Master Thesis

The Role of Climate, Provenance and Social Status on the Growth of Austrian Pine Trees

Handed in by
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ZUSAMMENFASSUNG

Prognosen zeigen, dass sich durch den Klimawandel die Durchschnittstemperatur in Europa bis 2100 bis zu 4 °C erhöht und sich auch das Niederschlagsmuster verändert. Eine weitere Folge ist, dass klimatische Extremereignisse, wie zum Beispiel Trockenperioden, öfters und stärker vorkommen werden. Aufgrund dieser schnellen und starken Änderung der Umweltbedingung ist es wichtig, Maßnahmen zu treffen, um unsere Wälder rechtzeitig an diese neuen Umstände anzupassen und die verschiedenen Funktionen der Waldökosysteme zu erhalten.

Eine Möglichkeit der Adaptierung der Wälder an dem Klimawandel ist, Baumarten oder Herkünfte aus warmen und trockenen Gebieten in Regionen einzubringen, bei welchen in Zukunft ähnliche klimatische Bedingungen erwartet werden. Hierbei spielt die Schwarzkiefer (*Pinus nigra*) für warme und trockene Standorte in Zentraleuropa eine interessante Rolle aufgrund ihres weiten Verbreitungsgebiets im Mittelmeerraum und ihrer hohen genetische Variabilität.

Im Zuge dieser Masterarbeit wurde eine Versuchsfläche mit vier Herkünften der Schwarzkiefer aus Korsika, Kalabrien und Österreich untersucht. Die Versuchsfläche liegt in der Nähe von Krems und wurde Anfang der 1960er Jahre angelegt.

Pro Parzelle wurden 10 Bäume für Stammanalysen gefällt und mit den gewonnen Daten das Wachstum der einzelnen Bäume rekonstruiert. Mit dieser Grundlage wurde untersucht, wie Radial-, Volumen- und Höhenzuwachs der Schwarzkiefer auf Niederschlag und Temperatur reagieren. Auch wurde überprüft, ob es diesbezüglich Unterschiede zwischen den Provenienzen und zwischen Bäumen unterschiedlicher sozialer Stellung gibt.

Die Auswirkungen von einzelnen Trockenjahren auf das Wachstum wurden mit Indices bewertet, welche die Resistenz und Resilienz beschreiben. Hierbei war es von Interesse, ob sich die Herkünfte unterscheiden und es wurde auch die Schwarzkiefer mit Fichten aus einem benachbarten Bestand verglichen.

Eine Vollaufnahme und die Ergebnisse der Stammanalysen zeigten, dass die österreichische Herkunft in der Wuchsleistung schlechter abschnitt als die Herkünfte aus Kalabrien und Korsika.

Mittels Mixed-Effects Modellen konnte nachgewiesen werden, dass eine höhere jährliche Durchschnittstemperatur zusammen mit der sozialen Stellung des Baumes einen signifikanten Einfluss auf den Radial- und Volumenzuwachs hat und sich auch negativ auf das Höhenwachstum der Schwarzkiefer auswirkt. Herbstniederschlag des Vorjahres, Frühjahrs- und Sommerniederschlag haben sowohl auf den Radialzuwachs, als auch auf den Volumen- und Höhenzuwachs einen signifikant positiven Einfluss. Bei der Reaktion des Radial- und Volumenzuwachs auf Frühjahrs- und Sommerniederschlag wurden zudem Unterschiede zwischen den verwendeten Herkünften gefunden.
Auch wurde nachgewiesen, dass Bäume mit einer besseren sozialen Stellung stärker auf Niederschlag reagieren und einen höheren Radial- und Volumenzuwachs aufweisen. Eine Wechselbeziehung zwischen sozialer Stellung und dem Einfluss des Niederschlags auf den Höhenzuwachs konnte hingegen nicht nachgewiesen werden.

Bei der Untersuchung der Auswirkung von einzelnen Trockenjahren auf das Wachstum konnte gezeigt werden, dass sich die Herkünfte bezüglich der Resistenz gegenüber Trockenjahren auf Ebene des Radial-, Volums- und Höhenzuwachs unterscheiden, aber es konnte nicht nachgewiesen werden, dass es Unterschiede bei der Fähigkeit gibt, sich von diesen Extremereignissen zu erholen.

ABSTRACT

Model predictions show that climate change will lead to an increase in average temperature of up to 4 °C by 2100 in Europe, as well as changes in precipitation patterns. Another consequence is that extreme climatic events, for example drought periods, are expected to occur more frequently and become more intense. Due to these rapid environmental changes, it is necessary to adapt our forests to the future climate in order to maintain the various services they provide.

One option for the adaptation of forests to climate change is to transfer tree species and populations from warm and dry regions into regions that are expected to have similar climatic conditions in the future. Thereby, Austrian pine (*Pinus nigra*) plays an interesting role for warm and dry sites in central Europe because of its wide distribution range from Spain to Minor Asia, as well as its high genetic variability.

This master's thesis investigates a plantation with Austrian pine established with three provenances from Corsica, Calabria and Austria. This trial site is located near Krems and was established in 1962. The data from stem analysis were used to examine how the radial, volume and height growth of Austrian pine trees reacted to precipitation and temperature. Differences among the provenances and between trees of different social status were also investigated.

The impact of drought years on growth was evaluated using indices of drought performance, which describe trees' resistance and resilience. The three provenances were compared with respect to their growth and reaction to drought. Moreover, Austrian pine was compared to Norway spruce (*Picea abies*).

The complete inventory and results of the stem analysis indicate that the Austrian provenance had a worse growth performance that than of the Calabrian and Corsican provenances.

The results of mixed-effects models show that a higher annual mean temperature together with the tree's social position had a significant impact on radial and volume increment, and also caused a decrease in height growth. Precipitation in the previous autumn and the current spring and summer had a significantly positive influence on radial, volume and height increment. Differences between the provenances were found for changes in radial and volume growth due to spring and summer precipitation.

Trees with a better social status reacted more strongly to changes in precipitation regarding radial and volume growth but not height growth. No interaction of social status and precipitation was observed for the height increment of Austrian pine trees. The radial increment at breast height was more strongly affected by precipitation than the radial increment in higher segments of the trunk.

The investigation of the reaction of growth to drought events shows that the provenances' resistance differed at the level of radial, volume and height growth, but there is a lack of evidence for differences in the provenances' ability to recover from these extreme events.

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ABBREVIATIONS

ANOVA	Analysis of variance
BFW	Austrian Research Centre for Forests
BOKU	University of Natural Resources and Life Sciences, Vienna
CR	Crowning height
DBH	Diameter at breast height
Dh	Height of stem disc in meters (m)
Dr	Drought year
H	Height increment in cm
H/D	Ratio between height and diameter
G	Basal area in m^2
G/ha	Basal area in m^2/ha
ha	Hectare
ID	Identification number of tree
lat	Latitude
long	Longitude
N	Number of stems
N/ha	Number of stems per ha
PostDr	Post-drought period
PreDr	Pre-drought period
Pprev	Precipitation sum for September and October of the previous year (1 = 100mm)
Pspring	Precipitation sum for March, April and May (1 = 100mm)
Psummer	Precipitation sum for June, July, August and September (1 = 100mm)
Pprev:Dh	Interaction effect between precipitation in autumn and height of stem disc
Pspring:Dh	Interaction effect between precipitation in spring and height of stem disc
Psummer:Dh	Interaction effect between precipitation in summer and height of stem disc
R^2	Coefficient of determination
RCP	Representative concentration pathways
REML	Radial increment in 1/100 mm
RI	Standardised DBH; Index for social status of tree
SD	Standard deviation
sDBH	Standardised annual mean temperature
sDBH:Pprev	Interaction effect between precipitation in autumn and social status of tree
sDBH:Pspring	Interaction effect between precipitation in spring and social status of tree
sDBH:Psummer	Interaction effect between precipitation in summer and social status of tree
sDBH:sT	Interaction effect between standardised annual temperature and social status of tree
SPI	Standardised precipitation index
sT	Volume increment in dm^3
sT:Dh	Interaction effect between standardised annual temperature and height of stem disc
V	Volume in m^3
V/ha	Volume in m^3/ha
ZAMG	Zentralanstalt für Meteorologie und Geodynamik

1. INTRODUCTION

It is incontestable that climate change is already occurring globally and will lead to further changes in temperature and precipitation in the future. The level of carbon dioxide is at 408 parts per million: the highest value in the last 650,000 years (NASA, 2018). A comparison to the preindustrial level in Europe shows that the mean temperature and frequency of heat waves have increased (EEA, 2012). The decade from 2002 to 2012 was the warmest on record and 1.3 °C warmer than the temperature at the preindustrial level (EEA, 2012; ZAMG, 2018). The five warmest summers in Europe between 1500 and 2010 occurred in that decade. Southern Europe is strongly affected by a decrease in precipitation (EEA, 2012). The frequency of drought spells is expected to increase in the southern and western regions of Europe (Stagge et al., 2015; cited after EEA, 2016). For the continental region (Central and Eastern Europe), it is projected that the frequency and magnitude of heat extremes will increase and that summer precipitation will be reduced (figure 1). Even if human society is able to stop greenhouse gas emissions in the very near future, climate change would continue for many years due to the time-lagged effects of past emissions (EEA 2017).

Forests and forestry are affected by these changes. In some of Europe’s central and western regions, storms, pests and diseases have been observed to lead to a lowered productivity of forest ecosystems. In the Mediterranean region, the number of forest fires increased between 1980 and 2000 (EEA 2012). It is projected that forest growth will increase in Northern Europe, but southern and western forests are expected to suffer under the projected future climate conditions (EEA 2012).

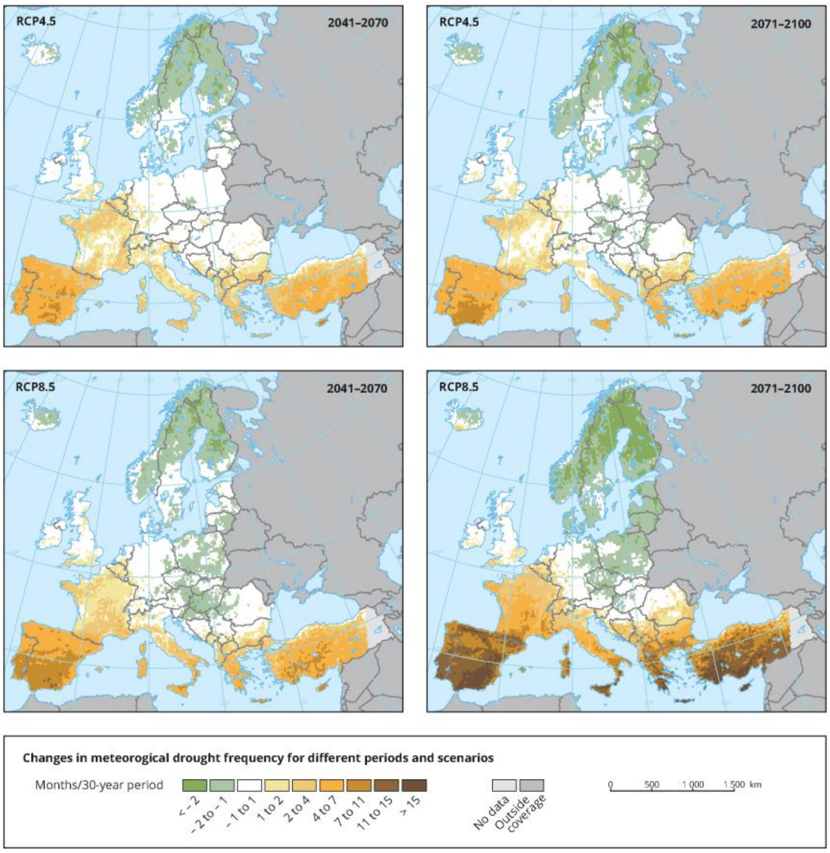

Figure 1: Projected changes in extreme meteorological drought frequency for the periods 2041–2070 and 2071–2100 based on the RCP4.5 and RCP8.5 emissions scenarios. The colours indicate the number of months in a 30-year period in which the SPI accumulated over a six-month period is below -2 (Stagge et al. 2015 cited after EEA 2016).

Measures to mitigate climate change, for example by reducing carbon emissions, are insufficient to protect various ecosystems. Achieving this also requires adapting forests to future climate conditions in order to maintain ecosystems' functions. One way to do so is to move species, populations or genotypes to new locations that lie outside of the known historical distribution. Richardson et al. call this strategy "managed relocation" (2009). To use the potential of managed relocation and understand the impact of the translocation of populations, it is necessary to explore whether southern populations, which are considered to be adapted to warm and dry conditions, can be safely translocated to northern regions. For example, Benito-Garzon et al. (2013) point to a possible maladaptation of a tree species' southern populations to extreme cold events such as spring frost. It is also unclear whether northern populations would benefit from population reinforcement with the translocation of provenances from southern areas of the distribution range (Benito-Garzon & Fernandez-Manjarres, 2015). Many species already changed their distribution range northwards and uphill, but without support this natural species migration is often too slow to adapt to the rapid progress of climate change (Gray and Hamann 2013). Intrinsic limitations, habitat use and fragmentations are also barriers impeding the natural movement of species (EEA 2016).

Due to its high adaptation potential, Austrian pine (*Pinus nigra*) can be regarded as a relevant tree species for afforestation campaigns in the future. This species is characterised by high drought tolerance and low nutrient requirements. Compared to Scots pine (*Pinus sylvestris)*, its growth performance also seems to be better (Klemmt et al. 2012).

The natural distribution range of Austrian pine is widely spread, reaching from Spain to Asia Minor and from the most northern habitat in Austria to the southern Mediterranean regions (figure 2). Because the north-eastern fringe of the Alps has thus far acted as the northern distribution limit, this species becomes an interesting alternative for regions outside of its natural distribution in Central and Eastern Europe. Its natural habitats are scattered and comprise a wide range of site conditions, climates and soils, suggesting a large number of Austrian pine populations are adapted to different site conditions. This tree species' genetic potential is ideal for transferral to northern regions.

Figure 2: Natural distribution range of Austrian pine (Euforgen 2009).

Austrian pine’s climatic suitability for cultivation is expected to change very strongly (figure 3). In the south, the conditions are becoming too dry and warm. The areas with a high or optimal suitability for cultivation are moving from the southern and western regions of Europe to the northeast. Thus, in Central and Eastern Europe, climate is expected to change in such a way that Austrian pines will fit very well with the future conditions in these regions.

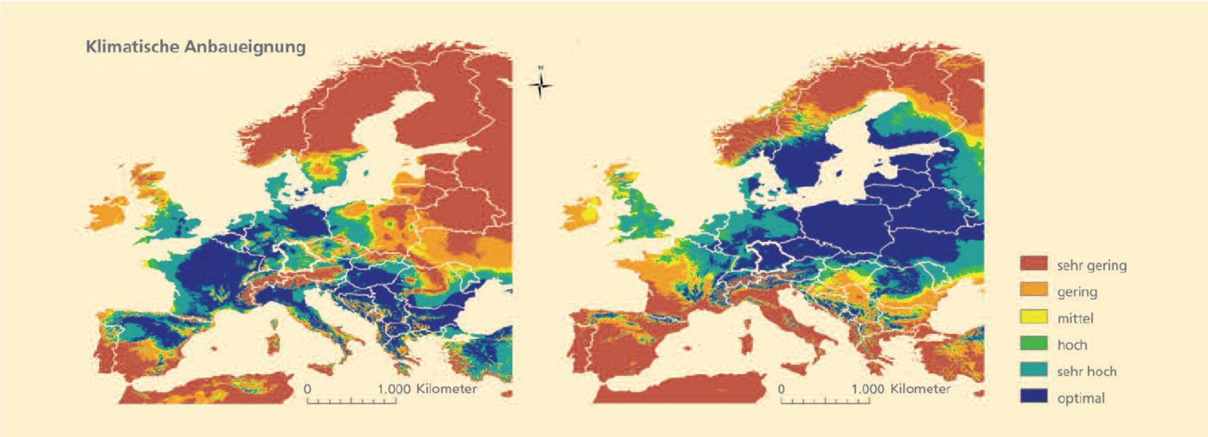

Figure 3: The left map shows Austrian pine’s current climatic suitability for cultivation and the right map shows its climatic suitability for cultivation in the future period of 2071–2100 (scenario A1B) (Klemmt et al. 2012).

To use the full potential of Austrian pine, it is necessary to know the different provenances’ characteristics and suitability for future climate conditions. The establishment and evaluation of provenance trials are necessary and important for compiling essential knowledge, as well as to formulate recommendations for forest practitioners.

2. OBJECTIVES

The aim of this master's thesis is to provide knowledge about Austrian pine's growth reactions to changing climatic conditions, especially temperature, precipitation and drought, whereby differences between the three provenances (Austria, Corsica and Calabria) are of particular interest. The results are expected to provide information about the provenances' suitability for future climate conditions.

The objectives are divided into the following research questions:

1. Do Austrian pine provenances significantly differ with respect to their productivity in terms of radial, volume and height increment?
2. How is Austrian pine trees' growth influenced by temperature and precipitation, and do differences exist between the provenances?
3. Does social position influence the trees' growth sensitivity to precipitation and temperature?
4. Are there any differences between provenances with respect to the impact of drought events on radial, volume and height growth, and are there differences between *Austrian pine* and Norway spruce (*Picea abies*) in this respect?
5. Is Austrian pine's radial increment in response to precipitation and temperature different in higher parts of the stem than in lower parts?

3. METHODS

3.1. TRIAL SITE

The former owner of the forest was very interested in non-native tree species and provenances, and established several trials with exotic species and tree populations. One of them is an Austrian pine test site with three (to four) different provenances, which are investigated in this master's thesis.

The trial site is located 5 km northwest of the city Krems in Lower Austria (lat: 48.43, long: 15.54) and is privately owned by Forstgut Waldhof (figure 4). Its elevation is 450 m above sea level (a.s.l.). Thus, the test site lies in the provenance region 9.2, named "Waldviertel". The average total annual precipitation is relatively low, with 530 mm (1960–2015), and the summer months (May, June, July and August) have the highest rates of precipitation (figure 6). The bedrock is gneiss and the soil type is brown soil with a sandy loam texture. Before the Austrian pine trial was established in 1962, the area was used as agricultural crop land. The terrain on the trial site is flat and the soil is relatively uniform. The test site consists of four plots, which are clearly separated with hornbeam hedges. Only one provenance was planted in each plot.

