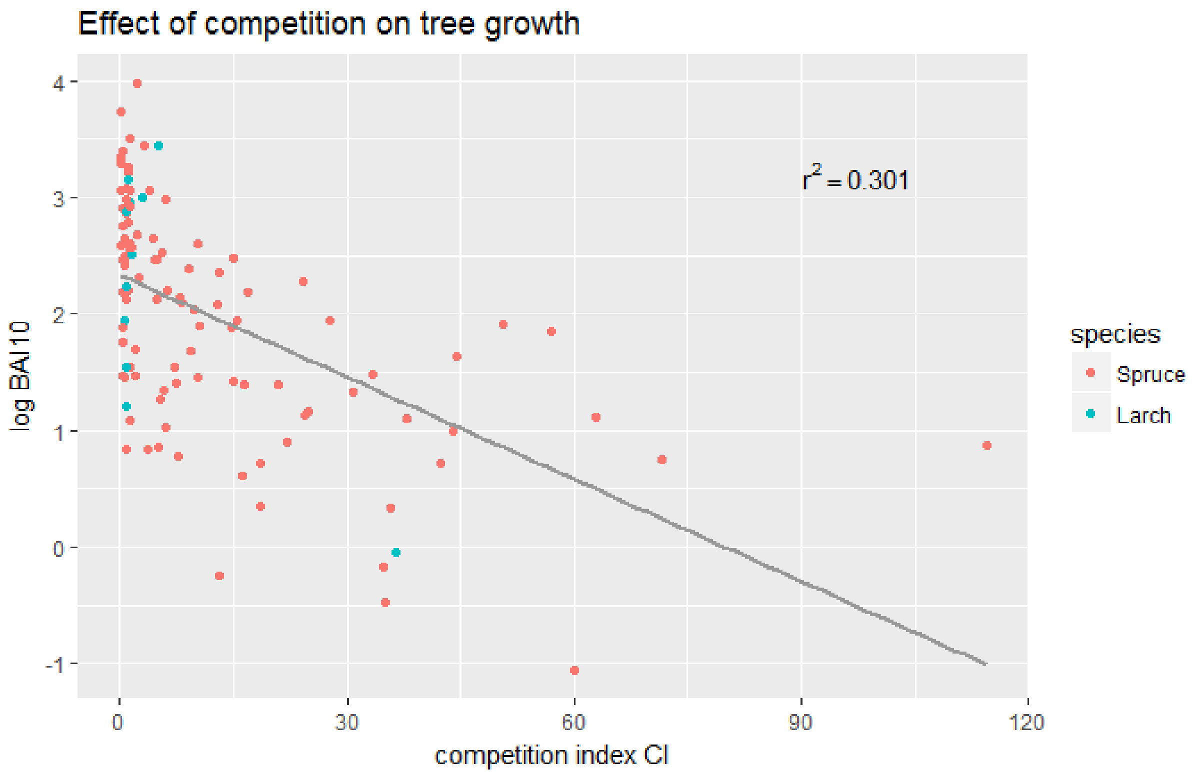

Fig. 16: The graph shows the influence competition (x-axis) has on the logarithmic mean of the last 10 years of basal area increment. A linear regression model was fitted (black line).

7 Discussion

7.1 Wood volume

The marteloscope has a very high wood volume, reaching a value of 1388.5 m^3/ha. This is approximately four times the volume an average Swiss forest has. There are different explanations for this high value. The volume in mountain forests is often higher than in lowland forests because the slopes are projected into a plane, leading to an increase in tree density in the projection of the stand. Looking at the high tree heights of more than 40 m at almost 2000 m.a.s.l, another reason for the high volume could also be high vigour of the site. Furthermore, the extensive wood harvesting of the last two centuries has probably also led to an increase in volume.

7.2 Age and size structure

The trees are not distributed homogeneously across the different age classes. Age structures are influenced by the temporal variability of past regeneration and mortality (Johnson *et al.*, 1994). Considering this, some interpretations about disturbances in the past can be made.

The age distribution shows two major peaks (Fig. 9). It is eye-catching that most of the European larch are old and have a large DBH while in several age classes larch is completely absent. Furthermore, a noticeable peak of trees is present that are approximately 70 years old. The trees that make up the second peak are 210 to 270 years old and date back to an establishment between 1740 and 1810. Since a lot of regeneration survived during that period, conditions must have been favourable for regeneration then. Since especially larch is a light demanding species, the forest must have been quite open then. I suspect that this open forest structure was either caused by more intense logging or by big natural disturbance such as an avalanche.

Regeneration conditions were not always so favourable for European larch as they were towards the end of the 18th century. Little larch regeneration from the 19th century has survived up to the present day. The forests had probably become much darker in the 19th century due to the large amount of trees that grew up at the end of the 18th century and were now growing up to denser stand, making it difficult for larch seedlings to get enough light. Different to larch, Norway spruce is not as light demanding and was therefore still able to grow up.

In the first half of the 20th century, regeneration conditions improved again. Both larch and spruce from trees that grew up in the first half of the 20th century were still alive in 2016. This can be related to extensive grazing of cattle inside the forest and possibly also to natural disturbances that both enabled more light to come into the forest and reach the seedlings. A bigger avalanche went down in 1951 (Bebi, personal communication, 2017), possibly giving the tree regeneration another boost.

Age and size distributions both lack trees in the lowest class (Fig. 9). This can be explained by the study design that only trees with a DBH of ≥ 8 cm were sampled (Motta and Nola, 2001)

7.3 Relationship between different growth parameters

Age has a positive relationship with both height and DBH. Both relationships are linear but have data points that deviate strongly from the expected value. Trees can be relatively young but be thick and tall already while other individuals are older than 200 years but have not exceeded a DBH of 15 cm or are not taller than 20 m yet (Fig. 10). This shows that the growth of trees varies considerably, probably due to local environmental conditions. European larch is often rather tall and thick in relation to its age compared to Norway spruce (Fig. 10). This supports the classification of European larch being a light-demanding species that cannot live under canopy for a long time. Norway spruce, contrariwise, is a semi shade-tolerant species that can be suppressed for a long time and then have a growth release as soon as it is provided with more favourable growth conditions (Aas *et al.*, 2002).