Unfortunately, the plots were not measured prior to the current survey. Thus, prior measurement data are not available from the past. Although the plots are clearly separated by rows of deciduous trees, no information was available on the inter-tree spacings used in the afforestation, nor on the thinnings or the stem numbers that were applied over the time. In addition, no replications of the treatments were available, which is also why the plots have different sizes. Plot A covers760 m^2, B 403 m^2, C 1016 m^2 and D 953 m^3 (figure 5).

The spruce stand, where the tree cores were sampled for comparing the drought reactions of Austrian pine and Norway spruce (*Picea abies*), is located at a distance of 450 m from the trial site on a moderate hillside with exposition to the east. According to personal communications with the forest owners, the neighbouring spruce stand has the same age as the Austrian pine trial stand.

Figure 4: Location of the trial site (circled area) (Google Maps 2018).

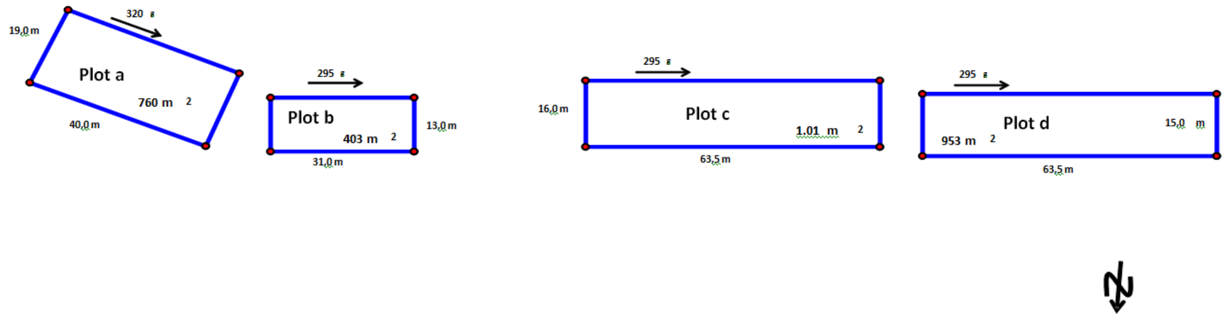

Figure 5: Spatial arrangement and sizes of the sample plots.

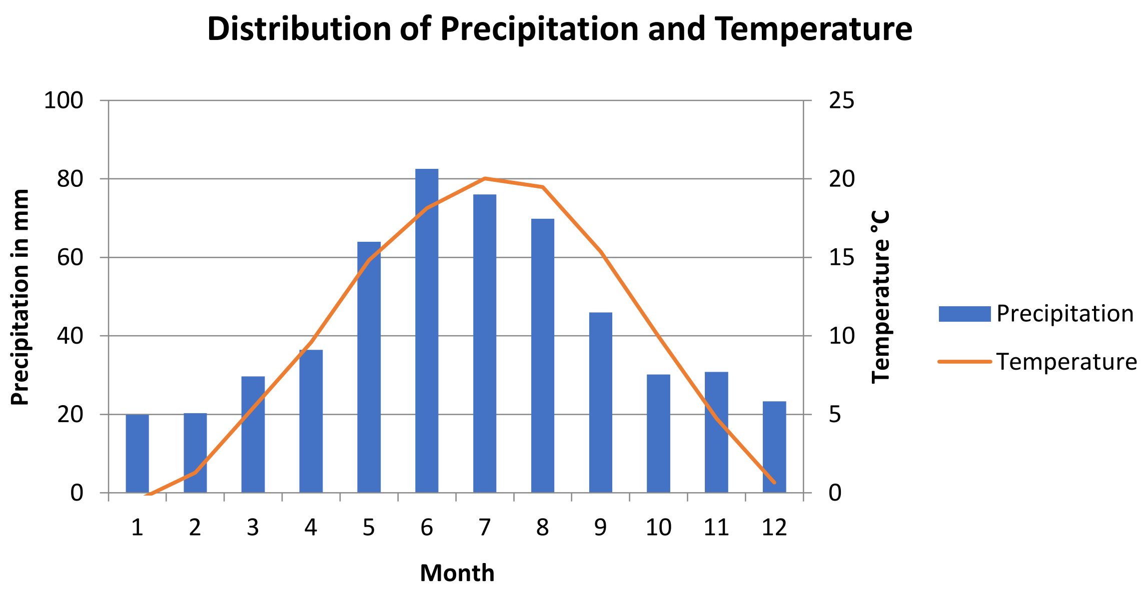

Figure 6: Average total monthly precipitation and average monthly temperature for the time period 1960–2016.

3.2. Provenances

Documentation of the correspondence between the Austrian Research Centre for Forests (BFW) and a former forest owner indicates three different provenances were used on the trial site: Austria, Southern Italy (Calabria) and Corsica.

In 2016, a genetic analysis conducted at the BFW's Department of Forest Genetics to investigate the genetic material of the Waldhof trial site (George 2016) found that the provenance growing on plots A and D most likely originated in Calabria, the trees growing on plot B in the Balkans and the trees growing on plot C in Corsica. Despite the information in the documentation of correspondence, the results of the genetic analysis indicate that the provenance on plot B did not originating in Austria but from the Balkans. It is very likely that the trees which were planted on plot B stem were from a seed orchard in Austria that was established with trees from the Balkans.

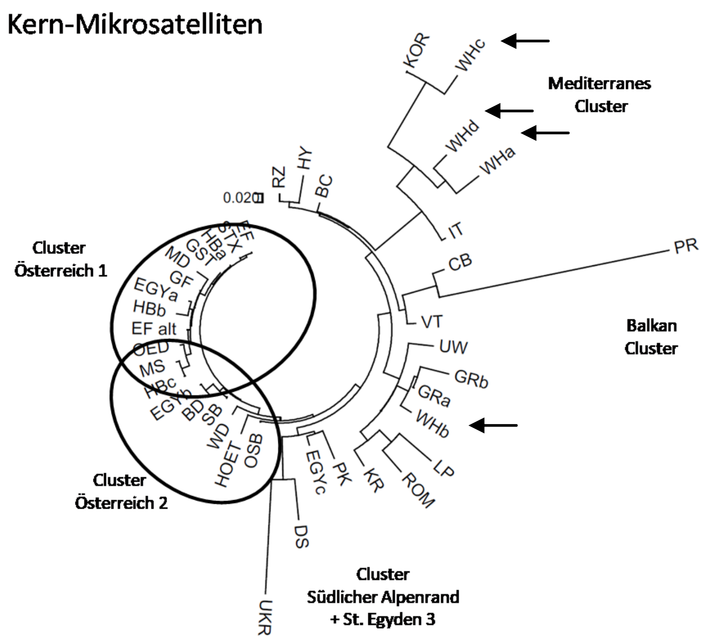

Figure 7: Results of genetic analysis conducted by George (2016). Arrows point at the four provenances used at the Austrian pine trial. “WHb” is the provenance on plot B, which belongs to the Balkans cluster, while “WHa” and “WHd” are the provenance from Calabria.

3.3. Data collection

During the summer in 2017, a comprehensive survey was conducted for all trees on the sample plots, and various attributes were measured, including tree height, diameter at breast height (DBH), crowning height and social class according to Kraft’s specifications (1984).

On each survey plot, a constant number of 10 sample trees were felled for stem analysis. To achieve representative samples from the entire DBH range, the sample for each plot consisted of the four thickest and the three thinnest, and an additional three trees with DBHs approximately corresponding to the mean DBH for that plot. Between seven and nine cross-sectional discs were cut from each sample tree. In the lower segments of the trunks, the distance between the stem discs was 4 m and in higher segments it was 1–2 m. The tree-ring widths of every disc were measured at the BFW Department of Forest Growth and Silviculture using a digital positiometer. In addition, the annual radial, volume and height increments were calculated using a software program developed at the BFW.

For the calculation of the felled trees’ shape constants, the diameters of the stems were measured with a distance of 1 m between measurements.

In the reference spruce stand, sample cores were additionally collected from 26 trees. Every tree was bored orthogonally on the east and north sides at breast height. Ring-width measurements on the sample cores were also made at the BFW using a digital positiometer.

Climate data were obtained from a weather station of the Austrian Meteorological Service ZAMG located in Krems, at a distance of 5 km from the trial site. Information on the daily average temperature and daily total precipitation was available for the period 1960–2016. For the subsequent analysis, the daily climate measures were aggregated to the monthly average temperatures and monthly total precipitations.

3.4. Analysis of Data

Statistical analyses were conducted in R (R Core Team 2017). Microsoft Excel was additionally used to evaluate the complete inventory, calculate the shape constants and prepare graphical material and tables.

3.4.1. Mixed-Effects Models

The complete data set had a clustered structure because sample trees were grouped into different plots. Thus, linear mixed-effects models were used to analyse the annual increment dependent on the regressor variables, comprising the monthly climatic variables (precipitation and temperature), tree age and social status. The mixed-effects model framework takes into account both the fixed effects of the covariates and random effects.

In this research, three linear mixed-effects models were built: the first for the reaction of radial increment, the second for volume and the third for height growth. In each model, the trial site's individual trees ("ID") and four plots ("Plot") were set as random parameters with the former nested within the latter. The models were fitted using the restricted maximum likelihood (REML) approach.

For fitting the models, the R package "lme4" and the function "lmer" were used (Bates et al. 2015). It was first tested whether the single random effects were significant. To do so, one model was calculated with and one without the random variable, after which they were compared using the function "anova" (Chamber and Hastie 1992). If the models were not significantly different and the model with the random effect was not better than the null model, the random variable was removed from the model. The package "lmerTest" (Kuznetsova et al. 2017) was used to test the significance of the fixed effects and obtain the p-values. This package uses Satterthwaite's method for approximating degrees of freedom for the t- and f-tests, and overloads the summary function by attaching the p-values in order to test them.

The function "ranef" of the "lme4" package provides the conditional predictions of the random parameters and also the variance-covariance matrices from a fitted model object. To illustrate this, I used the "lattice" package (Sarkar and Deepayan 2008).

Explanatory variables (table 1): All three models contain the variable "Age", which stands for the tree's age divided by 10. The standardised DBH (sDBH) is an index for the social status of a tree in a stand, which is given by the difference between its DBH and the mean diameter of all the trees divided by the standard deviation of the DBH measurements from a plot (Sikora 1967 cited after Sterba 2011). To calculate this index, the data from the complete inventory were used. The sDBH is an index for the social status of a tree in a stand. The higher this index, the better the tree's social status. The three increment models contain climatic variables, which describe the annual average temperature (standardised annual temperature [sT]), as well as the precipitation in autumn of the previous year (Pprev) and in spring (Pspring) and summer (Psummer) of the current year (table 1). The radial increment model contains the height of the stem disc (Dh), as well as the interaction effects between the height of the stem discs and the precipitation and temperature variables. The interaction effects served to test whether trees of a higher social status can use precipitation more efficiently than trees with a lower status and whether they differ in their reactions to a temperature change, as well as whether the allocation of increment alters across the stem length if the amount of precipitation or temperature level change.

Table 1: Variables of the linear mixed-effects model and their definitions.

Abbreviation of variable	Definition
RI	Radial increment in 1/100 mm
H	Height increment in cm
V	Volume increment in dm^3
Age	Tree age divided by 10
sDHB	Standardised DBH; Index for social status of tree (between -3 and 3 if distribution is normal)
Dh	Height of stem disc in meters (m)
sT	Standardised annual mean temperature
Pprev	Precipitation sum in September and October of the previous year (1 = 100mm)
Pspring	Precipitation sum in March, April and May (1 = 100mm)
Psummer	Precipitation sum in June, July, August and September (1 = 100mm)
Pprev:Dh	Interaction effect between precipitation in autumn and height of stem disc
Pspring:Dh	Interaction effect between precipitation in spring and height of stem disc
Psummer:Dh	Interaction effect between precipitation in summer and height of stem disc
sT:Dh	Interaction effect between standardised annual temperature and height of stem disc
sDBH:Pprev	Interaction effect between precipitation in autumn and social status of tree
sDBH:Pspring	Interaction effect between precipitation in spring and social status of tree
sDBH:Psummer	Interaction effect between precipitation in summer and social status of tree
sDBH:sT	Interaction effect between standardised annual temperature and social status of tree

3.4.2. *INDICES OF DROUGHT REACTION*

To analyse the impact of drought years, it was necessary to identify whether and when drought events occurred at the study site. To do so, the standardised precipitation index (SPI) was calculated according to McKee (1993). The advantage of this index is that it provides not only information about the amount of rainfall but also about the relation of that amount to the normal amount. To calculate this index, it is necessary to have a monthly precipitation dataset of at least 30 years. In the case of the present study, the series starts in 1962 and ends in 2016.

Table 2: Categories of drought after McKee (1993).

SPI Values	Drought Category
0 to -0.99	Mild drought
-1 to -1.49	Moderate drought
1.5 to -1.99	Severe drought
= < -2.00	Extreme drought

I used the R package "precintcon" to calculate the SPI for a six-month period including the vegetation period from April to September. When the value for a year was less than -1.0, it was considered to be a drought year (table 2 and figure 8).

To describe the reaction of tree growth to these drought events, the four different indicators explained by Lloret et al. (2011) were calculated for radial, volume and height increment (table 3):

Resistance is the ratio between the increment during and before the drought event. A tree with a value of 1 does not show any reaction to the drought year, while a tree with a value of nearly 0 shows a very high reduction of annual increment.

Recovery is the ratio between the performance after and during the drought year. The higher this value, the better the tree's ability to recover. Values lower than 1 indicate a decline in growth after the drought year.

Resilience describes the tree's capacity to reach the performance before the drought event shortly after the event, and is calculated as the ratio between the performance after and before the disturbance. If the resilience is lower than 1, the effect of the drought event is persistent.

Relative resilience also considers the increment during the drought year and describes how fast a tree is able to recover its pre-drought growth levels. A high value indicates a fast recovery.

The pre- and post-drought levels are calculated by averaging the yearly increment for a three-year period before and after a drought year.

Table 3: Formulas of the four indicators (Liored 2011).

Index	Formula
Resistance	Dr/PreDr
Recovery	PostDr/Dr
Resilience	PostDr/PreDr
Relative Resilience	(PostDr–Dr)/PreDr

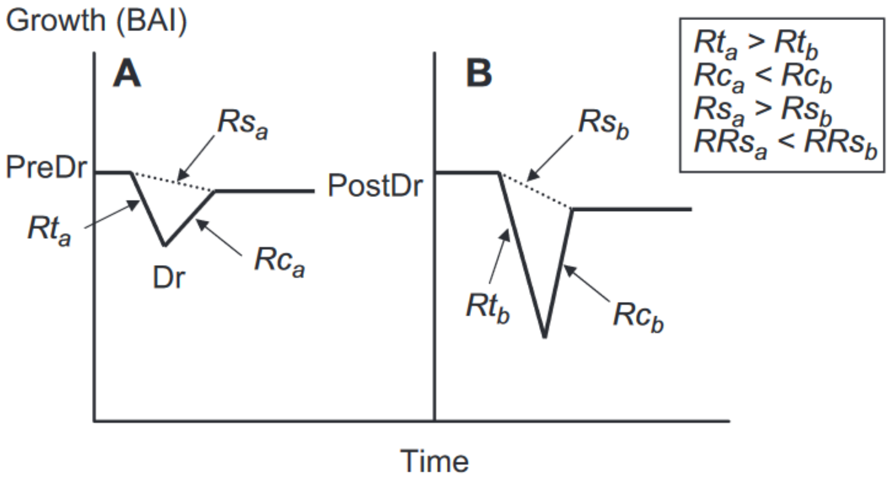

Figure 8: Graphical representation of the four drought indicators after Lloret et al. (2011). The left side of the table shows the reaction of a tree with high resistance and resilience and, while the right side shows a tree with a strong decrease in increment during the drought year but high recovery and relative resilience (Lloret et al. 2011).

For the statistical evaluation of the four drought indicators, an analysis of variance was conducted for repeated measures using the function "lmer" of the R package "lme4" (Bates et al. 2015) to test for significant differences between plots, respectively provenances. If there was a significant difference for an index, a post-hoc analysis was conducted using the function "glht" of the R package "multcomp" (Hothorn et al. 2008) to determine which plots (provenances) differed. This function makes it possible to do a pairwise comparison with a linear mixed-effect model. The same procedure was followed to compare the reactions of Austrian pine and spruce.

4. RESULTS

4.1. COMPLETE INVENTORY

A complete inventory was created to describe the actual state of the four plots and demonstrate the differences between the Austrian pine provenances and the plots of the trial site. Information was collected about key figures such as number of stems per hectare (N/ha), tree height (H), diameter at breast height (DBH), ratio between H and DBH (H/D), crown base height (CR), volume per hectare (V/ha) and basal area per hectare (G/ha).

Table 4: Results of the complete inventory of the trial site.

Plot **Provenance**	**A** **Calabria**	**B** **Austria**	**C** **Corsica**	**D** **Calabria**
Area in ha	0.0650	0.0403	0.1016	0.0953
N	24.0	31.0	48.0	60.0
N/ha	369.2	769.2	472.4	629.6
G in m²	1.812	1.124	2.848	3.644
G/ha	23.840	27.897	28.034	38.234
V in m³	15.73	8.25	26.72	30.66
V/ha	206.97	204.81	262.97	321.74
Mean H in dm	173.4	142.7	178.5	179.0
SD H	13.0	9.3	11.0	14.0
Mean DBH in mm	306.2	212.6	271.3	275.8
SD DBH	49.9	31.7	44.7	36.1
Mean CR in dm	79.4	81.5	90.2	96.9
SD CR	12.6	8.6	12.4	14.2
Mean H/D	57.61	68.07	67.03	65.51
SD H/D	7.03	7.35	8.26	5.89

The trial site's four plots had different values for N/ha (table 4). Plot A, with the Calabrian provenance had only 369 stems per hectare, while plot B with the Austrian provenance had the highest value for N/ha with 769. Plot C with the Corsica provenance and plot D with the Calabrian provenance had intermediate stem densities with 472 and 630 N/ha, respectively. Accordingly, large differences were also found between the plots' basal area per hectare (G/ha). Plot A had the lowest basal area (23.8 m^2/ha) and plot D had the highest (38.2 m^2/ha). The basal areas on Plots B and C were similar with 27.9 and 28.0 m^2/ha, respectively. The volume per hectare (V/ha) differed significantly between the four plots. Plot D had the highest volume with 322 m^3/ha, while plots A and B had a significantly lower volume with 207 and 205 m^3/ha, respectively. Plot C was in the intermediate with 263 m^3/ha.

The result of the height measurements show that the trees of plots A, C and D had a similar mean height, ranging from 173.4 dm on plot A to 179.0 dm on plot D (figure 9). An analysis of variance and a pairwise t-test (table 5) shows that the mean value for the height of plot B, the Austrian provenance, was significantly smaller (142.7 dm) compared to the other plots.

The Austrian provenance was also found to have a significantly smaller DBH with 212.6 mm. The Calabrian provenance in plot A had a significantly larger DBH compared to the other plots. The mean values of plot C (271.3 mm) and D (275.8 mm) lie close together (table 5 and figure 9).

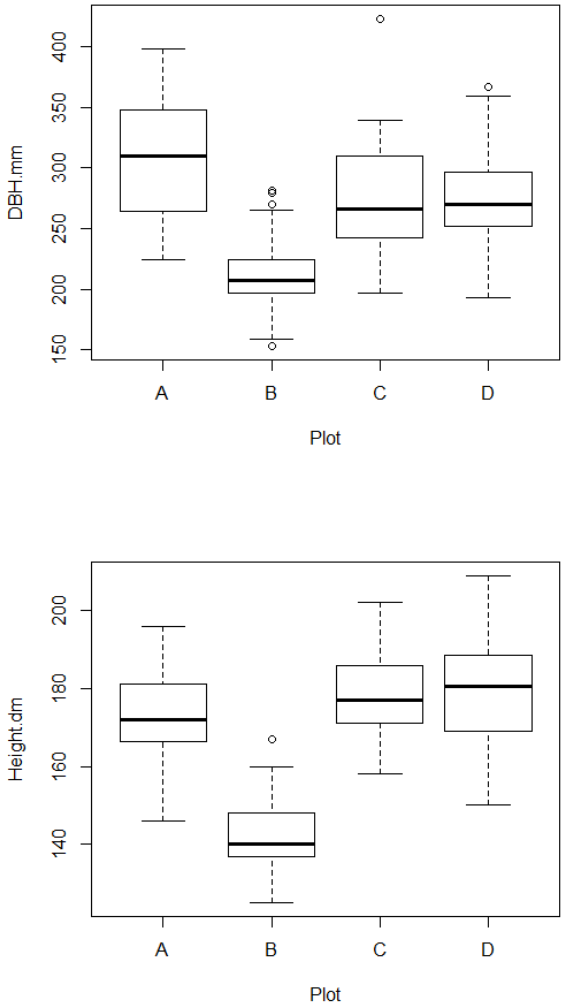

Figure 9: Boxplots of height and DBH measurements on the four sample plots of the Austrian pine trial site. Plot B (Austrian provenance) was found to have a significantly smaller height and DBH compared to the others (A = Calabria, B = Austria, C = Corsica and D = Calabria).

Table 5: Results of the comparison of the four plots (A = Calabria, B = Austria, C = Corsica and D = Calabria).

Anova					
Height					
	Df	Sum Sq	Mean Sq	F value	P value
Plot	3	31,471	10,490	69.98	< 2e-16 ***
Residuals	159	23,833	150		
Diameter at breast height (DBH)					
	Df	Sum Sq	Mean Sq	F value	P value
Plot	3	133,990	44,663	27.52	2.17e-14***
Residuals	159	258,022	1,623		

Pairwise *t*-Test			
Height			
Plot	A	B	C
B	6.70e-16 ***	-	-
C	0.19	< 2e-16 ***	-
D	0.19	< 2e-16 ***	0.86
Diameter at breast height (DBH)			
Plot	A	B	C
B	6.10e-14 ***	-	-
C	0.0021 **	1.00e-08 ***	-
D	0.0042 **	2.10e-10 ***	0.5685

4.2. Stem-Form Factors

With the results of the felled trunks' diameter measurements, the precise volume of each trunk was calculated, after which the tree's volume was divided by the volume of a cylinder with the same diameter as the DBH. This rendered the stem-form factors, which more or less indicate taper.

An analysis of variance shows a significant difference in the results of the form-factor calculations between the plots (p = 0.024 *). The post-hoc analysis with a pairwise t-test indicates that the form factors of plot D, the Calabrian provenance, were significantly smaller than those of plot C, the Corsican provenance (0.025 *). The plot with the Corsican provenance, plot B, had the highest mean value and plot D with the Calabrian provenance had the lowest (table 6 and figure 10).

Table 6: The results of the shape-constant calculations. The value of plot D is significantly smaller than that of plot C.

Plot Provenance	Mean of shape constant	SD
A Calabrian	0.492	0.035
B Austrian	0.507	0.042
C Corsican	0.518	0.047
D Calabrian	0.464	0.033

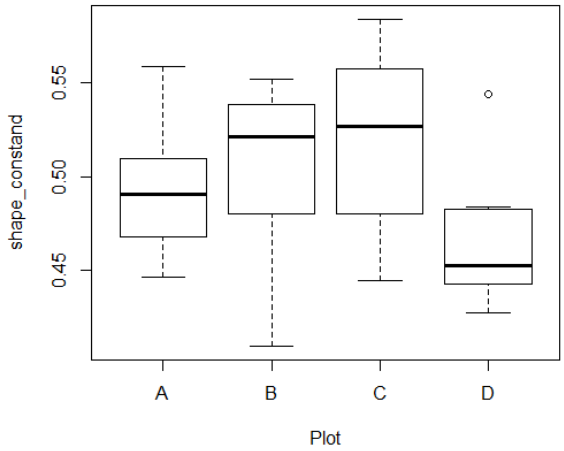

Figure 10: Boxplots for the shape constants of felled trees from the four plots.

4.3. Stem analysis and Tree cores

The reconstruction of the average height and DBH growth over time based on the felled trees shows that the Austrian provenance (plot B) had a lower growth (performance) than the Corsican and Calabrian provenances (figures 11 and 12). The Calabrian provenance in plot A was superior with respect to the DBH growth, especially during the last 10 years of the trees' lifespan (figure 12). The curves for plots C, the Corsican provenance, and D, the Calabrian provenance, lie close together in both graphs. In figure 11, the trees from plot A (Calabrian provenance) also had a very similar height-growth development to those in plots C and D. However, the variance is relatively high because trees of different social classes were felled within each plot. In all plots, it is remarkable that the increment was highest in the early stage (the first five years) and in the time period 2005–2010, near the end of the investigated period (diagrams with the annual radial increment at breast height are included in the appendix).

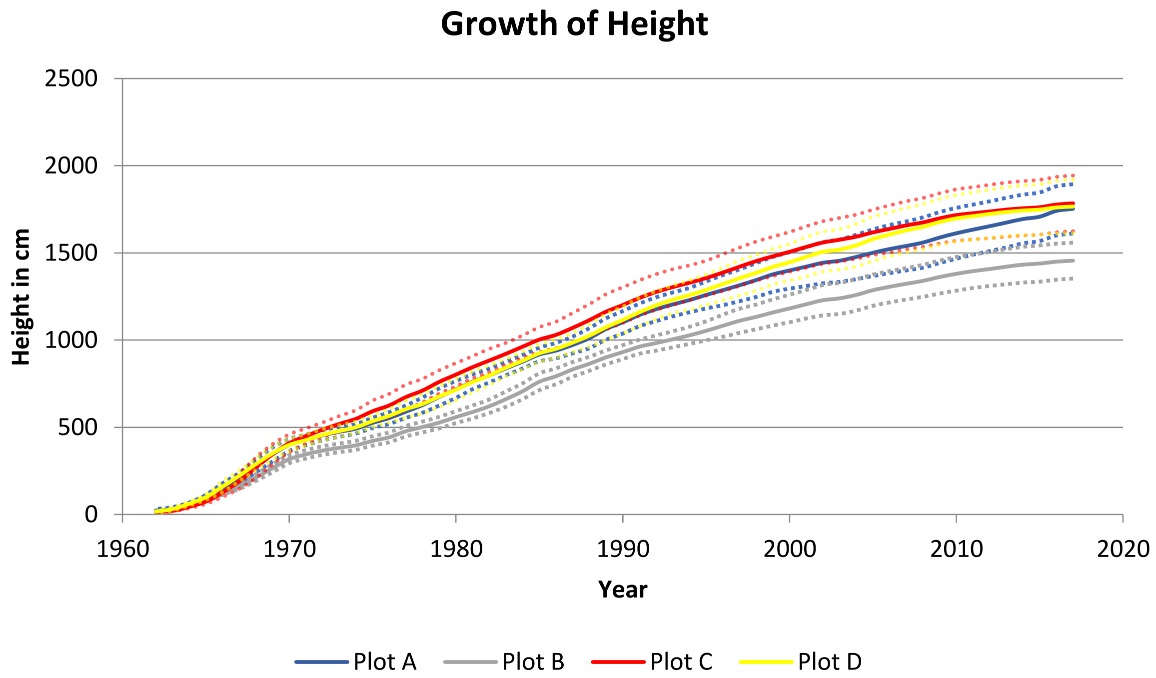

Figure 11: Height development within the four plots, as given by the mean (solid lines) of N = 10 per plot, and the plot SD (dashed lines).

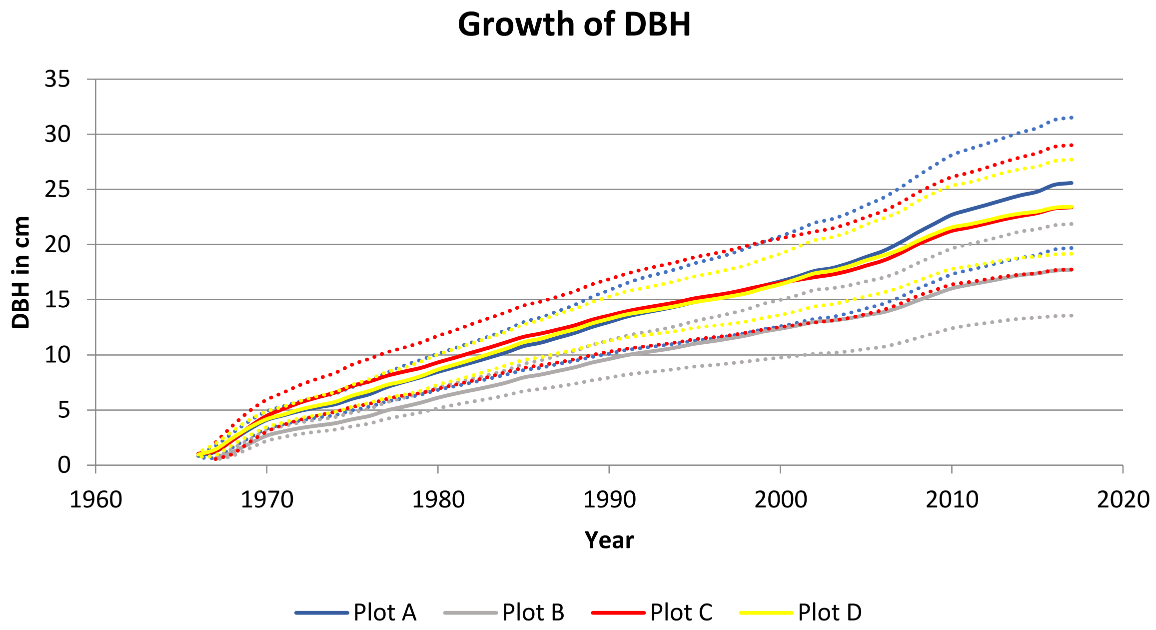

Figure 12: DBH development within the four plots, as given by the mean (solid lines) of *N* = 10 per plot, and the plot SD (dashed lines).

For every tree from the Norway spruce stand, two samples were taken and the values of the tree-ring widths were averaged. The trees reached breast height at very different ages (figure 13). One tree, of which the core of the stem was hit, reached breast height in 1969. In comparison, trees 16 and 17, of which the cores were also hit, reached the same height very late, in 1994.

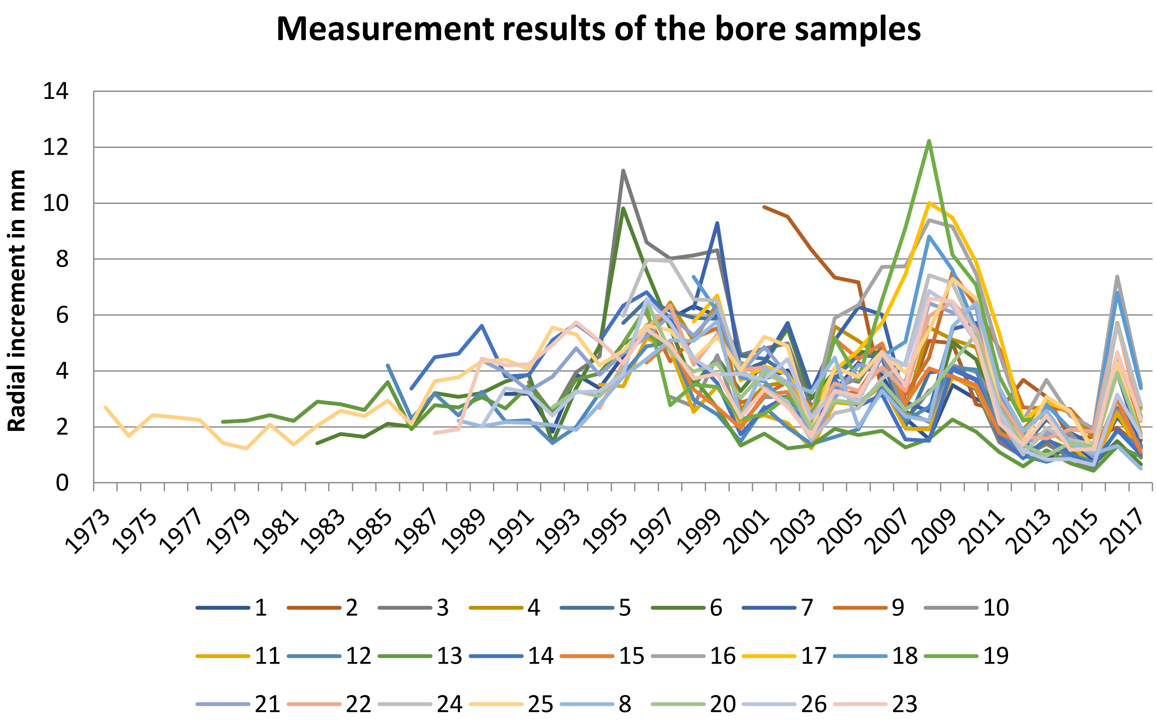

Figure 13: Results of the bore samples collected at the spruce site.

4.4. Results of the Mixed-Effects Models

To investigate the relationship between the tree growth of Austrian pine and the climate variables, especially precipitation, linear mixed-effects models were calculated. Differences between plots/provenances were also shown. The following section presents the results of these models, in which radial, height and volume increments were examined. The full results of the models are included in the appendix.

4.4.1. Radial Increment Model

The linear mixed-effects model for the radial increment (in 1/100 mm) was fitted with 9,039 observations from 41 trees of the four plots. The marginal R^2 (without the random effects) was 0.387 and the conditional (with fixed and random effects) was 0.564.

The results of the fixed effects (table 7) show that precipitation in the previous autumn and the spring and summer of the current year had a significant influence on the radial increment. The precipitation mean effects were significantly positive and the interaction effects between the height of the stem disc and the precipitation variables were significantly negative. Thus, dry conditions lead to a stronger reduction of the radial increment in lower parts of the trunk than in higher sections (figure 16). It was also observed that the interaction between the precipitation in the previous autumn and the current summer, as well as the social class (sDBH) was significantly positive, which indicates that trees with a better social status reacted more strongly to a change in precipitation than trees with a lower social status (figure 15).

Similar results were also observed for temperature. The main effect was positive and significant, and the interaction effect between temperature and height of the stem disc was significantly negative. A significant interaction with the social status of the tree could not be observed for the radial increment.

The main effects for the height of the stem disc (Dh) was significantly positive and the main effect for the sDBH was not significant.

The results of the random effects indicate significant differences between provenances for the temperature and spring precipitation variables (tables 7 and 8, and figure 14). The Corsican provenance in plot C had the highest coefficient for temperature, which was significantly higher than that of the Austrian provenance in plot B and the Calabrian provenance in plot D. The Austrian provenance had the lowest coefficient for temperature. The Austrian and Calabrian provenances in plot A differed significantly with regard to the effect of precipitation in spring (Pspring). The Austrian population had the lowest coefficient for Pspring and the Calabrian in plot A had the highest.

Table 7: Variance components of the random effects and results and fit statistics of the fixed effects of the radial increment model.