7.4 Spatial patterns of the trees within the stand

Interpretations about stand development based only on currently living trees as in this study should be made with caution as dead trees might have played an important role in the stand development, too. Based on the retrospective analyses done in this study, the following interpretations can be made.

Trees are not spread homogeneously across the marteloscope. Rather, they grow in groups (Fig. 11). This is a typical phenomenon in mountain forests that is mainly caused by the mosaic of favourable and unfavourable micro-sites within the stand (Bebi, 1999). Some patches are not inhabited by trees at all. I suggest that this is mainly caused by the lush ground vegetation that is a characteristic of this forest community in Switzerland (Ott *et al.*, 1997). Plants like *Adenostyles alliariae* and *Cicerbita alpina* can grow very tall in summer, out-competing upcoming regeneration. In forest communities like these, dead wood is often an important substrate for regeneration to be successful (Ott *et al.*, 1997).

7.5 Growth trends

The BAI reached the first peak around 1950 with approximately 0.3 m^2/ha/a. These growth rates are considerably lower compared with growth-rates of other spruce dominated mountain forests presented by Zingg (1996).

The forests in Morissen GR (Switzerland) with comparable elevation and exposition had mean BAI values of 1.15 m^2/ha/a. However, a study from the Trentino (Italy) by Castagneri et al. (2012) showed very similar BAI values as the stand in Dischma (Switzerland). Thus, the stand in Morissen might have just been in a different stage with higher growth than the stand in Dischma.

The ring width index fluctuates with alternating decades of being below or above the average. In the last couple of decades, a clear positive growth trend is visible for both European larch and Norway spruce. I hypothesise that this recent positive growth trend could be caused by an increase in temperature. Growth in mountain forests close to the tree line is mainly restricted by climatic conditions. Therefore a higher mean annual temperature would affect growth in forests like these the first.

7.6 Competition

Secondary tree growth is negatively correlated with above-ground competition. With an R^2 of 0.301, a linear model describes roughly a third of the growth variation caused by competition. The low p-value of 4.7×10^{-10} suggests that the negative correlation between competition and tree growth does not exist by chance. All trees that had high $logBAI_{10}$ values were trees with a low competition index and vice versa. The results confirm the findings of other studies, showing that competition can have a significant effect on tree growth (Biging and Dobbertin, 1992; Bigler and Bugmann, 2003).

Asymmetric competition occurs when taller trees have a disproportionate competitive effect on shorter trees or if they obtain a disproportionate share of a limited resource in relation to their size. This form of competition usually occurs when trees compete for light. Symmetric competition is rather observed when trees compete for resources below ground (Lundqvist, 1994). The BAI scale is logarithmic and its relationship with the competition index approximately linear. This means that the competition is asymmetric, as trees with a large DBH, and therefore a high competition index, seem to have a disproportionately high share of the light. From these results, I interpret that above-ground competition and therefore competition for light has a remarkable effect on tree growth in mountain forests.

7.7 Method of age calculation

With the assumption that the number of missing rings to the pith (Duncan, 1989) and the estimated height of the tree at drilling height (Rammig *et al.*, 2007) are correct, the following results can be observed. Missing the chronological centre when drilling caused age estimation errors of 0 % – 7 % with most of the values being below 4 % (Fig. 17). Tree rings missed caused by not drilling at ground level can lead to a drastically higher error. The error values go up as high as 30 % (Fig. 17). To validate these high values, a comparison with another paper was made. Motta and Nola (2001) sampled all trees at 0.5 m above ground. For age correction, they added 18 years for Norway spruce and 12 years for European larch. With the method used in this paper (Rammig *et al.*, 2007), for drilling heights of 0.5 m, 9 years were added for Norway spruce and 7 years for European larch. The error would, therefore, be even larger if the same amount of years had been added as Motta and Nola (2001) did.

This means that when tree age is of interest for a dendrochronological study, increment cores should be taken as close to the ground as possible, as otherwise, the error may be big enough to affect the interpretation of the age structure or other relationships with age. The mathematically logical consequence is that the error of the age estimation increases exponentially with decreasing age as the proportion of the time the tree took to grow to the drilling height becomes bigger with lower age (Fig. 18).

This implies that drilling at ground level is especially important for young trees. As the age of a tree is impossible to judge by eye (Fig. 10), all trees should be drilled at ground level if the exact age is of interest.

8 Conclusions

In this study, I evaluated different stand characteristics, age-related growth variables, long-term growth trends and stand dynamics. From the collected results I drew the following conclusions:

- Stand characteristics such as wood volume and age distribution can be used to reconstruct the history of a stand. On the one hand, phases with high larch regeneration suggest an open forest, caused by human activities or natural disturbances. On the other hand, the currently high volume and low count of young larches suggest extensive land use and few significant natural disturbances since the establishment of the oldest larches.
- Tree height, diameter and ring width are correlated with tree age. While diameter and tree height are positively correlated with age, the ring width tends to decrease with increasing lifespan of a tree.
- In the marteloscope in Dischma (Davos Switzerland), trees are not distributed homogeneously. They develop in small groups because regeneration conditions are only favourable on some micro-sites, while seedlings cannot survive in other parts of the forests.
- Long-term growth trends showed fluctuating growth trends in the last 300 years. Since about 3 decades, growth trends have been clearly positive. I hypothesize that this increase in tree growth might be related to an increase in temperature as mountain growth of forests is mainly restricted by low temperatures
- Competition has a significant negative effect on tree growth. The more trees there are in close proximity to another tree and the thicker these trees are, the smaller is the average basal area increment of the last 10 years.

The study shows that dendrochronological methods are useful tools for better understanding the characteristics and dynamics of a stand. Although the forest has not been intensively used for a long time, past human activities and/or natural disturbances can still be seen in the characteristics of a stand. With the stand becoming denser, one can see that competition for light affects the growth of a tree. While some trees suffer reduced growth caused by competition, it can be expected, that the growth of the stand as a whole will increase in the next decades due to higher mean annual temperatures.