Random Effects			
Groups	**Name**	**Variance**	**Std.Dev.**
ID	**Intercept**	930.255	30.5
	Age	142.501	11.937
	Dh	4.1	2.025
	sDBH:Psummer	9.673	3.11
Plot	**Intercept**	2,355.73	48.536
	Age	195.942	13.998
	sDBH	286.056	16.913
	sT	78.874	8.881
	Pspring	81.8	9.044
Residuals		8,101.985	90.011

Fixed Effects					
Variable	**Estimate**	**Std. Error**	**df**	***t*-value**	***p*-value**
Intercept	88.94	25.91	3	3.41	0.034273 *
Age	-44.88	7.32	3	-6.12	0.008641 **
sDBH	14.36	10.06	4	1.55	0.20054
sT	30.45	4.77	3	6.32	0.005182 **
Pprev	77.05	4.64	8,846	16.61	< 2e-16 ***
Pspring	78.15	5.79	5	13.47	6.60e-05 ***
Psummer	36.79	1.96	980	18.8	< 2e-16 ***
Dh	20.39	1.08	2,178	18.87	< 2e-16 ***
Dh:Pprev	-5.38	0.56	8,842	-9.53	< 2e-16 ***
Dh:Pspring	-3.68	0.49	8,845	-7.47	8.79e-14 ***
Dh:Psummer	-0.84	0.25	8,861	-3.37	0.000761 ***
Dh:sT	-5.53	0.2	8,872	-27.05	< 2e-16 ***
sDBH:Pprev	4.64	2.34	8,833	1.98	0.047847 *
sDBH:Pspring	3.15	1.94	7,948	1.62	0.104815
sDBH:Psummer	6.14	1.15	58	5.35	1.57e-06 ***
sDBH:sT	-0.78	0.92	3972	-0.85	0.392795

Table 8: Coefficients of the random variables in the four plots

Plot Provenance	Intercept	Age	sDBH	sT	Pspring
A Calabria	61.16	-31.30	30.21	33.39	91.12
B Austria	36.67	-33.60	-1.37	18.13	67.11
C Corsica	143.10	-61.33	28.01	40.57	71.73
D Calabria	114.81	-53.30	0.59	29.70	82.62

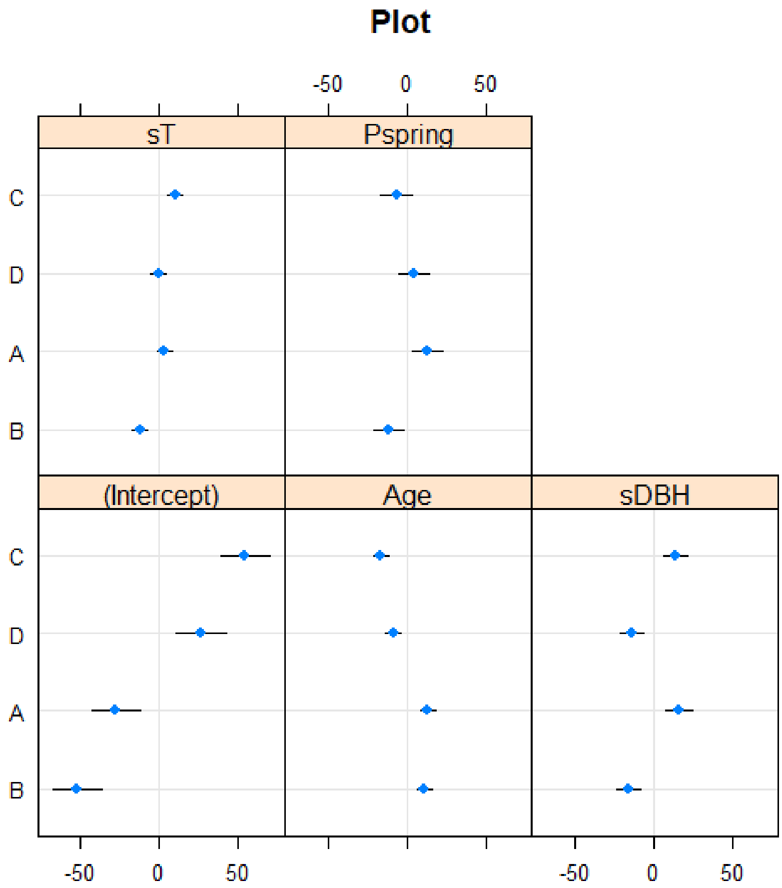

Figure 14: Illustrated conditional modes of the random variables for the grouping factor "Plot". Plot A = Calabria, Plot B = Austria, Plot C = Corsica and Plot D = Calabria.

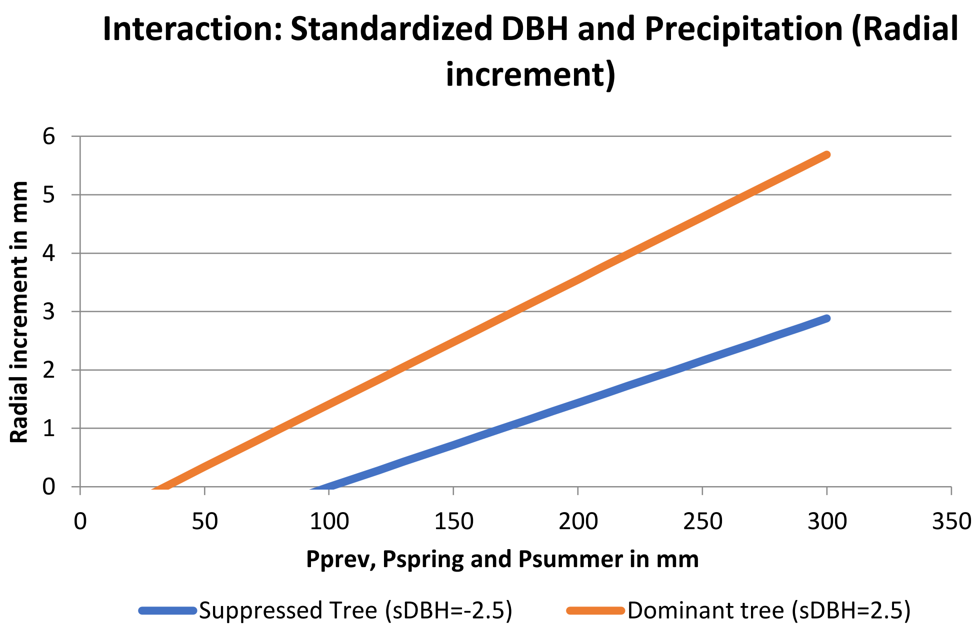

Figure 15: The illustrated interaction effect between sDBH and precipitation. The blue line stands for the radial increment at breast height of a suppressed tree and the orange line for the increment of a dominant tree.

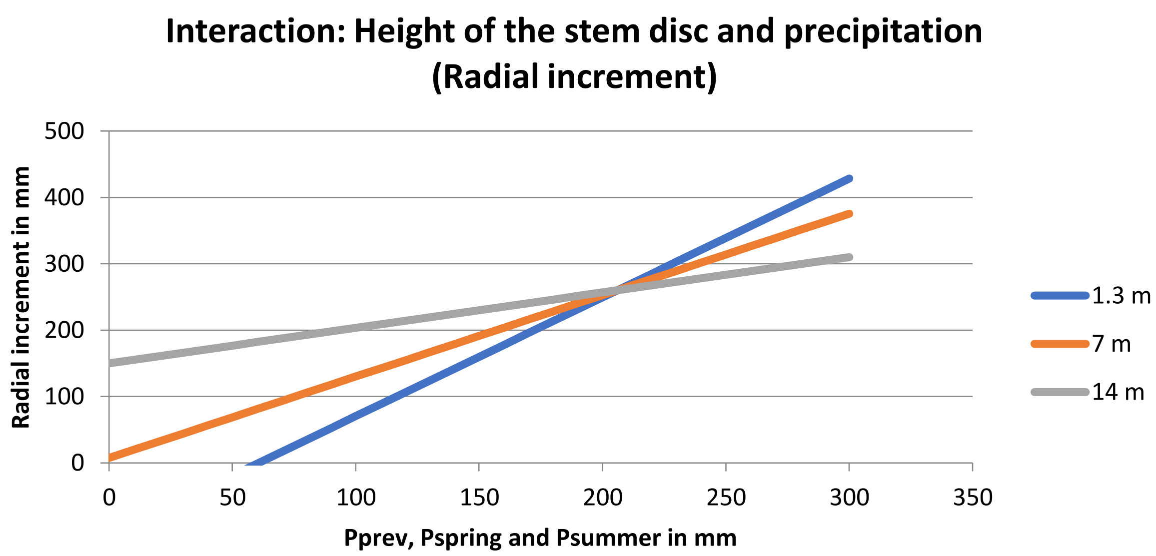

Figure 16: Illustration of the interaction effect of the stem disc height and precipitation. The lines show the reaction of the radial increment at different heights to precipitation.

4.4.2. Height Increment Model

Two linear mixed-effects models were built for the height increment (in cm) with 2,185 observations from 41 trees. The first model (table 9) contained the interaction effects between the social status of the tree (sDBH) and precipitation (Pprev, Pspring, Psummer), as well as the annual temperature (sT) variables. The main effect sDBH and the interaction effects were not significant. The full results can be found in the appendix.

The second model was simpler and did not contain the interaction effects. The marginal R^2 was 0.347 and the conditional R^2 was 0.522. The results for the fixed effects parameters (table 9) indicate that a high annual temperature had a significantly negative impact on the annual height increment. Precipitation in the previous autumn and the current summer was significantly positive and precipitation in the current spring had a significantly negative influence on the height increment. It was observed that the social status of the tree (sDBH) had a significantly positive impact on the height growth.

The estimated random parameters (tables 9 and 10, and figure 17) suggest that there were significant differences between the provenances. The Austrian provenance in plot B had the lowest coefficient for the annual temperature (sT), namely -3.85, which is significantly lower than the coefficients of the other provenances (figure 17).

Table 9: Variance components of the significant random variables and results and fit statistics of the fixed effects of the height increment model without the interaction effects between sDBH and the precipitation and temperature variables.

Random Effects					
Groups	**Name**	**Variance**	**Std.Dev.**		
Plot	**Intercept**	48.309	6.95		
	Age	2.743	1.656		
	sT	1.154	1.074		
Residual		131.455	11.465		
Fixed Effects					
Variable	**Estimate**	**Std. Error**	**df**	***t*-value**	***p*-value**
Intercept	34.34	3.73	3.8	9.203	0.001037 **
Age	-5.31	0.85	3.1	-6.218	0.007978 **
sDBH	1.60	0.19	2,168.3	8.57	< 2e-16 ***
sT	-2.47	0.62	3.3	-3.994	0.024048 *
Pprev	4.35	0.84	2,167.7	5.165	2.63e-07 ***
Pspring	-2.25	0.62	2,167.7	-3.62	0.000301 ***
Psummer	3.86	0.34	2,167.7	11.418	< 2e-16 ***

Table 10: Coefficients of the random variables in the four plots.

Plot	**Intercept**	**Age**	**sT**
A	34.06	-4.77	-1.85
B	24.77	-3.33	-4.34
C	42.55	-7.56	-1.62
D	35.99	-5.62	-2.09

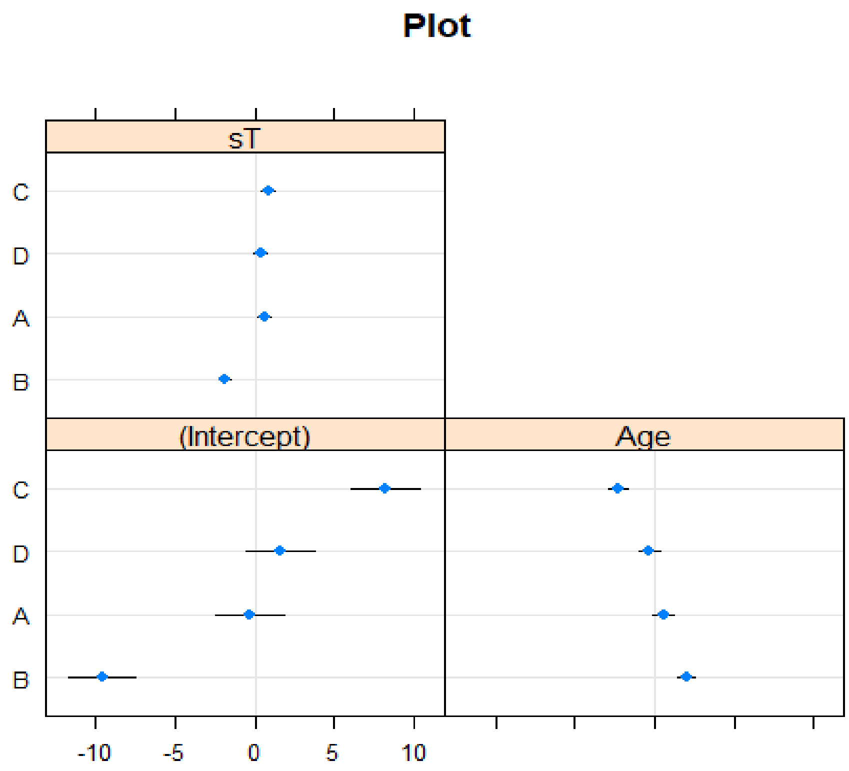

Figure 17: Illustrated conditional modes of the random variables for the grouping factor “Plot”. Plot A = Calabria, Plot B = Austria, Plot C = Corsica and Plot D = Calabria.

4.4.3 Volume Increment Model

The linear mixed-effects model for the annual volume increment (in dm^3) was fitted with 2,226 observations from 41 trees. The marginal R^2 was 0.690 and the conditional R^2 was 0.781.

The results of the fixed effects (table 11) indicate that precipitation had a positive impact on volume increment. The main effects Pprev, Pspring and Psummer were significantly positive. The interaction effects between the tree’s social status (sDBH) and the precipitation variables were also significantly positive, which indicates that trees with a higher social status reacted more sensitively to a change in precipitation than trees with a lower social status.

The main effect of the annual temperature (sT) was not significant. However, a significant interaction was observed between sDBH and sT, which was positive.

With respect to the random-slope parameter on the precipitation in the current spring (Pspring), the results (tables 11 and 12) provide evidence of a significant difference between the three provenances. The coefficient for Pspring was significantly lower for the Austrian provenance (1.89) in plot B in comparison to the others (figure 18).

Table 11: Variance components of the significant random variables and results and fit statistics of the fixed effects of the volume increment model with the interaction effects between sDBH and the precipitation and temperature variables.

Random Effects					
Groups	**Name**	**Variance**	**Std.Dev.**		
ID	**Intercept**	0.675	0.8216		
	Age	2.7031	1.6441		
Plot	**Intercept**	3.7576	1.9384		
	Age	1.2402	1.1136		
	Pspring	0.4718	0.6869		
Residuals		10.7147	3.2733		
Fixed Effects					
Variable	**Estimate**	**Std. Error**	**df**	***t*-value**	***p*-value**
Intercept	-9.37	1.056	3.5	-8.453	0.00179 **
Age	3.246	0.616	3.1	5.262	0.01274 *
sDBH	-3.118	0.307	616.4	-10.16	< 2e-16 ***
sT	0.071	0.093	2127.2	0.756	0.44961
Pprev	1.201	0.250	2123.6	4.815	1.58e-06 ***
Pspring	2.468	0.389	3.2	6.323	0.00656 **
Psummer	1.232	0.099	2122.5	12.444	< 2e-16 ***
sDBH:Pprev	0.549	0.182	2141.9	3.015	0.00260 **
sDBH:Pspring	0.744	0.134	2127.2	5.542	3.37e-08 ***
sDBH:Psummer	0.442	0.072	2124.7	6.111	1.17e-09 ***
sDBH:sT	0.135	0.068	2168.8	1.997	0.04599 *

Table 12: Coefficients of the random variables in the four plots.

Plot	**Intercept**	**Age**	**Pspring**
A	-11.16	4.23	3.12
B	-6.98	1.67	1.40
C	-10.10	3.86	2.89
D	-9.23	3.23	2.46

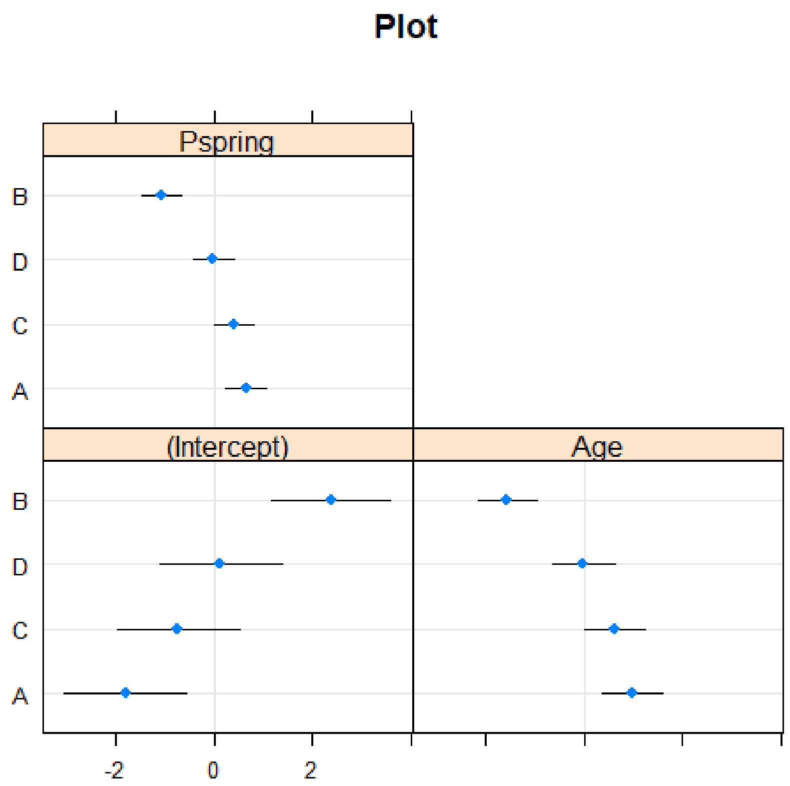

Figure 18: Illustrated conditional modes of the random variables for the grouping factor “Plot”. Plot A = Calabria, Plot B = Austria, Plot C = Corsica and Plot D = Calabria.