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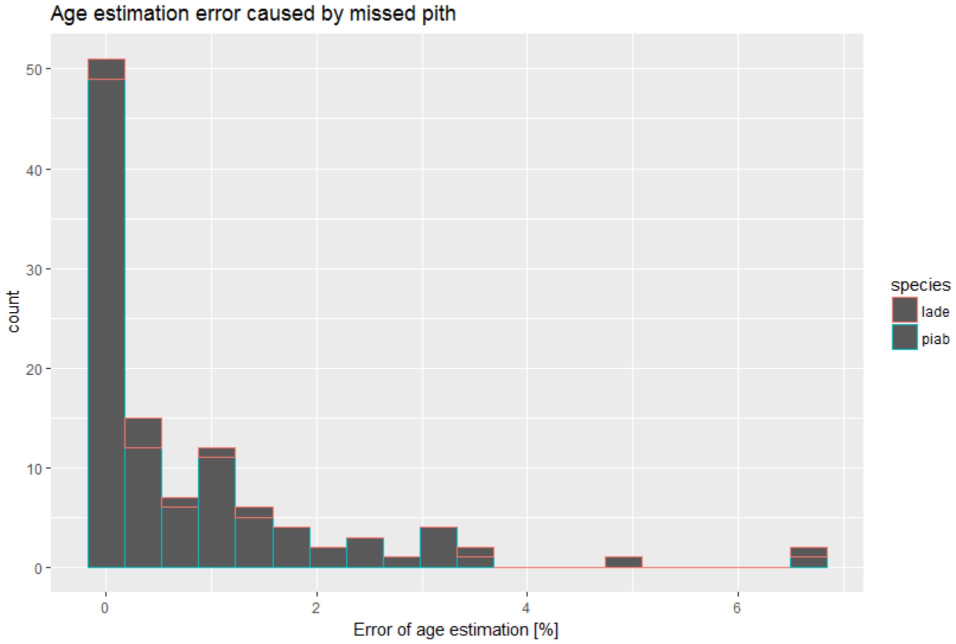
11 Appendix

11.1 Method of tree age estimation

A)



B)

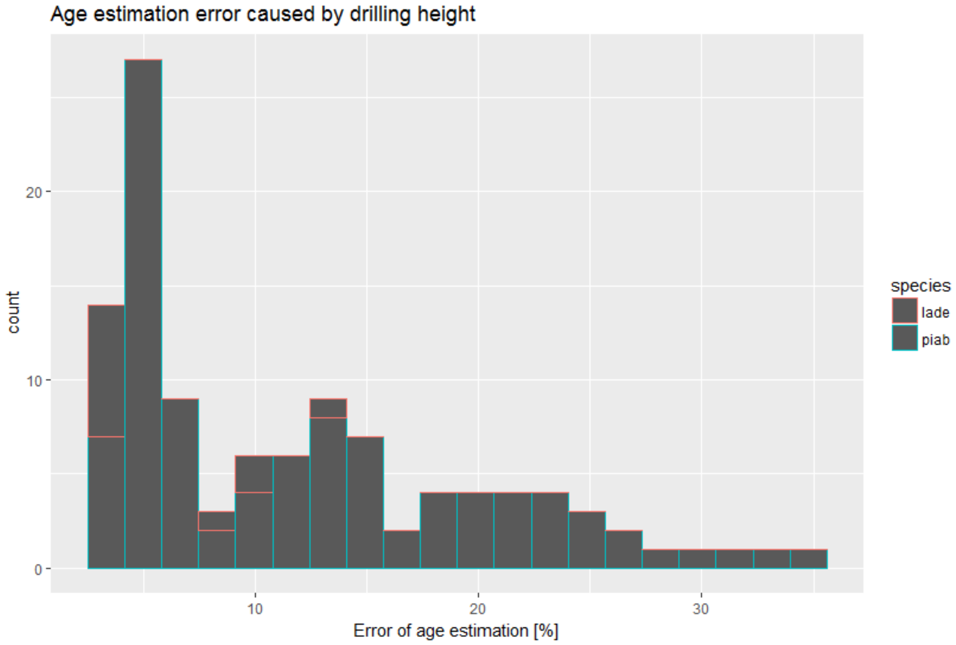


Fig. 17: A) Age estimation error caused by not reaching the chronological centre of the tree. This was calculated by dividing the number of missing trees by the corrected age (rings measured + missing rings). B) Age estimation error causes by drilling above ground level and therefore not accounting for the growth up to the drilling height. The error was estimated by dividing the calculated age at drilling height by the corrected age (rings measured +missing rings + calculated age at drilling height).

Fig. 18: Relationship between the corrected age and the error percentage of the age estimation. The blue line represents a negative exponential smoothing function. The negative exponential function accounts for 90% of the data variability.

11.2 Summary of tree ring data

Table 2: Summary of tree rings as produced by the function stats.rwl from the package dplR (Bunn, 2008). For each tree ID (=series), the years of the first and last tree rings that were measured are shown (=first,last), with the difference of the two numbers showing the age in 2016 (age=last – first + 1). The information about the tree ring widths consists of the average ring widths (=mean,median), the standard deviation (=stdev) and the gini coefficient (=gini).