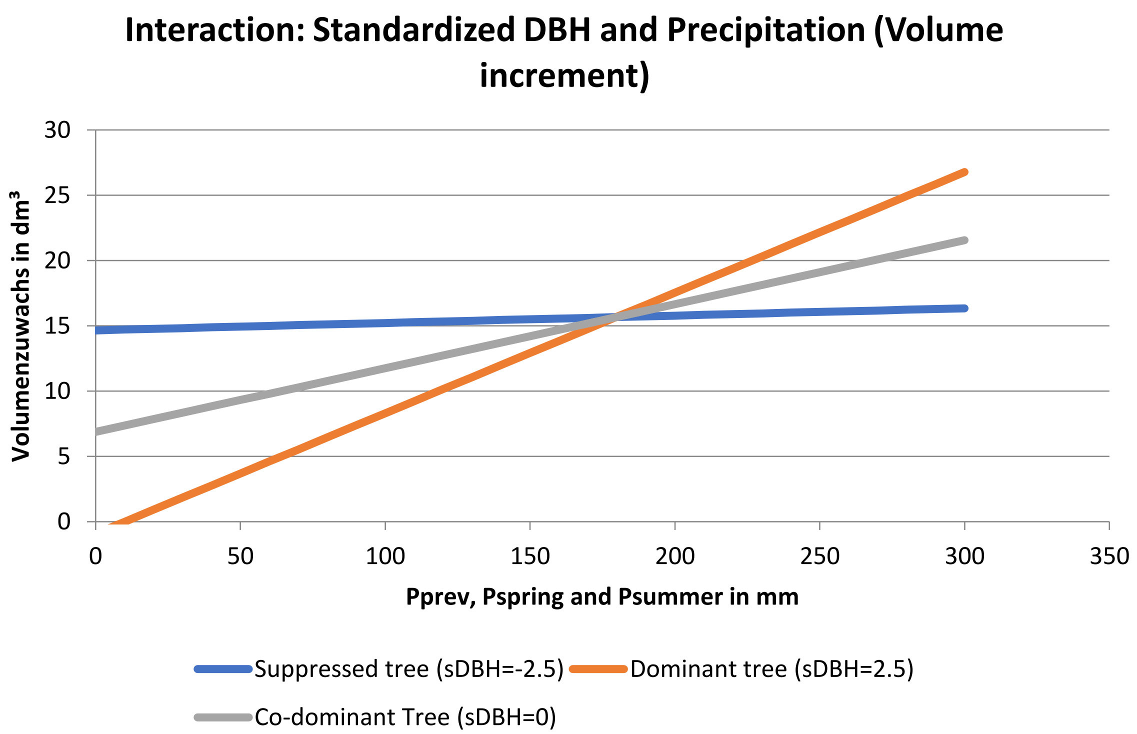

Figure 19: The illustrated interaction effect between sDBH and precipitation at level of volume increment. The lines show the yearly increment of trees of different social classes.

4.5. Reaction of Tree Growth to Drought Years

To investigate the reaction of Austrian pine trees to extreme drought events, drought indicators were calculated for every tree at the trial site and a comparison between the four plots was made using an ANOVA for repeated measures. A comparison of the species Austrian pine and Norway spruce was also conducted. The following section presents the results of the drought year selection and the analysis of the drought indicators.

4.5.1. Selection of Drought Years

The SPI index was calculated for a six-month-period from April to September. The following years with an SPI value lower than -1 were selected as drought years: 1971, 1977, 1978, 1980, 1986, 1994, 2003, 2011 and 2015 (figure 20).

The first drought years (1971–1980) were discarded from the analyses because they were too close to each other, so that the three-year pre- and post-drought periods of the different drought years overlapped. The diagrams below (figure 21) show the distribution of precipitation during the single drought years in comparison to the average monthly precipitation. In 1986 rainfall in April and in summer was sparse. The year 1994 is characterised by a very dry summer in comparison to the mean. In 2003 spring was dry and in 2011 the months July, August and September were very dry. The drought year 2015 had a small amount of precipitation in April, June and July.

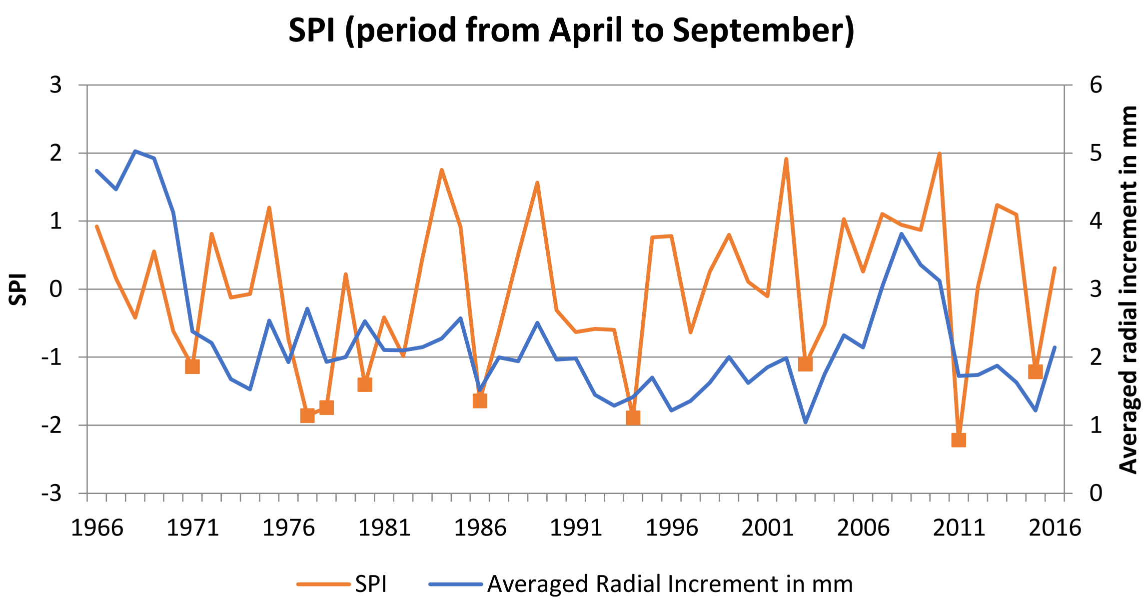

Figure 20: Results of the SPI calculation and averaged radial increment at breast height of the felled Austrian pine trees. The quadratic points show the years that were dropped out as drought years.

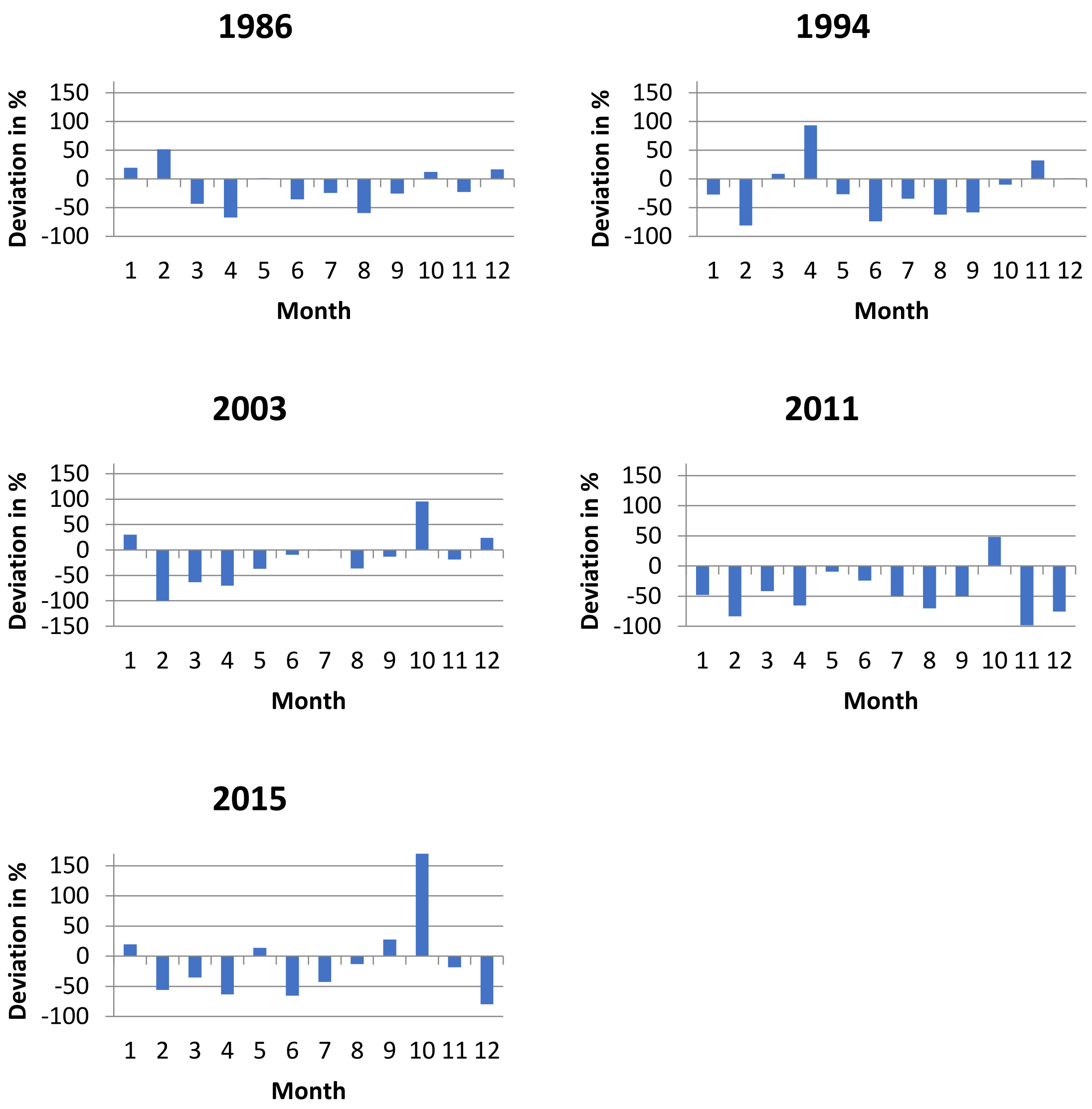

Figure 21: Deviation from the average total monthly precipitation in the single drought years.

4.5.2. Comparison of the four Austrian Pine Plots

For every Austrian pine tree, the drought indicators described above (resistance, recovery, resilience and relative resilience) were calculated for every selected drought year. These indicators describe the reaction of the radial increment at breast height and of the volume and height increment to drought events. The calculations were done with the data obtained from 10 trees per plot. The mean values are shown in table 13 and figure 22 for the four plots and the single drought years.

Table 13: Mean values and SDs of drought indicators separated by plot and drought year.

Drought year	Type of increment	Plot	Res		Rec		Rsl		relRsl	
1986	Radial increment at breast height	A	0.630	(±0.115)	1.576	(±0.348)	0.997	(±0.239)	0.355	(±0.217)
		B	0.683	(±0.113)	1.391	(±0.177)	0.915	(±0.099)	0.256	(±0.098)
		C	0.652	(±0.091)	1.366	(±0.164)	0.883	(±0.119)	0.231	(±0.108)
		D	0.635	(±0.083)	1.425	(±0.198)	0.900	(±0.131)	0.265	(±0.108)
	Volume increment	A	0.713	(±0.152)	1.827	(±0.261)	1.294	(±0.288)	0.581	(±0.197)
		B	0.876	(±0.129)	1.617	(±0.265)	1.409	(±0.276)	0.533	(±0.254)
		C	0.722	(±0.086)	1.676	(±0.230)	1.211	(±0.228)	0.489	(±0.184)
		D	0.746	(±0.090)	1.690	(±0.248)	1.253	(±0.202)	0.507	(±0.188)
	Height increment	A	0.575	(±0.183)	1.875	(±0.364)	1.038	(±0.233)	0.463	(±0.185)
		B	0.776	(±0.350)	1.216	(±0.254)	0.729	(±0.269)	0.077	(±0.291)
		C	0.702	(±0.240)	1.631	(±0.201)	1.131	(±0.335)	0.428	(±0.154)
		D	0.584	(±0.233)	1.623	(±0.348)	0.920	(±0.398)	0.336	(±0.253)
1994	Radial increment at breast height	A	0.898	(±0.277)	1.092	(±0.275)	0.905	(±0.214)	0.045	(±0.253)
		B	0.976	(±0.194)	0.970	(±0.168)	0.939	(±0.240)	-0.029	(±0.169)
		C	0.899	(±0.163)	1.005	(±0.169)	0.888	(±0.141)	-0.011	(±0.143)
		D	0.938	(±0.128)	1.018	(±0.189)	0.953	(±0.212)	0.015	(±0.170)
	Volume increment	A	0.910	(±0.099)	1.203	(±0.195)	1.085	(±0.153)	0.175	(±0.167)
		B	1.000	(±0.189)	1.155	(±0.168)	1.172	(±0.357)	0.172	(±0.194)
		C	0.852	(±0.122)	1.168	(±0.156)	0.991	(±0.174)	0.139	(±0.132)
		D	0.925	(±0.090)	1.196	(±0.130)	1.113	(±0.197)	0.188	(±0.125)
	Height increment	A	0.729	(±0.121)	1.140	(±0.308)	0.821	(±0.200)	0.093	(±0.202)
		B	0.913	(±0.432)	1.274	(±0.281)	1.020	(±0.436)	0.160	(±0.147)
		C	0.767	(±0.386)	1.257	(±0.327)	0.905	(±0.277)	0.139	(±0.275)
		D	0.618	(±0.224)	1.236	(±0.230)	0.771	(±0.322)	0.152	(±0.158)
2003	Radial increment at breast height	A	0.607	(±0.188)	2.103	(±0.230)	1.110	(±0.376)	0.680	(±0.302)
		B	0.432	(±0.154)	2.284	(±0.641)	0.936	(±0.287)	0.506	(±0.149)
		C	0.905	(±0.141)	2.032	(±0.817)	1.865	(±0.892)	0.960	(±0.829)
		D	0.517	(±0.130)	2.000	(±0.303)	1.009	(±0.174)	0.492	(±0.100)
	Volume increment	A	0.646	(±0.162)	2.285	(±0.329)	1.465	(±0.415)	0.820	(±0.288)
		B	0.519	(±0.236)	2.521	(±0.601)	1.233	(±0.337)	0.714	(±0.226)
		C	0.929	(±0.168)	1.953	(±0.331)	1.835	(±0.559)	0.906	(±0.423)
		D	0.529	(±0.084)	2.321	(±0.357)	1.207	(±0.111)	0.678	(±0.094)
	Height increment	A	0.548	(±0.226)	2.126	(±0.802)	1.034	(±0.194)	0.486	(±0.287)
		B	0.582	(±0.360)	2.248	(±0.604)	0.898	(±0.409)	0.454	(±0.319)
		C	0.620	(±0.239)	1.421	(±0.481)	0.797	(±0.152)	0.177	(±0.210)
		D	0.413	(±0.146)	2.300	(±0.609)	0.932	(±0.360)	0.519	(±0.293)
2011	Radial increment at breast height	A	0.559	(±0.052)	0.949	(±0.153)	0.812	(±0.307)	-0.029	(±0.086)
		B	0.599	(±0.094)	0.861	(±0.196)	0.529	(±0.123)	-0.094	(±0.117)
		C	0.441	(±0.134)	1.116	(±0.133)	0.498	(±0.166)	0.057	(±0.053)
		D	0.416	(±0.103)	1.119	(±0.312)	0.472	(±0.159)	0.056	(±0.105)
	Volume increment	A	0.661	(±0.057)	1.013	(±0.172)	0.667	(±0.112)	0.005	(±0.115)
		B	0.639	(±0.073)	0.873	(±0.199)	0.551	(±0.111)	-0.087	(±0.131)
		C	0.495	(±0.136)	1.090	(±0.114)	0.543	(±0.166)	0.049	(±0.057)
		D	0.466	(±0.099)	1.086	(±0.288)	0.517	(±0.174)	0.051	(±0.111)
	Height	A	0.880	(±0.252)	1.004	(±0.224)	0.877	(±0.269)	-0.004	(±0.178)

	increment	**B**	0.691 (±0.296)	0.821 (±0.245)	0.618 (±0.243)	-0.166 (±0.227)
		C	0.559 (±0.243)	0.963 (±0.309)	0.503 (±0.200)	-0.057 (±0.167)
		D	0.529 (±0.231)	0.798 (±0.249)	0.431 (±0.209)	-0.097 (±0.144)
2015	**Radial increment at breast height**	**A**	0.774 (±0.106)			
		B	0.602 (±0.199)			
		C	0.752 (±0.167)			
		D	0.530 (±0.170)			
	Volume increment	**A**	0.797 (±0.118)			
		B	0.592 (±0.150)			
		C	0.742 (±0.148)			
		D	0.547 (±0.176)			
	Height increment	**A**	0.670 (±0.120)			
		B	0.755 (±0.576)			
		C	0.590 (±0.310)			
		D	0.450 (±0.216)			

The analysis of variance for repeated measures reveals that significant differences between the plots only existed for the resistance index (radial, volume and height increments). The differences between plots were not significant for the recovery, resilience and relative resilience indicators (table 14).

The post-hoc analysis with the pairwise comparison of the resistance indicators (table 15) shows that the Calabrian provenance (plot D) had lower index values than the other provenances. With respect to the radial increment, the Corsican provenance (plot C) had significantly higher indexes. With respect to the volume increment, the Corsican provenance likewise had significantly higher resistance values than the Calabrian provenance (plot D). The Austrian provenance (plot B) had a significantly higher resistance with respect to height increment.

Table 14: *P*-values of the analysis of variance for repeated measures. Significant differences were detected only for the resistance indicators.

Index	Radial	Volume	Height
Resistance	0.0332 *	0.02966 *	0.02892 *
Recovery	0.9707	0.8177	0.3614
Resilience	0.0613	0.5788	0.2194
Rel. Resilience	0.2778	0.8192	0.2155

Table 15: Results of the pairwise comparison of the resistance indicators at the level of radial, volume and height increment. Plot A = Calabria, Plot B = Austria, Plot C = Corsica and Plot D = Calabria.