series	first	last	year	mean	median	stdev	gini
65	1923	2016	94	1.105	1.035	0.488	0.248
66	1939	2016	78	2.14	2.07	0.619	0.16
89	1779	2016	238	1.244	1.01	0.837	0.343
92	1975	2016	42	0.705	0.705	0.269	0.214
165	1782	2016	235	0.864	0.79	0.443	0.279
166	1785	2016	232	0.672	0.52	0.459	0.351
271	1802	2016	215	1.038	0.97	0.491	0.263
272	1783	2016	234	0.687	0.53	0.569	0.378
273	1755	2016	262	1.205	0.83	0.917	0.38
286	1906	2016	111	2.152	2.13	0.683	0.178
371	1781	2016	236	1.162	1.025	0.678	0.293
372	1770	2016	247	1.136	0.79	0.912	0.412
14	1766	2016	251	1.394	1.22	0.661	0.239
15	1848	2016	169	0.395	0.34	0.232	0.315
21	1982	2016	35	1.61	1.72	0.521	0.175
22	1990	2016	27	1.407	1.3	0.589	0.235
23	1971	2016	46	0.584	0.58	0.22	0.206
24	1958	2016	59	0.831	0.78	0.468	0.304
25	1948	2016	69	0.473	0.32	0.378	0.396
26	1954	2016	63	1.011	0.93	0.339	0.188
27	1952	2016	65	0.679	0.7	0.163	0.135
28	1776	2016	241	1.085	0.87	0.616	0.288
30	1968	2016	49	1.095	1.07	0.38	0.193
31	1953	2016	64	1.932	1.885	0.372	0.107
32	1976	2016	41	0.564	0.53	0.305	0.299
33	1989	2016	28	2.871	3.165	1.027	0.185
38	1883	2016	134	1.467	0.985	1.017	0.38
39	1938	2016	79	1.373	1.25	0.481	0.183
40	1926	2016	91	1.493	1.48	0.521	0.191
41	1902	2016	115	2.014	1.9	0.55	0.152
42	1768	2016	249	1.014	0.72	0.795	0.39
45	1952	2013	62	0.435	0.435	0.132	0.167
46	1955	2016	62	1.323	1.365	0.489	0.208
48	1990	2016	27	1.649	1.54	0.572	0.193
49	1943	2016	74	1.102	0.92	0.746	0.377
50	1946	2016	71	1.441	1.53	0.571	0.225
51	1996	2016	21	2.749	2.3	0.995	0.19
52	1778	2016	239	1.821	1.68	0.699	0.21
53	1803	2016	214	0.643	0.58	0.331	0.289
55	1759	2016	258	1.005	0.77	0.575	0.311
56	1760	2016	257	1.157	0.85	0.734	0.33
57	1778	2016	239	0.936	0.77	0.482	0.276

58	1815	2016	202	0.997	0.98	0.339	0.191
60	1959	2016	58	1.181	1.38	0.656	0.311
61	1968	2016	49	1.998	2.02	0.663	0.183
63	1952	2016	65	1.843	1.71	0.562	0.17
64	1972	2016	45	2.463	2.42	0.666	0.153
67	1977	2016	40	3.657	3.745	0.994	0.15
68	1906	2016	111	1.996	2.01	0.654	0.186
69	1943	2016	74	1.425	1.37	0.246	0.093
70	1877	2016	140	1.621	1.41	0.754	0.259
71	1841	2016	176	1.58	1.53	0.603	0.216
75	1830	2016	187	1.022	0.92	0.376	0.207
76	1831	2016	186	1.406	1.365	0.433	0.17
77	1768	2016	249	0.741	0.41	0.679	0.446
80	1781	2016	236	0.726	0.58	0.454	0.305
81	1762	2016	255	1.002	0.71	0.802	0.394
82	1763	2016	254	1.124	0.81	0.709	0.326
83	1779	2016	238	0.966	0.77	0.579	0.291
84	1779	2016	238	0.883	0.77	0.348	0.204
85	1764	2016	253	1.001	0.87	0.576	0.318
86	1778	2016	239	0.637	0.59	0.277	0.229
88	1982	2016	35	2.115	2.08	0.377	0.1
90	1780	2016	237	0.746	0.43	0.623	0.419
91	1799	2016	218	1.145	0.97	0.545	0.261
93	1992	2016	25	1.21	1.28	0.523	0.235
95	1977	2016	40	1.546	1.38	0.785	0.283
131	1762	2016	255	1.044	0.94	0.557	0.287
132	1771	2016	246	1.245	1.18	0.421	0.188
167	1707	2016	310	0.874	0.76	0.518	0.323
169	1752	2016	265	1.159	0.89	0.745	0.32
224	1979	2016	38	1.139	1.1	0.32	0.151
227	1731	2016	286	0.703	0.675	0.308	0.25
228	1731	2016	286	1.216	1.17	0.353	0.156
229	1985	2016	32	2.26	2.08	0.711	0.174
242	1773	2016	244	0.833	0.77	0.449	0.288
243	1743	2016	274	1.2	1.13	0.579	0.261
244	1981	2016	36	1.141	1.015	0.434	0.213
245	1972	2016	45	1.098	1.05	0.505	0.262
246	1981	2016	36	1.227	1.275	0.411	0.188
247	1982	2016	35	1.459	1.46	0.457	0.175
248	1985	2016	32	1.042	1.035	0.326	0.176
249	1972	2016	45	1.012	0.76	0.633	0.339
250	1983	2016	34	1.745	1.72	0.469	0.152
251	1990	2016	27	2.19	2.19	0.694	0.176
252	1988	2016	29	1.59	1.5	0.483	0.17
260	1853	2016	164	1.319	1.295	0.292	0.12

261	1859	2016	158	1.518	1.495	0.582	0.217
262	1785	2016	232	0.799	0.71	0.402	0.244
276	1797	2016	220	1.799	1.65	0.758	0.232
279	1939	2016	78	1.522	1.515	0.211	0.077
280	1879	2016	138	0.534	0.51	0.326	0.32
281	1938	2016	79	0.997	0.75	0.667	0.356
282	1912	2016	105	2.76	2.73	0.543	0.11
283	1925	2016	92	1.182	1.18	0.256	0.119
284	1908	2016	109	0.98	0.94	0.427	0.247
366	1783	2016	234	0.629	0.41	0.54	0.439
367	1981	2016	36	2.763	2.61	1.246	0.253
373	1972	2016	45	1.067	1.07	0.34	0.168
374	1987	2016	30	1.149	1.095	0.354	0.168
375	1980	2016	37	1.506	1.61	0.366	0.134
376	1983	2016	34	1.618	1.35	0.546	0.186
377	1992	2016	25	1.465	1.43	0.445	0.161
433	1811	2016	206	0.617	0.475	0.416	0.357
434	1974	2016	43	2.124	2.13	0.717	0.188
435	1985	2016	32	1.994	2.08	0.679	0.191
437	1787	2016	230	1.295	1.27	0.4	0.17
443	1802	2016	215	1.252	1.2	0.317	0.14
444	1782	2016	235	0.825	0.71	0.462	0.316
446	1826	2016	191	1.094	1.01	0.595	0.31
447	1851	2016	166	2.073	2.06	0.931	0.251
448	1816	2016	201	1.471	1.45	0.504	0.196

11.3 Quantitative crossdating with COFECHA

11.3.1 Norway spruce

Table 3: COFECHA output of Norway spruce tree ring series

```
Time span of Master dating series is  1707 to  2016   310 years
Continuous time span is               1707 to  2016   310 years
Portion with two or more series is    1731 to  2016   286 years

>> 15         1910 absent in   1 of   49 series, but is not usually narrow: master index is  -.029
>> 15         1911 absent in   1 of   49 series, but is not usually narrow: master index is  1.165
>> 15         1912 absent in   1 of   50 series, but is not usually narrow: master index is  -.222
>> 42         2012 absent in   1 of  100 series, but is not usually narrow: master index is   .693
>> 60         2015 absent in   2 of   99 series, but is not usually narrow: master index is   .596
>> 167        1767 absent in   1 of   12 series, but is not usually narrow: master index is   .208
>> 167        1769 absent in   1 of   14 series, but is not usually narrow: master index is  -.025
>> 167        2015 absent in   2 of   99 series, but is not usually narrow: master index is   .596

                                ****************************************
                                *C* Number of dated series       100 *C*
                                *O* Master series 1707 2016  310 yrs *O*
                                *F* Total rings in all series  13139 *F*
                                *E* Total dated rings checked  13115 *E*
                                *C* Series intercorrelation     .597 *C*
                                *H* Average mean sensitivity    .182 *H*
                                *A* Segments, possible problems   35 *A*
                                *** Mean length of series      131.4 ***
                                ****************************************
```

Seq	Series	Interval	No. Years	No. Segmt	No. Flags	with Master	Mean msmt	Max msmt	Std dev	Auto corr	Mean sens	Max value	Std dev	Auto corr	AR ()
1	14	1766 2016	251	10	0	.669	1.39	3.60	.661	.871	.182	2.59	.382	-.071	1
2	15	1848 2016	169	7	0	.554	.40	1.24	.232	.829	.290	2.52	.276	-.037	2
3	21	1982 2016	35	1	1	.172	1.61	2.54	.521	.741	.236	2.49	.513	.097	1
4	22	1990 2016	27	1	0	.359	1.41	2.42	.589	.882	.208	2.68	.555	-.001	1
5	23	1971 2016	46	1	0	.570	.58	1.28	.220	.302	.320	2.59	.533	-.049	1
6	24	1958 2016	59	2	0	.406	.83	2.24	.468	.761	.325	2.53	.426	.070	1
7	25	1948 2016	69	3	2	.363	.47	1.86	.378	.879	.284	2.49	.506	-.041	3
8	26	1954 2016	63	2	2	.263	1.01	1.81	.339	.708	.216	2.57	.538	.018	1
9	27	1952 2016	65	2	1	.330	.68	1.05	.163	.543	.188	2.59	.500	.081	1
10	28	1776 2016	241	9	0	.646	1.09	3.11	.616	.932	.159	2.56	.356	.007	1
11	30	1968 2016	49	1	1	.157	1.09	2.06	.380	.763	.201	2.56	.420	-.017	1
12	31	1953 2016	64	2	0	.555	1.93	2.82	.372	.573	.133	2.70	.524	-.071	1
13	32	1976 2016	41	1	0	.454	.56	1.43	.305	.725	.335	2.67	.488	-.015	1
14	33	1989 2016	28	1	1	.102	2.87	3.92	1.027	.674	.233	2.24	.413	.006	1
15	38	1883 2016	134	5	0	.602	1.47	4.77	1.017	.935	.186	2.71	.482	.054	1
16	39	1938 2016	79	3	0	.705	1.37	2.96	.481	.666	.191	2.60	.418	-.013	1
17	40	1926 2016	91	3	0	.470	1.49	3.54	.521	.795	.147	2.58	.434	.027	2
18	41	1902 2016	115	4	0	.602	2.01	3.50	.550	.853	.127	2.45	.398	-.021	1
19	42	1768 2016	249	10	0	.729	1.01	3.56	.795	.948	.223	2.64	.395	-.023	1
20	45	1952 2013	62	2	0	.452	.43	.76	.132	.554	.220	2.69	.528	.080	1
21	46	1955 2016	62	2	2	.260	1.32	2.20	.489	.792	.185	2.62	.518	.058	1
22	48	1990 2016	27	1	0	.571	1.65	2.78	.572	.616	.266	2.67	.696	-.012	1
23	49	1943 2016	74	3	3	.235	1.10	2.73	.746	.884	.226	2.46	.430	-.055	1
24	50	1946 2016	71	3	1	.366	1.44	2.77	.571	.836	.184	2.65	.570	-.089	1
25	51	1996 2016	21	1	0	.435	2.75	5.22	.995	.595	.199	2.55	.572	-.151	1
26	52	1778 2016	239	9	0	.682	1.82	4.59	.699	.838	.169	2.47	.316	-.031	1
27	53	1803 2016	214	8	0	.695	.64	1.61	.331	.850	.227	2.59	.378	.016	3
28	55	1759 2016	258	10	0	.699	1.00	2.42	.575	.908	.180	2.73	.489	.021	1
29	56	1760 2016	257	10	0	.760	1.16	3.58	.734	.936	.158	2.50	.304	-.026	1
30	57	1778 2016	239	9	0	.640	.94	2.69	.482	.900	.151	2.44	.357	-.035	1
31	58	1815 2016	202	8	0	.663	1.00	2.17	.339	.847	.143	2.67	.420	.001	1
32	60	1959 2016	58	2	0	.347	1.18	2.18	.656	.898	.246	2.67	.578	.063	1
33	61	1968 2016	49	1	1	.159	2.00	3.86	.663	.671	.198	2.43	.435	.019	1
34	63	1952 2016	65	2	0	.496	1.84	3.22	.562	.737	.159	2.64	.554	-.017	1
35	64	1972 2016	45	1	0	.349	2.46	3.83	.666	.681	.168	2.53	.534	-.069	1
36	67	1977 2016	40	1	0	.436	3.66	5.20	.994	.593	.205	2.54	.504	-.106	1
37	68	1906 2016	111	4	0	.516	2.00	3.88	.654	.813	.163	2.76	.435	.029	1
38	69	1943 2016	74	3	0	.465	1.42	2.18	.246	.275	.149	2.59	.490	-.062	1
39	70	1877 2016	140	5	1	.600	1.62	3.57	.754	.928	.132	2.46	.334	-.008	2
40	71	1841 2016	176	7	0	.569	1.58	3.07	.603	.901	.138	2.49	.388	-.020	2
41	75	1830 2016	187	7	0	.672	1.02	2.07	.376	.832	.166	2.70	.456	-.001	1
42	76	1831 2016	186	7	0	.625	1.41	2.98	.433	.717	.172	2.53	.301	.021	1
43	77	1768 2016	249	10	0	.728	.74	3.09	.679	.976	.157	2.54	.344	-.038	1
44	80	1781 2016	236	9	0	.705	.73	2.48	.454	.935	.170	2.56	.319	-.030	1
45	81	1762 2016	255	10	0	.720	1.00	3.66	.802	.952	.195	2.57	.357	-.017	1
46	82	1763 2016	254	10	0	.680	1.12	3.41	.709	.935	.161	2.51	.328	-.039	1
47	83	1779 2016	238	9	0	.724	.97	3.11	.579	.936	.163	2.59	.353	-.037	1
48	84	1779 2016	238	9	0	.628	.88	2.09	.348	.879	.151	2.64	.472	-.018	1