Indicator	Compared Plots	Estimate	Std. Error	z-value	Pr(>|z|)
Resistance Radial increment	**B - A**	-0.03509	0.04263	-0.823	0.8436
	C - A	0.03643	0.04363	0.835	0.8378
	D - A	-0.08481	0.04282	-1.981	0.1952
	C - B	0.07152	0.04263	1.678	0.3355
	D - B	-0.04972	0.0418	-1.19	0.6333
	D - C	-0.12124	0.04282	-2.832	0.0244 *
Resistance Volume increment	**B - A**	-0.019362	0.039255	-0.493	0.9606
	C - A	0.003399	0.040179	0.085	0.9998
	D - A	-0.099788	0.039428	-2.531	0.0551 .
	C - B	0.022761	0.039255	0.58	0.9382
	D - B	-0.080426	0.038486	-2.09	0.1563
	D - C	-0.103187	0.039428	-2.617	0.044 *
Resistance Height increment	**B - A**	0.06565	0.07319	0.897	0.8064
	C - A	-0.03016	0.07492	-0.403	0.9779
	D - A	-0.16037	0.07448	-2.153	0.1365
	C - B	-0.09582	0.07319	-1.309	0.5571
	D - B	-0.22602	0.07275	-3.107	0.0105 *
	D - C	-0.1302	0.07448	-1.748	0.2987

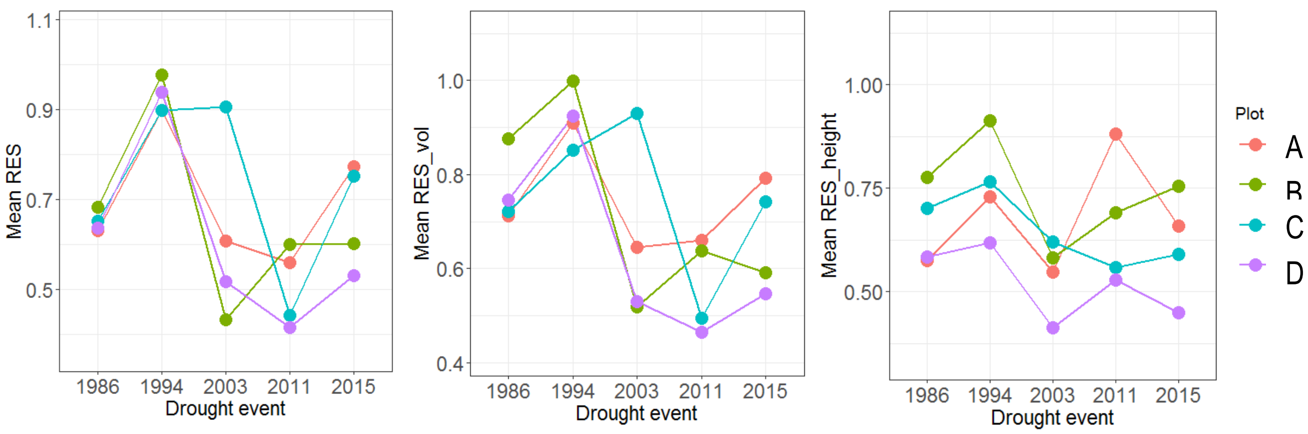

Figure 22: Mean values of the resistance indicators (radial, volume and height increment) for the four Austrian pine plots. Plot A = Calabria, Plot B = Austria, Plot C = Corsica and Plot D = Calabria.

Comparison of Austrian Pine and Spruce

Table 16: Mean values and SDs of the drought indicators for Norway spruce.

Drought year	Res	SD	Rec	SD	Rsl	SD	relRsl	SD
1994	1.225	0.281	1.492	0.297	1.808	0.628	0.583	0.407
2003	0.653	0.156	1.823	0.483	1.187	0.304	0.534	0.269
2011	0.536	0.155	0.681	0.185	0.356	0.109	-0.179	0.133
2015	0.650	0.175						

The drought indicators for Norway spruce were calculated with the measurement data of the tree cores from the spruce stand (table 16 and figure 23). Because data from the reference spruce trees were sparse for the drought year 1986, this year was not included in the analysis. However, sufficient observations were available to conduct a comparison between spruce and Austrian pine for the drought events in 1994, 2003, 2011 and 2015 (only for the resistance index).

The comparison between spruce and Austrian pine was made using an ANOVA for repeated measures. First, each of the Austrian pine provenances and spruce were compared, and a comparison of Austrian pine (all four plots together) and spruce was also made. There were no significant differences (table 17). The probable reason, that there were even no significant differences between the Austrian pine plots, is that there was one less drought year in this comparison.

Table 17: *P*-values of the analysis of variance. There are no significant differences between spruce and Austrian pine's reactions to drought years.

Comparison	Res	Rec	Rsl	relRsl
Species wise	0.704	0.423	0.592	0.694
Plot wise	0.081	0.957	0.184	0.391

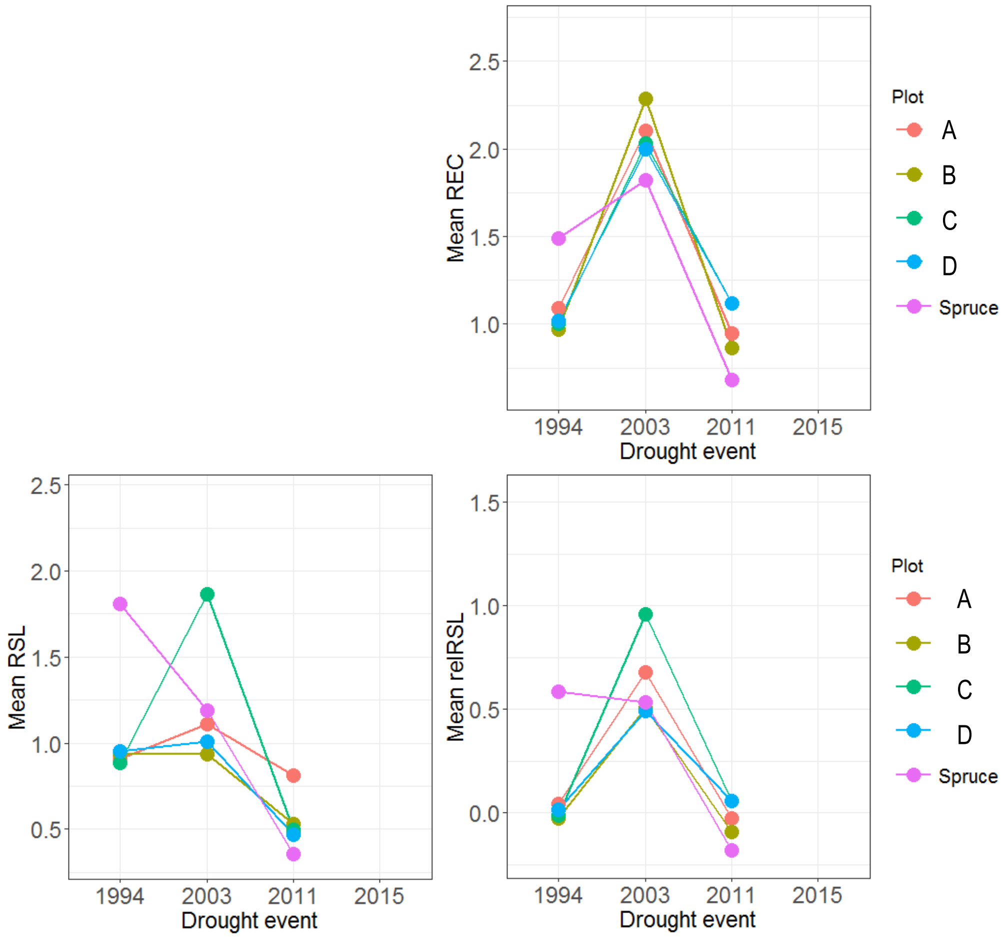

Figure 23: Mean values of the drought indicators for the four Austrian pine plots and the spruce stand. Plot A = Calabria, Plot B = Austria, Plot C = Corsica and Plot D = Calabria.

5. Discussion

The investigated Austrian pine trial site is located on a relatively dry site with an average annual precipitation of 530 mm. Several severe drought events affected the growth of these trees. Despite the dry conditions, Austrian pine showed a good growing performance and a good suitability for cultivation in this region, especially the Calabrian and Corsican provenances.

5.1. Overall Growth Performance of the Austrian Pine Provenances

The results of the complete inventory (table 4) and the stem analysis (figures 11 and 12) indicate that the Austrian provenance had a weaker diameter and height growth compared to the Corsican and Calabrian provenances. The average DBH and average height of the trees on plot B were significantly lower those on the other three plots. However, it is noteworthy that the trial did not completely fulfil the requirements of a standardised experimental design given the lack of repetitions and the unknown management activities. The different numbers of trees per ha indicate that the four plots were obviously managed differently and no information was available about the number of plants at the establishment of the trial, nor about the applied thinnings. Through plot A, a power line even crossed the trial area, also affecting a small part of plot B. Another limitation was the lack of replications of blocks to compensate for site variations among plots. Thus, it was not possible to declare with certainty that one provenance had a better or worse growth performance on the trial site than others. However, no significant differences in height were found between plots A and D, which were actually established with plants from the same provenance (Calabrian), although they showed significant differences in stem number, basal area and volume per ha. In addition, the height and DBH development of the trees' stem analysis over time showed nearly uniform growth curves for plots A (Calabria), C (Corsica) and D (Calabria) (figures 11 and 12). On all four plots, the trees showed an increased DBH increment after the year 2005, which might indicate that a thinning was applied near this time point. From that thinning, the Calabrian provenance in plot A was able to profit significantly, gaining an accelerated DBH growth. This suggests that the different plot treatments only affected the average DBH and total volume production, while differences in the site conditions were rather small between the sample plots.

The Bayrisches Amt für forstliche Saat- und Pflanzenzucht (ASP) in Bavaria established an Austrian pine trial at four sites with provenances that represent nearly the entire natural distribution range. The results from two trial sites (Gickelhausen and Vilseck) indicate that the provenances from the south of the distribution range had better height growth performance. Especially populations from Corsica, Calabria, Soria (Spain) and Chaldiki (Greek) showed a better growth on both sites. It was also observed in this trial that the Austrian provenance Dreistetten had a poor performance regarding height growth (Huber and Seho 2016).

At a Greek Austrian pine trial (Varelides et al. 2001) established in 1986 on three sites, 17 provenances were tested. The population from Corsica showed a very good performance in height and diameter growth on two sites and is described as a fast growing provenance. In contrast to the results of this master's thesis and the Bavarian trial, the Calabrian provenance did not perform well at either of the Greek trial sites and was characterized as a slow-growing provenance. At the third site, with the slowest growth rates of the trial, no significant growth differences were found between the provenances (Varelides et al. 2001). Thus, it seems that provenance growth differentiation is more likely to appear on more productive sites. This is in conformance with the results of Taibi et al. (2016), who observed that Austrian pine seed sources on trial sites with better site conditions showed differences in height growth performance but not in survival. In the aforementioned study, in which only Spanish Austrian pine provenances were tested on three contrasting sites, Austrian pine populations had a good growth performance if they were moved from a cold continental climate to productive sub-humid sites. On the other hand, provenances from the warm sub-dry population group with a large transfer distance from their origin site to the trial site performed worse (Taibi et al. 2016). In contrast to the observation regarding growth performance, provenances from the warm sub-dry population group had a better survival rate at the continental trial site after the drought years 2011 and 2012 than local provenances. Provenances from the continental region had a higher survival rate at the upper-north warm sub-humid site (Taibi et al. 2016).

These results suggest that performance in height and diameter growth are not the only factors that should be considered in choosing an appropriate provenance. A further relevant factor, especially for sites with climate or soil constraints, is resistance to abiotic disturbances (for example drought periods or frost) and biotic disturbances (for example diplodia dieback). A disease of pine trees, which is connected to water stress, is diplodia dieback (*Sphaeropsis* sapinea). This fungus moved quickly from Southern Europe to the north in the last 20 years, especially in drought periods (Hanso and Drenkan 2009). Stanosz et al. (2001) describe that this pathogen can persist in a latent stage until water stress causes its release from the quiescent condition and induces a rapid disease development. It is recommended to use provenances with a higher resistance to this pathogen (Petercord and Straßer 2017). For Scots pine (*Pinus sylvestris*), Schumacher and Kehr (2011 cited after Heydeck and Dahms 2012) observed that significant differences in resistance existed between provenances. Provenances originating in warm and dry regions showed a lower sensitivity to diplodia dieback.

Mottiner-Kroupa and Halmschlager (2016a, 2016b) examined the intensity of diplodia infestation at the four plots of the Austrian pine trial investigated in this master's thesis. The results, which can be found in figure 24, indicate that differences existed between the provenances. The Austrian provenance (plot B/Waldhof 2) seemed to be more strongly affected by diplodia dieback than the trees in the other three plots. In plot B, 39% of the trees showed a very high degree of infestation (levels 7–9) and there were no trees without infection (level 0).

Considering these results, a useful recommendation for forest practitioners is to also collect information about the resistance of provenances against abiotic and biotic diseases.

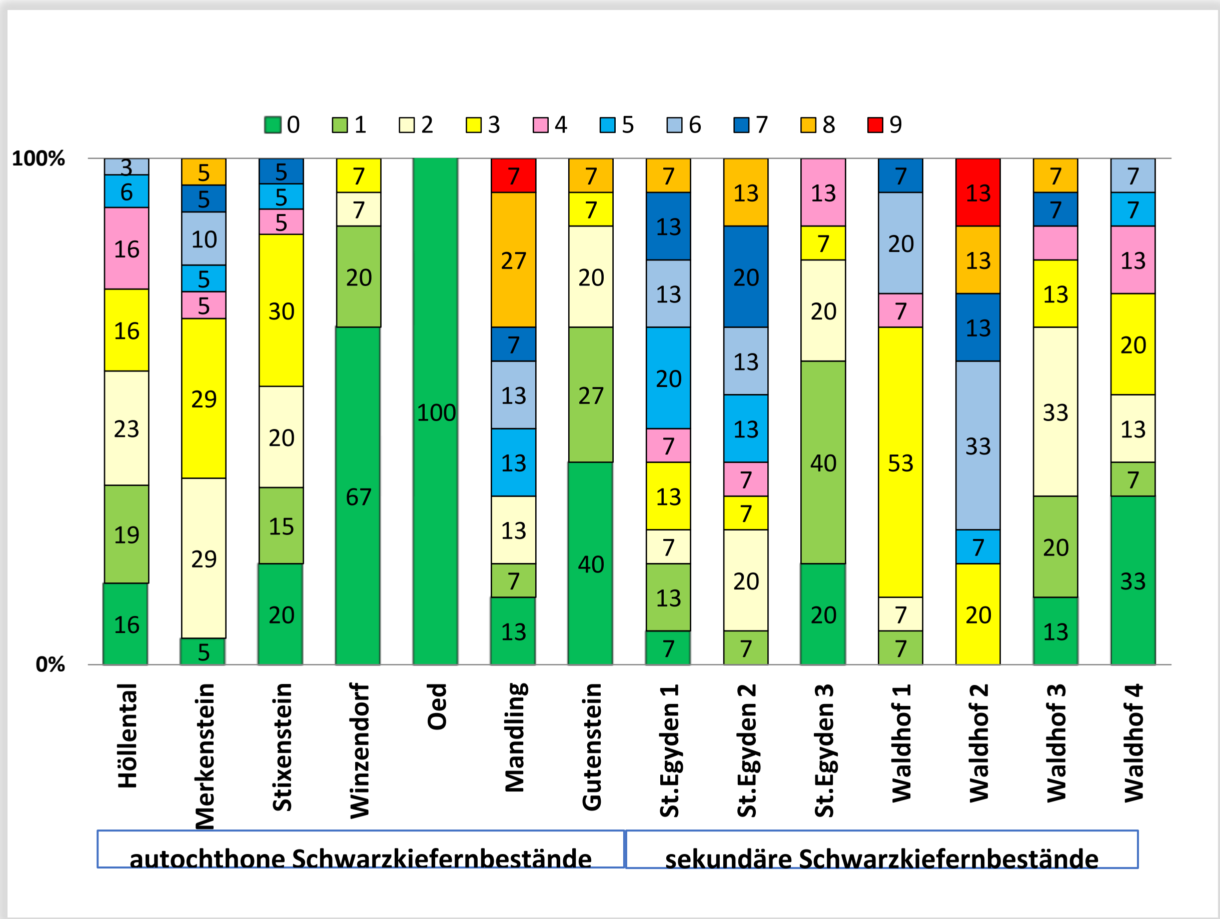

Figure 24: Intensity of diplodia dieback at different sites. 0 = no infestation and 9 = strongest intensity. The percentage represents the amount of trees with a particular level of infestation (Mottiner-Kroupa and Halmschlager 2016a). Waldhof1 = plot A (Calabrian provenance), Waldhof 2 = plot B (Austrian provenance), Waldhof 3 = plot C (Corsican provenance) and Waldhof 4 = plot D (Calabrian provenance).

5.2. Linear mixed effects Model

To investigate the relationship between tree growth and climatic variables such as standardised annual temperature (sT) and precipitation (Pprev, Pspring, Psummer), three linear mixed-effects models were built for the radial, height and volume increments of Austrian pine trees. The radial increment model also reveals the interaction between the trees' social status (sDBH) and the climatic variables, as well as the interaction between the height of the stem disc (Dh) and the climatic variables. The models for height and volume also take into account the interaction with social status.

5.2.1. Precipitation

To interpret the models correctly, it is important to analyse the main effects together with the interaction effects. To develop a better understanding of the interaction of sDBH and precipitation, and height of the stem discs and precipitation, additional diagrams were prepared, which depict the predictions of the conditional expectations obtained with the respective models (figures 15, 16 and 19).

The results of the radial increment model (table 7) indicate that the autumn precipitation of the previous year and the spring precipitation of the current year had a stronger effect on the radial growth that the summer rainfall. The interaction effects between the sDBH and the precipitation variables were all significantly positive and the coefficients of the interaction variables were on a similar level. This means that larger trees, or trees with a better social status, obtained more benefit from increasing precipitations than smaller trees (figure 15). It is important to consider that the sDBH did not have a significant main effect on the radial growth but acted only indirectly through its interaction with the precipitation and temperature variables.

For the height growth, it was not possible to prove an interaction between the social status and the climatic variables. In addition, the main effect of the social status (sDBH) and the corresponding interaction effects were likewise not significant. However, the results of the simpler model without the interaction effects indicate that the sDBH had a significantly positive impact on the height increment, although with an estimated coefficient of 1.6 the impact was still quite small. The main effects of precipitation were also significant in the height increment model. Parameter estimates and hypothesis tests suggest that precipitation in the autumn of the previous year and rainfall in the summer resulted in a higher annual height increment. In contrast, a wet spring had a negative impact (table 9).

In the volume increment model, spring precipitation had the highest main effect compared to autumn and summer precipitation (table 11). It seems that water availability in spring played an important role for the volume growth of trees. Also in this model, the interaction effects between the sDBH and all the precipitation variables were significantly positive and conformed well with the results from the radial increment model. However, the main effect of the sDBH was significantly negative in the volume increment model. This indicates that larger trees showed a greater reduction in radial increment under dry conditions but had an advantage when the precipitation was high in comparison to smaller trees (figure 19).

The comparison of the four plots indicates that the Calabrian provenance obtained more benefit from higher spring precipitations with respect to its radial growth (figure 14). In contrast, the Austrian population showed the weakest effect for Pspring. Similar conditions were observed for volume increment (figure 18): The Austrian provenance had a significantly lower coefficient for Pspring than the other provenances. Regarding height growth, it was not possible to observe different reactions to a change in precipitation between the four plots.