49	85	1764 2016	253	10	0	.721	1.00	2.66	.576	.873	.206	2.65	.420	.014	1
50	86	1778 2016	239	9	0	.555	.64	1.86	.277	.838	.182	2.57	.331	-.026	1
51	88	1982 2016	35	1	0	.437	2.11	2.80	.377	.504	.155	2.45	.492	-.010	1
52	90	1780 2016	237	9	0	.640	.75	2.70	.623	.958	.154	2.46	.280	-.001	2
53	91	1799 2016	218	9	0	.719	1.14	2.76	.545	.910	.140	2.53	.288	-.040	1
54	93	1992 2016	25	1	1	.228	1.21	2.30	.523	.718	.330	2.20	.412	-.226	1
55	95	1977 2016	40	1	0	.428	1.55	3.02	.785	.886	.242	2.37	.396	.053	1
56	131	1762 2016	255	10	0	.646	1.04	2.87	.557	.891	.206	2.54	.331	-.041	1
57	132	1771 2016	246	10	0	.773	1.25	2.53	.421	.752	.190	2.40	.296	-.030	1
58	167	1707 2016	310	11	1	.597	.87	2.51	.518	.913	.222	2.59	.417	.013	1
59	169	1752 2016	265	10	0	.670	1.16	4.48	.745	.812	.218	2.59	.315	-.026	1
60	224	1979 2016	38	1	0	.524	1.14	1.96	.320	.501	.230	2.66	.471	-.017	1
61	227	1731 2016	286	11	0	.666	.70	1.48	.308	.860	.202	2.52	.377	-.029	3
62	228	1731 2016	286	11	1	.590	1.22	2.71	.353	.795	.138	2.59	.341	-.040	1
63	229	1985 2016	32	1	0	.513	2.26	3.65	.711	.692	.201	2.59	.493	-.109	1
64	242	1773 2016	244	10	0	.641	.83	2.49	.449	.901	.180	2.59	.378	.021	1
65	243	1743 2016	274	11	0	.570	1.20	3.83	.579	.892	.168	2.68	.389	.008	1
66	244	1981 2016	36	1	1	.435	1.14	2.11	.434	.623	.251	2.71	.503	-.066	1
67	245	1972 2016	45	1	1	.313	1.10	2.00	.505	.664	.338	2.57	.601	-.038	1
68	246	1981 2016	36	1	0	.480	1.23	1.94	.411	.677	.197	2.10	.336	-.009	1
69	247	1982 2016	35	1	0	.397	1.46	2.27	.457	.667	.214	2.40	.444	-.039	1
70	248	1985 2016	32	1	0	.597	1.04	1.65	.326	.757	.190	2.57	.476	.072	1
71	249	1972 2016	45	1	1	.318	1.01	2.51	.633	.934	.227	2.39	.410	.058	1
72	250	1983 2016	34	1	1	.255	1.74	2.73	.469	.555	.201	2.57	.492	-.130	2
73	251	1990 2016	27	1	0	.651	2.19	3.38	.694	.848	.151	2.59	.559	-.024	1
74	252	1988 2016	29	1	1	.067	1.59	2.51	.483	.659	.194	2.27	.463	-.148	2
75	260	1853 2016	164	6	0	.478	1.32	2.21	.292	.796	.110	2.47	.342	.010	1
76	261	1859 2016	158	6	2	.439	1.52	3.21	.582	.824	.182	2.58	.434	.056	1
77	262	1785 2016	232	9	0	.631	.80	2.61	.402	.925	.153	2.64	.425	-.020	2
78	276	1797 2016	220	9	0	.681	1.80	4.85	.758	.868	.159	2.60	.367	-.016	1
79	279	1939 2016	78	3	0	.621	1.52	2.02	.211	.474	.110	2.59	.482	-.044	1
80	280	1879 2016	138	5	1	.546	.53	1.95	.326	.877	.217	2.72	.452	-.019	1
81	281	1938 2016	79	3	0	.506	1.00	2.78	.667	.934	.207	2.54	.426	-.025	1
82	282	1912 2016	105	4	0	.701	2.76	4.36	.543	.540	.150	2.54	.349	.003	1
83	283	1925 2016	92	3	0	.656	1.18	2.04	.256	.623	.147	2.61	.519	-.001	2
84	284	1908 2016	109	4	0	.596	.98	2.05	.427	.829	.220	2.68	.471	-.041	2
85	366	1783 2016	234	9	0	.574	.63	2.53	.540	.943	.210	2.46	.269	-.043	1
86	367	1981 2016	36	1	0	.517	2.76	4.81	1.246	.842	.233	2.43	.547	-.003	1
87	373	1972 2016	45	1	1	-.042	1.07	2.07	.340	.442	.224	3.10	.603	.032	1
88	374	1987 2016	30	1	0	.428	1.15	1.97	.354	.623	.207	2.65	.563	.064	1
89	375	1980 2016	37	1	0	.389	1.51	2.14	.366	.451	.225	2.50	.568	-.014	1
90	376	1983 2016	34	1	1	.162	1.62	2.54	.546	.874	.135	2.37	.417	.073	1
91	377	1992 2016	25	1	1	-.263	1.47	2.59	.445	.680	.193	2.44	.447	.020	3
92	433	1811 2016	206	8	2	.436	.62	2.53	.416	.906	.228	2.68	.380	-.021	1
93	434	1974 2016	43	1	0	.347	2.12	3.79	.717	.880	.133	2.50	.475	-.063	1
94	435	1985 2016	32	1	1	.146	1.99	3.23	.679	.723	.186	2.67	.581	-.030	1
95	437	1787 2016	230	9	0	.674	1.30	2.86	.400	.696	.188	2.61	.348	-.019	1
96	443	1802 2016	215	8	0	.716	1.25	2.18	.317	.786	.127	2.53	.324	-.017	1
97	444	1782 2016	235	9	1	.524	.83	2.19	.462	.931	.183	2.46	.287	-.031	1
98	446	1826 2016	191	7	1	.491	1.09	2.71	.595	.922	.147	2.48	.231	-.003	1
99	447	1851 2016	166	6	0	.675	2.07	4.75	.931	.835	.197	2.52	.422	.005	1
100	448	1816 2016	201	8	0	.723	1.47	2.81	.504	.836	.148	2.62	.410	-.060	1

Correlations of 50-year dated segments, lagged 25 years
Flags: A = correlation under .3281 but highest as dated; B = correlation higher at other than dated position

Seq	Series	Time_span	1725 1774	1750 1799	1775 1824	1800 1849	1825 1874	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999	1975 2024
1	14	1766 2016		.52	.57	.75	.76	.69	.75	.78	.74	.59	.56
2	15	1848 2016					.62	.64	.34	.64	.79	.47	.46
3	21	1982 2016											.17B
4	22	1990 2016											.36
5	23	1971 2016										.57	
6	24	1958 2016										.40	.39
7	25	1948 2016									.33A	.28A	.35
8	26	1954 2016										.26B	.23A
9	27	1952 2016										.24B	.36
10	28	1776 2016			.37	.55	.82	.83	.71	.70	.66	.70	.75
11	30	1968 2016										.16B	
12	31	1953 2016										.52	.60
13	32	1976 2016											.45
14	33	1989 2016											.10B
15	38	1883 2016							.36	.60	.65	.69	.78
16	39	1938 2016									.71	.58	.63
17	40	1926 2016									.39	.46	.52
18	41	1902 2016								.60	.66	.59	.67
19	42	1768 2016		.65	.75	.76	.71	.70	.75	.86	.83	.67	.64
20	45	1952 2013										.44	.48
21	46	1955 2016										.30A	.24A
22	48	1990 2016											.57

23	49	1943	2016									.19B	.26B	.27A
24	50	1946	2016									.28A	.41	.52
25	51	1996	2016											.44
26	52	1778	2016			.50	.65	.71	.64	.56	.75	.83	.75	.78
27	53	1803	2016				.68	.63	.64	.77	.80	.80	.64	.70
28	55	1759	2016		.53	.67	.66	.66	.77	.75	.80	.79	.72	.74
29	56	1760	2016		.59	.76	.77	.75	.82	.88	.88	.84	.68	.72
30	57	1778	2016			.43	.52	.50	.50	.79	.83	.81	.75	.75
31	58	1815	2016				.55	.69	.64	.72	.82	.80	.67	.62
32	60	1959	2016										.43	.45
33	61	1968	2016										.16B	
34	63	1952	2016										.40	.56
35	64	1972	2016										.35	
36	67	1977	2016											.44
37	68	1906	2016								.47	.56	.51	.63
38	69	1943	2016									.45	.55	.62
39	70	1877	2016							.29A	.76	.73	.57	.71
40	71	1841	2016					.56	.68	.58	.57	.59	.66	.65
41	75	1830	2016					.63	.68	.70	.78	.71	.56	.65
42	76	1831	2016					.62	.71	.60	.67	.68	.66	.66
43	77	1768	2016		.60	.65	.84	.76	.67	.74	.81	.82	.71	.66
44	80	1781	2016			.66	.74	.73	.67	.73	.86	.86	.67	.46
45	81	1762	2016		.65	.79	.83	.81	.78	.72	.69	.69	.74	.71
46	82	1763	2016		.61	.72	.70	.51	.61	.83	.77	.70	.71	.74
47	83	1779	2016			.69	.79	.82	.81	.78	.83	.73	.49	.52
48	84	1779	2016			.63	.73	.71	.73	.75	.60	.49	.54	.64
49	85	1764	2016		.72	.78	.90	.74	.68	.79	.68	.63	.68	.73
50	86	1778	2016			.49	.51	.61	.60	.63	.59	.56	.58	.53
51	88	1982	2016											.44
52	90	1780	2016			.57	.69	.66	.60	.49	.78	.86	.49	.51
53	91	1799	2016			.75	.75	.74	.48	.60	.88	.84	.64	.68
54	93	1992	2016											.23B
55	95	1977	2016											.43
56	131	1762	2016		.51	.58	.80	.75	.66	.68	.72	.61	.53	.62
57	132	1771	2016		.61	.68	.73	.77	.87	.85	.86	.86	.81	.81
58	167	1707	2016	.53	.22B	.42	.63	.76	.77	.70	.77	.72	.54	.52
59	169	1752	2016		.45	.72	.68	.58	.58	.68	.86	.80	.59	.69
60	224	1979	2016											.52
61	227	1731	2016	.57	.50	.63	.74	.62	.61	.71	.87	.79	.65	.69
62	228	1731	2016	.42	.32B	.54	.79	.81	.76	.69	.61	.52	.66	.60
63	229	1985	2016											.51
64	242	1773	2016		.58	.59	.65	.69	.64	.67	.75	.67	.59	.61
65	243	1743	2016	.51	.67	.72	.71	.62	.63	.61	.39	.42	.67	.66
66	244	1981	2016											.44B
67	245	1972	2016										.31A	
68	246	1981	2016											.48
69	247	1982	2016											.40
70	248	1985	2016											.60
71	249	1972	2016										.32A	
72	250	1983	2016											.26A
73	251	1990	2016											.65
74	252	1988	2016											.07B
75	260	1853	2016						.38	.43	.52	.54	.55	.65
76	261	1859	2016						.23B	.38	.57	.51	.36B	.53
77	262	1785	2016			.54	.63	.72	.55	.57	.78	.73	.43	.59
78	276	1797	2016			.76	.75	.69	.65	.70	.78	.68	.55	.66
79	279	1939	2016									.66	.67	.61
80	280	1879	2016							.23B	.60	.71	.54	.72
81	281	1938	2016									.47	.45	.52
82	282	1912	2016								.73	.73	.66	.68
83	283	1925	2016									.71	.58	.68
84	284	1908	2016								.55	.62	.63	.69
85	366	1783	2016			.48	.57	.59	.63	.65	.76	.77	.47	.48
86	367	1981	2016											.52
87	373	1972	2016										-.04B	
88	374	1987	2016											.43
89	375	1980	2016											.39
90	376	1983	2016											.16B
91	377	1992	2016											-.26B
92	433	1811	2016				.55	.49	.50	.53	.50	.46	.31A	.29A
93	434	1974	2016										.35	
94	435	1985	2016											.15B
95	437	1787	2016			.62	.65	.70	.56	.67	.75	.76	.67	.68
96	443	1802	2016				.63	.63	.67	.73	.83	.85	.66	.71
97	444	1782	2016			.31A	.55	.57	.40	.53	.77	.69	.46	.51
98	446	1826	2016					.39	.39	.50	.74	.75	.37	.03B
99	447	1851	2016						.36	.65	.82	.78	.64	.81
100	448	1816	2016				.76	.69	.63	.67	.78	.82	.78	.74
Av segment correlation				.51	.55	.61	.69	.67	.63	.64	.72	.67	.53	.53