Pretzsch (2017) investigated the distribution of increment between trees, also considering social status, and obtained similar results for spruce trees. In dry years, dominant trees reduced the volume increment more than suppressed trees and small trees had an advantage. Similar results were obtained from a comprehensive dendrometer study conducted by Vospernik and Nothdurft (2018). In contrast, when water availability was favourable, the increment of larger trees became disproportionately high (Pretzsch). It seems that suppressed trees were more affected by water and light concurrence in years with high precipitation but in dry years profited from the shades of larger and dominant trees, which provided them with an environment that buffered the effects of drought, high temperature and wind (Pretzsch 2017). Martin-Benito et al. (2007) examined growth response to climate and drought in Austrian pine trees of different crown classes, also observing that dominant trees had a stronger reaction to drought than suppressed trees. Here, it also seems that suppression reduced the effect of extreme climate on trees' radial growth. For Scots pine, Merlin et al. (2015)

observed that trees of smaller size had a better resistance and resilience to summer drought than larger trees. These findings are largely in conformance with the results of Ding et al. (2017), who analysed how the size of individual Norway spruce and common beech *Fagus sylvatica* trees affected their reactions to drought events. With increasing tree size, the resistance and resilience of spruce individuals to drought significantly decreased, while their recovery after drought increased (Ding et al. 2017). A higher resistance and robustness in resilience was observed for beech, although here tree size did not have a significant impact.

These findings suggest that competition between small and large trees in a forest increases under dry conditions because small trees can maintain transpiration for a longer time. A consideration is that thinning treatments may reduce this effect (Pretzsch 2017). Sohn et al. (2013) describe the impact of thinnings on the behaviour of spruce trees under drought stress. Shortly after the thinning, the trees maintained higher stomatal aperture and growth rates during drought. This advantage was reduced over time because the remaining trees increased their leaf area and fine root biomass, resulting in a higher water demand. The ability to recover immediately after a drought event was improved by thinning treatments and the duration between treatment and drought had no effect on this ability (Sohn et al. 2013). The authors explain that this improved recovery is due to large trees' structural adaptation, such as higher foliage area and fine root biomass. A meta-analysis by Sohn et al. (2016) shows that thinning forms an appropriate approach to adapting forests to drought, though conifers and broadleaves' reactions to drought periods after thinning differed. Thinned conifer stands mainly showed better recovery and resilience after a drought period, while thinned broadleaves stands showed a higher resistance during drought periods.

One primary cause of productivity loss is hydraulic failure, which is caused by cavitation, a phase change from liquid water to vapour due to negative pressure in xylem (Pockman 1995 after Choat et al. 2012). The ability to survive and recover from drought periods is strongly related to embolism resistance (Choat et al. 2012). Choat et al. (2018) describe that the recovery of trees is determined by the degree of damage to the apical and cambial meristematic tissues; the functional status of the remaining hydraulic pathway; nutrients, water and non-structural carbohydrates during the recovery phase; and the health of trees, especially the remaining foliage and roots. Two mechanisms for hydraulic recovery are the regrowth of xylem by new wood formation and the refilling of embolized conduits (Choat et al. 2018). Carbohydrate transformations may be integral to these mechanisms of hydraulic recovery, and stored and soluble carbon may play an important role in avoiding catastrophic xylem failure (Sala et al. 2011).

Regarding the role of the distribution of precipitation, Janssen et al. (2018) observed that spring and summer water availability was the main climatic driver of growth for Austrian pine trees in the Mediterranean region. The authors relate these observations to a decreasing growth trend since the 1970s, as spring and summer temperatures, as well as droughts saw an increase in the 20th century in this region.

In the mountains of East-Central Spain, Martin-Benito et al. (2013) describe that precipitation during the previous autumn and the current spring and summer increased the radial growth of Austrian pine and *P. sylvestris*, and that early wood growth was more affected by previous-year climate. Lebourgeois (2000) supposes that carbohydrate reserves were built up in October of the previous year and stored over winter until the next vegetation period. Warm and dry conditions in October of the previous year also had a negative influence on the growth of the current year (Lebourgeois 2000).

5.2.2. Radial increment and the interaction of Precipitation and Height of Stem Disc

The estimates of the interaction effects between the precipitation variables and the height of the stem disc (Dh) in the radial increment model (table 7) were significantly negative for Pprev, Pspring and Psummer. The main effect of the Dh was significantly positive. The same was observed for the annual temperature (sT), indicating that radial growth tended to occur in lower parts of the stem when rainfall was high and temperature was low. In contrast, dry conditions led to a stronger reduction in radial increment in lower parts of the trunk than in higher sections. Figure 15 illustrates this interaction effect.

For Norway spruce, Sterba (1981) observed similar relationships between growth-promoting conditions and the allocation of radial increment across the stem. Under good growth conditions, the increment was located disproportionally at the basis of the trunk and under poor conditions there was a disproportionally high reduction in the radial growth at breast height. The author explains this interaction by the assimilates that are produced in the needles of the trees. In Sterba's study, the assimilates were first located in the crown section of the trunk and only when there was a surplus were they transported downwards to the stem basis. This is also the reason for the missing tree rings at breast height for the years with bad growth conditions (Sterba 1981).

Hoffmann et al. (2018) investigated the stem-growth variation and drought sensitivity of nine different tree species. Their stem analysis shows that the inter-annual variation of the basal area index at breast height overestimated the mean sensitivity (year-to-year variation) of the volume increment for six of the nine species. The results of the drought indices also suggest an overall greater response to drought in the radial increment at breast height in comparison to the response of volume increment (Hoffmann et al. 2018). The authors also explain these differences by a disproportionally higher carbon allocation at upper parts of the trunk.

5.2.3. Annual mean temperature

The results of the radial increment model show sT had a significant impact on radial growth (table 7). The main effect was significantly positive, but the estimate of the interaction effect between sT and Dh was significantly negative. This means the higher sT and Dh, the lower or more negative the impact of sT on radial growth. No significant interaction between sT and sDBH could be observed.

The sT had a significantly negative impact on height increment (table 9). No interaction between sT and social status (sDBH) was observed for height growth. The comparison of the provenances shows the Austrian population in Plot B had the lowest negative coefficient for sT in the height increment model and was the most sensitive provenance to changes in sT. A direct effect of temperature on volume increment was not observed (table 11) but affected volume growth in an indirect way via its significant interaction with sDBH. Trees with a high social position reacted positively to higher temperatures and negatively to lower temperatures, while trees with a low social position reacted in the opposite way.

To gain a better understanding of the influence of temperature on the growth of Austrian pine, it is necessary to investigate the effect of monthly temperature, which was not done in the present study. Martin-Benito et al. (2007) examined the tree-ring chronologies of Austrian pine trees from southeastern Spain to investigate the influence of temperature and precipitation on radial growth. In this research, radial growth was negatively influenced by high temperatures in the late summer and early autumn of the previous year and the spring and September of the current year. In contrast, higher temperatures in winter lead to an increase in growth. In another study of Martin-Benito, Beeckman and Canellas (2012), in which they investigated the influence of climate on the xylem anatomy and tree-ring increment of Austrian pine and Scots pine the authors obtained similar results, concluding that Austrian pine trees profit from mild winters. Janssen et al. (2018) examined the relationship between growth and climate for Austrian pine trees in Turkey. They show that high monthly temperatures had a significantly negative impact on radial increment for July, August and September of the previous year and May, June, July and August of the current year. Temperature in winter had no significant effect. Lebourgious (2000) explains this reaction to mild winter by an extended growing season; a warm winter might influence the breaking of dormancy and the starting of physiological activity in trees.

5.3. Reaction of Tree Growth to Drought Years

Comparing between provenances the reactions of tree growth to drought years shows there were only significant differences for the resistance indicator (table 14). The post-hoc analysis (table 15) suggests the trees of plot D (Calabrian provenance) had the lowest resistance to drought events in terms of radial, height and volume increment. Interestingly, the trees in plot A of the same provenance had a nearly significantly higher resistance (p = 0.0551) at the level of volume increment than the trees in plot D. The different number of trees per hectare (N/ha) suggests the plots were thinned in different ways, leading to unequal tree sizes and different resistances to drought events. In plot A, stem density was far lower (370) than in plot D (630) and the DBH was significantly higher in plot A than plot D. The observations of Sohn et al. (2013) provide a possible explanation for the unequal resistance at the plots with the Calabrian populations. They observed for Norway spruce that trees in thinned stands maintained higher stomatal apertures and growth rates during droughts.

For the recovery, resilience, and relative resilience indicators, no significant differences between plots could be observed, making it impossible to claim that any the provenances had a better performance in drought events than the others. Another possible reason for the ambiguous results is the low number of observations. For every provenance, data were collected from only 10 or 11 trees. The resistance index was compared at five drought events (50–55 observations) and the other indicator, recovery, resilience and relative resilience, at four events (40–44 observations). This might also be one of the reasons why the comparison between Austrian pine and Norway spruce or between Norway spruce and each of the other provenances showed no significant differences. For the species comparison there was even one drought year less because the Norway spruce trees reached breast height at very different ages; only two observations were available for this species in the drought year 1986.

It must also be considered that the seasonal occurrence of a drought event plays an important role in tree growth. George et al. (2015) describe that, despite its severity, the 1990 drought had no significant effect on the tree growth of silver fir (*Abies alba*) because it occurred in August, when tree-ring formation was almost completed. In contrast, drought events occurring in spring and early summer have been found to have a strong effect on silver fir growth (George et al. 2015). It cannot be excluded that this study's analysis of all drought events by an ANOVA for repeated measures led to an underestimation of the true differences between provenances.

In a common-garden experiment, Thiel et al. (2012) investigated the reaction of six different Austrian pine provenances at the juvenile age of six years. They observed that the simulated drought event (42 days without precipitation) had no effect on height growth in the same year. Only in the year after the drought treatment did the plants show a strong decrease in height growth. During drought events, newly fixed carbon may be used for osmotic adjustment or be invested into root growth for better drought resistance (Thiel et al. 2012), which may explain the reduced carbohydrate reserves (Guehl et al. 1993 cited after Lebourgeois 2000). In this research, the warming treatment amplified the negative impact of drought on survival. The authors describe that the six different Austrian pine provenances performed uniformly under dry and warm conditions (Thiel et al. 2012).

7. Summary and Conclusion

The complete inventory of the Austrian pine trial and the results of the stem analysis indicate the Calabrian and Corsican provenances had a better growth than the Austrian provenance. The Calabrian provenance in Plot A showed a higher DBH than trees in the other plots, while the Austrian population had a comparatively lower DBH and height. The results also indicate the four plots might have been managed differently; the number of trees and basal area per hectare were clearly different between the plots.

The results of the linear mixed-effects models show the trees' social status played an important role in their drought sensitivity. Compared to suppressed trees, dominant individuals showed a greater reduction in radial and volume increment when precipitation was low, but benefited more in periods with higher amounts of rainfall. No interaction effect between social status and precipitation was observed at the level of height growth. The results also show that changes in precipitation affect the radial increment of Austrian pines more strongly in lower segments of the trunk than in higher parts, which might be caused by a disproportionally higher carbon allocation at the upper parts of the trunk. An increase in the yearly mean temperature had a significantly negative influence on the height increment of Austrian pine trees.

The comparison of the trees' reactions to drought years using the drought indicators shows differences between the four plots of the Austrian pine trial site in terms of resistance, but the analysis of variance shows no significant differences for the recovery, resilience, and relative resilience indicators. Thus, it was not possible to identify a specific provenance with an outstanding drought resistance. However, analyses of the random effects of the three increment models show there were significant differences in the provenances' reactions to precipitation. The Austrian population had the lowest coefficient for spring precipitation in the radial and volume increment model and also seemed to be more sensitive to higher sT.

Austrian pine is an interesting species for Central Europe. Its widespread natural distribution range in the southern regions of Europe suggests a great genetic potential for transferring suitable provenances to northern regions outside of their natural distribution. Austrian pine trees show a high tolerance to drought and appear to be well adapted to future climate conditions (Thiel et al. 2012). As Austrian pine is tolerant to nutrient-poor sites and shows relatively good growing performance on such sites, this species becomes an interesting alternative for traditionally prominent species in European forests. Differences between provenances, especially in growth performance and resistance to biotic and abiotic disturbances, must be considered in the selection of seeds and planting material. However, no comprehensive recommendation for the use of Austrian pine provenances for forest practitioners was found in the literature research. To compile a good and useful recommendation that also considers site conditions and abiotic and biotic threats, it is necessary to further investigate this topic and/or conduct a meta-analysis by which to recap the results of already existing Austrian pine trials at different sites.

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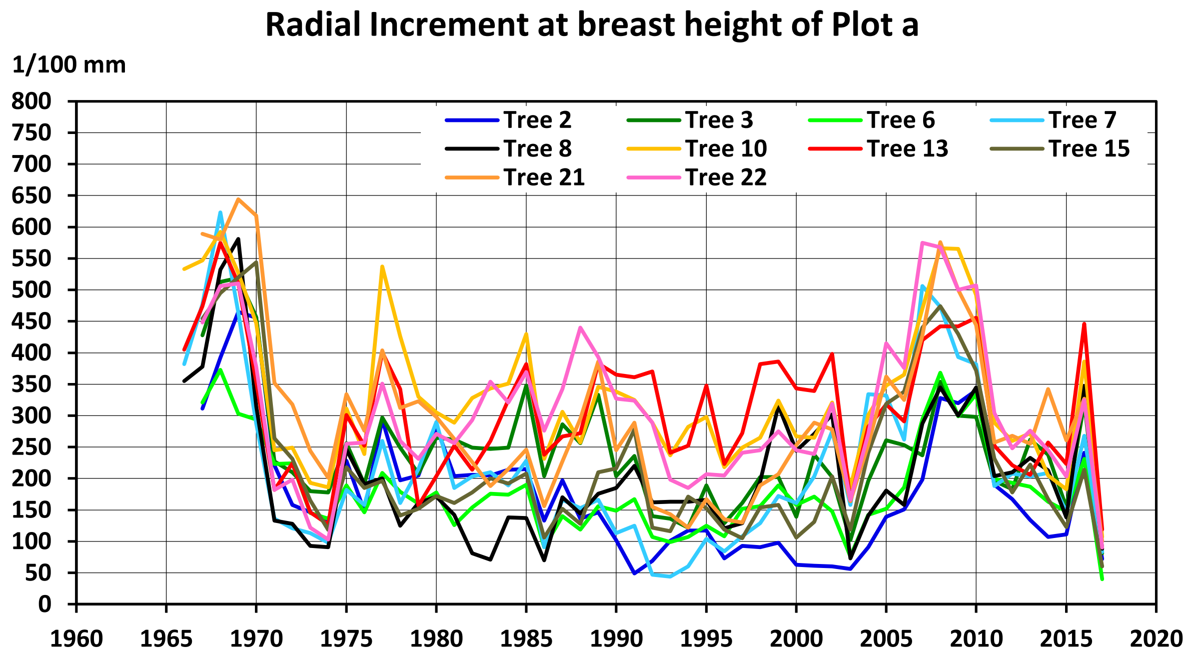
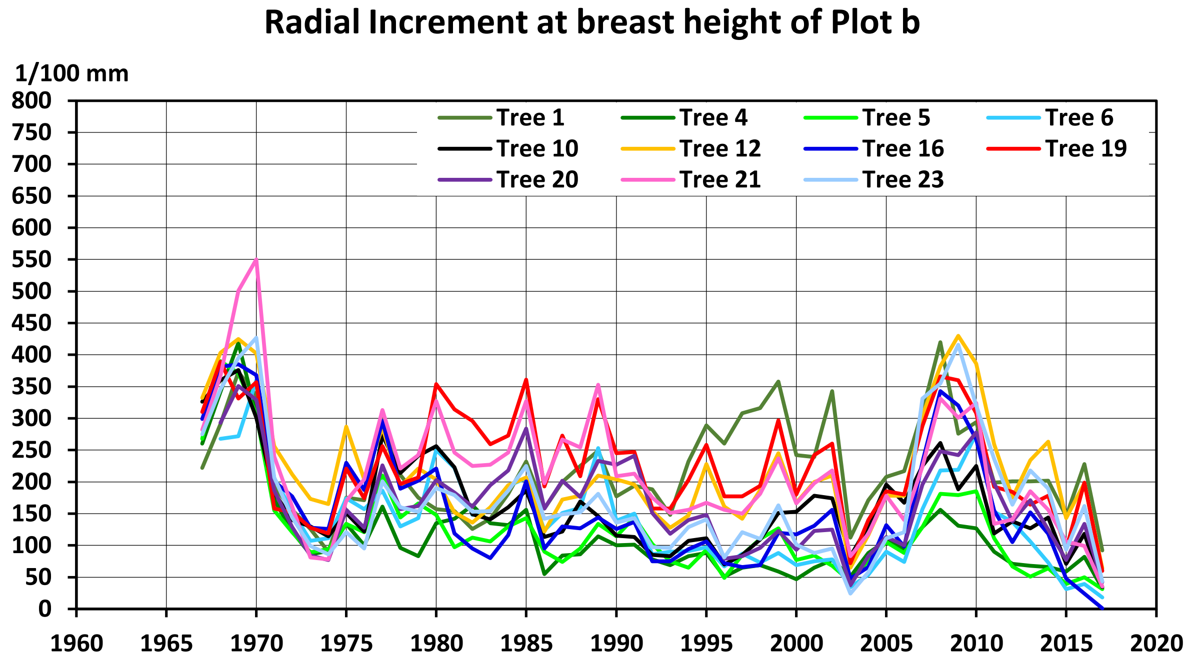
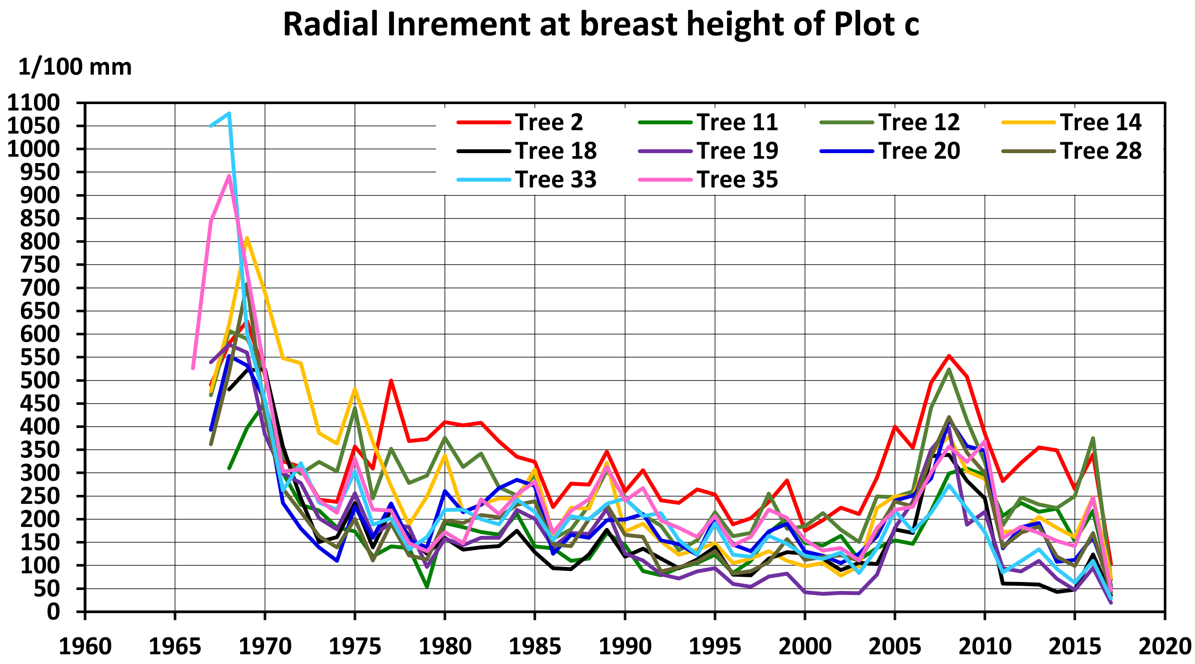
APPENDIX