11.2.2 European larch

Table 4: COFECHA output of European larch tree ring series

```
Time span of Master dating series is  1755 to  2016   262 years
Continuous time span is               1755 to  2016   262 years
Portion with two or more series is    1770 to  2016   247 years

>> 372        1892 absent in   1 of    8 series, but is not usually narrow: master index is   .395
>> 372        1893 absent in   1 of    8 series, but is not usually narrow: master index is  1.172

                                        ****************************************
                                        *C* Number of dated series        12 *C*
                                        *O* Master series 1755 2016  262 yrs *O*
                                        *F* Total rings in all series   2224 *F*
                                        *E* Total dated rings checked   2209 *E*
                                        *C* Series intercorrelation     .627 *C*
                                        *H* Average mean sensitivity    .268 *H*
                                        *A* Segments, possible problems    1 *A*
                                        *** Mean length of series      185.3 ***
                                        ****************************************
```

Seq	Series	Interval	No. Years	No. Segmt	No. Flags	Corr with Master	Unfiltered Mean msmt	Unfiltered Max msmt	Unfiltered Std dev	Unfiltered Auto corr	Unfiltered Mean sens	Filtered Max value	Filtered Std dev	Filtered Auto corr	AR ()
1	65	1923 2016	94	4	0	.498	1.10	2.22	.488	.742	.267	2.38	.366	.081	1
2	66	1939 2016	78	3	0	.737	2.14	3.86	.619	.530	.225	2.60	.482	.006	1
3	89	1779 2016	238	9	0	.555	1.24	4.36	.837	.887	.219	2.76	.458	-.041	1
4	92	1975 2016	42	1	1	.144	.70	1.36	.269	.660	.277	2.70	.576	.015	1
5	165	1782 2016	235	9	0	.597	.86	2.70	.443	.770	.254	2.84	.453	-.016	1
6	166	1785 2016	232	9	0	.658	.67	2.38	.459	.846	.277	2.50	.308	-.044	1
7	271	1802 2016	215	8	0	.770	1.04	2.76	.491	.679	.304	2.70	.502	-.030	1
8	272	1783 2016	234	9	0	.654	.69	5.27	.569	.806	.353	2.86	.515	.031	1
9	273	1755 2016	262	10	0	.621	1.21	4.76	.917	.857	.239	2.57	.405	-.032	5
10	286	1906 2016	111	4	0	.575	2.15	4.13	.683	.654	.191	2.61	.405	-.062	2
11	371	1781 2016	236	9	0	.691	1.16	4.44	.678	.719	.307	2.79	.454	.008	1
12	372	1770 2016	247	10	0	.614	1.14	4.17	.912	.901	.250	2.73	.379	.026	1
Total or mean:			2224	85	1	.627	1.10	5.27	.654	.787	.268	2.86	.433	-.010	

```
Correlations of  50-year dated segments, lagged  25 years
Flags:  A = correlation under   .3281 but highest as dated;  B = correlation higher at other than dated position
```

Seq	Series	Time_span	1750 1799	1775 1824	1800 1849	1825 1874	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999	1975 2024
1	65	1923 2016							.43	.52	.44	.53
2	66	1939 2016								.63	.71	.81
3	89	1779 2016		.43	.59	.52	.50	.63	.68	.68	.75	.57
4	92	1975 2016										.14B
5	165	1782 2016		.57	.70	.65	.45	.40	.66	.76	.73	.64
6	166	1785 2016		.49	.53	.64	.62	.72	.74	.72	.74	.66
7	271	1802 2016			.81	.76	.68	.70	.82	.83	.80	.76
8	272	1783 2016		.67	.79	.84	.78	.65	.61	.68	.61	.51
9	273	1755 2016	.48	.49	.60	.54	.64	.77	.82	.77	.61	.61
10	286	1906 2016							.53	.58	.62	.66
11	371	1781 2016		.56	.71	.70	.70	.66	.74	.83	.80	.75
12	372	1770 2016	.72	.74	.78	.63	.57	.64	.68	.70	.75	.72
Av segment correlation			.60	.56	.69	.66	.62	.65	.67	.70	.69	.61