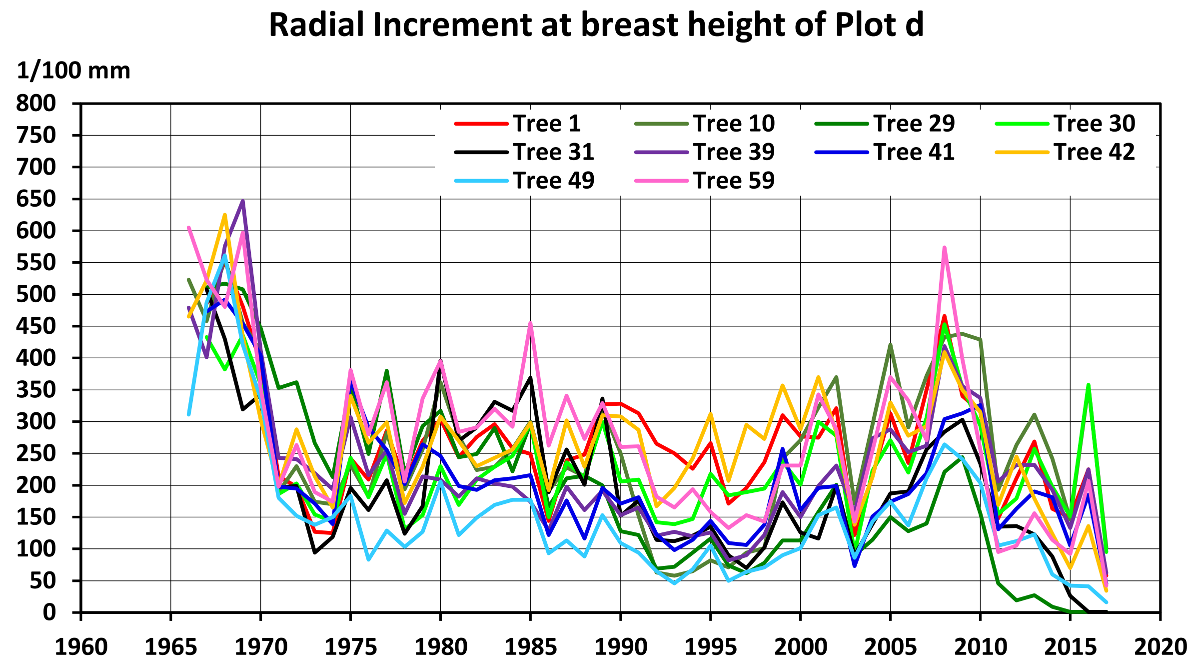
ANNUAL RADIAL INCREMENT AT BREAST HEIGHT

The diagrams below (A.Figure 1) show the yearly radial increment at breast height of every felled tree separated by the four plots. In every plot it is remarkable, that the increment was higher in the early stage, the first five years, and in the time period from 2005 to 2010, near the end of the life span of the felled trees.









A.Figure 1: Radial increment at breast height of all felled trees separated by plot.

Results of the Linear Mixed-Effects Models

Radial Increment Model

A.Table 1: Marginal R^2 and conditional R^2 of the radial increment model.

marginal R2	conditional R2
0.387	0.564

A.Table 2: Results and fit statistic of the fixed effects of the radial increment model.

Variable	Estimate	Std. Error	df	*t*-value	p-value
Intercept	88.94	25.91	3	3.41	0.034273 *
Age	-44.88	7.32	3	-6.12	0.008641 **
sDBH	14.36	10.06	4	1.55	0.20054
sT	30.45	4.77	3	6.32	0.005182 **
Pprev	77.05	4.64	8846	16.61	< 2e-16 ***
Pspring	78.15	5.79	5	13.47	6.60e-05 ***
Psummer	36.79	1.96	980	18.8	< 2e-16 ***
Dh	20.39	1.08	2178	18.87	< 2e-16 ***
Dh:Pprev	-5.38	0.56	8842	-9.53	< 2e-16 ***
Dh:Pspring	-3.68	0.49	8845	-7.47	8.79e-14 ***
Dh:Psummer	-0.84	0.25	8861	-3.37	0.000761 ***
Dh:sT	-5.53	0.2	8872	-27.05	< 2e-16 ***
sDBH:Pprev	4.64	2.34	8833	1.98	0.047847 *
sDBH:Pspring	3.15	1.94	7948	1.62	0.104815
sDBH:Psummer	6.14	1.15	58	5.35	1.57e-06 ***
sDBH:sT	-0.78	0.92	3972	-0.85	0.392795

A.Table 3: Results of testing the random variables by comparing with null-model.

Groups	Name	p-value
ID	**Intercept**	7.326e-10 ***
	Age	2.2e-16 ***
	sDBH	0.746
	sT	0.3663
	Pprev	0.8984
	Pspring	1
	Psummer	1
	Dh	1.332e-12 ***
	Dh:Pprev	1
	Dh:Pspring	0.258
	Dh:Psummer	1
	Dh:sT	0.8407
	sDBH:Pprev	0.6102
	sDBH:Pspring	1

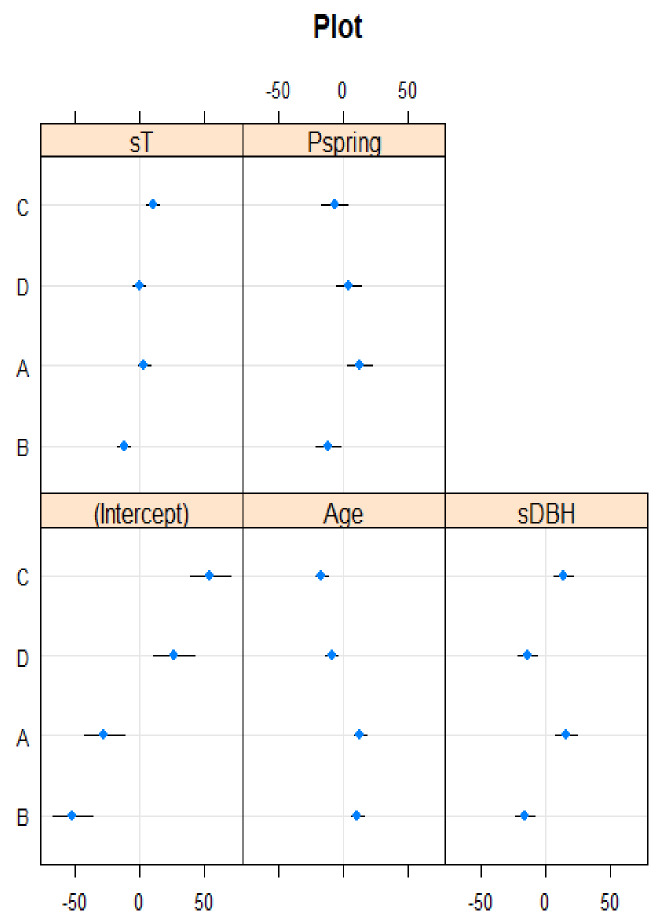
	sDBH:Psummer	0.009226 **
	sDBH:sT	0.3594
Plot	**Intercept**	1.524e-06 ***
	Age	3.601e-05 ***
	sDBH	0.02232 *
	sT	1.773e-08 ***
	Pprev	0.05119
	Pspring	0.02162 *
	Psummer	0.1205
	Dh	0.7544
	Dh:Pprev	0.7478
	Dh:Pspring	0.2514
	Dh:Psummer	0.1419
	Dh:sT	0.8191
	sDBH:Pprev	1
	sDBH:Pspring	1
	sDBH:Psummer	0.7736
	sDBH:sT	0.5295

A.Table 4: Variance component and standard deviation of the significant random variables.

Groups	Name	Variance	Std.Dev.
ID	**Intercept**	930.255	30.5
	Age	142.501	11.937
	Dh	4.1	2.025
	sDBH:Psummer	9.673	3.11
Plot	**Intercept**	2355.73	48.536
	Age	195.942	13.998
	sDBH	286.056	16.913
	sT	78.874	8.881
	Pspring	81.8	9.044
Residuals		8101.985	90.011

A.Table 5: Coefficients of the random variables for the four plots.

Plot	Intercept	Age	sDBH	sT	Pspring
A	61.16	-31.30	30.21	33.39	91.12
B	36.67	-33.60	-1.37	18.13	67.11
C	143.10	-61.33	28.01	40.57	71.73
D	114.81	-53.30	0.59	29.70	82.62



A.Figure 2: Illustrated conditional modes of the random variables for the grouping factor “plot”.

HEIGHT INCREMENT MODEL WITH INTERACTION EFFECTS

A.Table 6: Marginal R² and conditional R² of the height increment model with the interaction effects.

margial R2	Conditional R2
0.348	0.523

A.Table 7: Results and fit statistic of the fixed effects of the height increment model with the interaction effects.

Variable	Estimate	Std. Error	df	t-value	p-value
Intercept	34.55988	3.73934	3.8	9.237	0.000954 ***
Age	-5.31559	0.85174	3.1	-6.232	0.007928 **
sDBH	0.9607	1.01547	2165.2	0.946	0.344221
sT	-2.42362	0.62595	3.3	-3.899	0.024794 *
Pprev	4.53645	0.86316	2163.7	5.256	1.62e-07 ***
Pspring	-2.24089	0.63785	2163.6	-3.513	0.000452 ***
Psummer	3.72444	0.34738	2163.6	10.722	< 2e-16 ***
sDBH:Pprev	-0.59743	0.60281	2164.9	-0.991	0.321758
sDBH:Pspring	-0.01738	0.45647	2164.2	-0.038	0.969637
sDBH:Psummer	0.40385	0.25294	2163.7	1.597	0.110501
sDBH:sT	-0.14248	0.19299	2160.8	-0.738	0.460441

A.Table 8: Results of testing the random variables by comparing with null-model.

Groups	Name	p-value
ID	Intercept	1
	Age	1
	sDBH	1
	sT	1
	Pprev	1
	Pspring	1
	Psummer	1
	sDBH:Pprev	1
	sDBH:Pspring	1
	sDBH:Psummer	1
	sDBH:sT	1
Plot	Intercept	< 2.2e-16 ***
	Age	3.006e-12 ***
	sDBH	1
	sT	0.0152 *
	Pprev	1
	Pspring	0.05985 .
	Psummer	1
	sDBH:Pprev	1
	sDBH:Pspring	1
	sDBH:Psummer	1

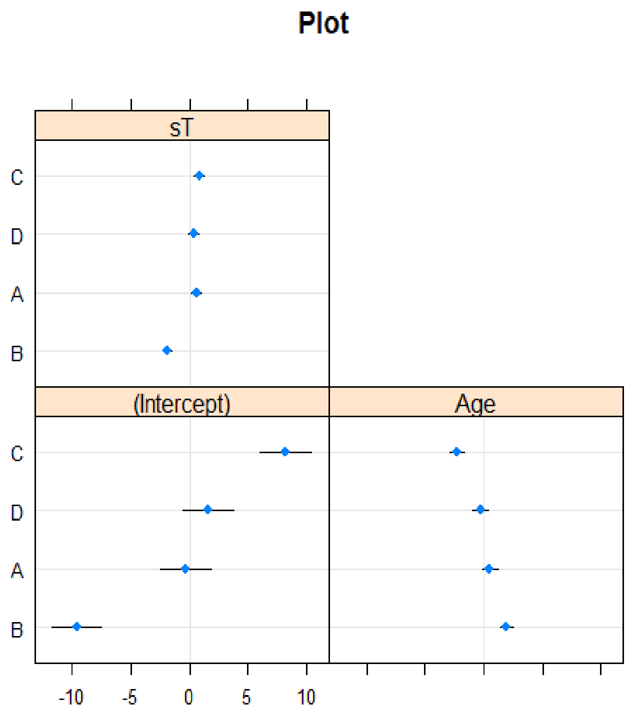
	sDBH:sT	1

A.Table 9: Variance component and standard deviation of the significant random variables.

Groups	Name	Variance	Std.Dev.
Plot	Intercept	48.175	6.941
	Age	2.729	1.652
	sT	1.155	1.075
Residual		131.428	11.464

A.Table 10: Coefficients of the random variables for the four plots.

Plot	Intercept	Age	sT
A	34.31	-4.78	-1.81
B	24.99	-3.33	-4.29
C	42.77	-7.56	-1.56
D	36.17	-5.60	-2.04



A.Figure 3: Illustrated conditional modes of the random variables for the grouping factor “plot”.

Height Increment Model without Interaction Effects

A.Table 11: Marginal R² and conditional R² of the height increment model without the interaction effects.

margial R2	Conditional R2
0.347	0.522

A.Table 12: Results and fit statistic of the fixed effects of the height increment model without the interaction effects.

Variable	Estimate	Std. Error	df	t-value	p-value
Intercept	34.34	3.73	3.8	9.203	0.001037 **
Age	-5.31	0.85	3.1	-6.218	0.007978 **
sDBH	1.60	0.19	2168.3	8.57	< 2e-16 ***
sT	-2.47	0.62	3.3	-3.994	0.024048 *
Pprev	4.35	0.84	2167.7	5.165	2.63e-07 ***
Pspring	-2.25	0.62	2167.7	-3.62	0.000301 ***
Psummer	3.86	0.34	2167.7	11.418	< 2e-16 ***

A.Table 13: Results of testing the random variables by comparing with null-model.

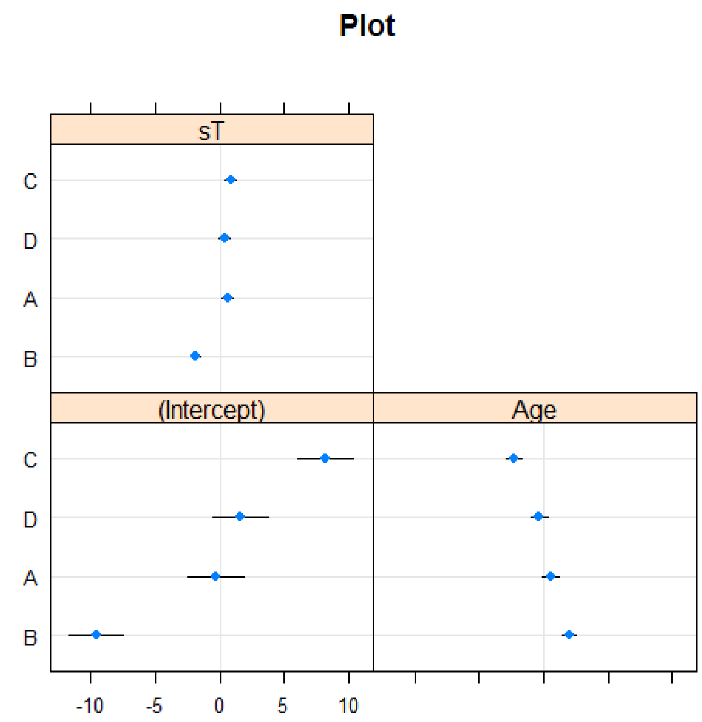
Groups	Name	p-value
ID	Intercept	1
	Age	1
	sDBH	1
	sT	1
	Pprev	1
	Pspring	1
	Psummer	1
Plot	Intercept	< 2.2e-16 ***
	Age	2.535e-12 ***
	sDBH	1
	sT	0.01528 *
	Pprev	1
	Pspring	1
	Psummer	1

A.Table 14: Variance component and standard deviation of the significant random variables.

Groups	Name	Variance	Std.Dev.
Plot	Intercept	48.309	6.95
	Age	2.743	1.656
	sT	1.154	1.074
Residual		131.455	11.465

A.Table 15: Coefficients of the random variables for the four plots.

Plot	Intercept	Age	sT
A	34.06	-4.77	-1.85
B	24.77	-3.33	-4.34
C	42.55	-7.56	-1.62
D	35.99	-5.62	-2.09



A.Figure 3: Illustrated conditional modes of the random variables for the grouping factor “plot”.

Volume Increment Model

A.Table 16: Marginal R² and conditional R² of the volume increment model.

marginal R2	conditional R2
0.69	0.781

A.Table 17: Results and fit statistic of the fixed effects of the volume increment.

Variable	Estimate	Std. Error	df	t-value	p-value
Intercept	-9.37	1.056	3.5	-8.453	0.00179 **
Age	3.246	0.616	3.1	5.262	0.01274 *
sDBH	-3.118	0.307	616.4	-10.16	< 2e-16 ***
sT	0.071	0.093	2127.2	0.756	0.44961
Pprev	1.201	0.250	2123.6	4.815	1.58e-06 ***
Pspring	2.468	0.389	3.2	6.323	0.00656 **
Psummer	1.232	0.099	2122.5	12.444	< 2e-16 ***
sDBH:Pprev	0.549	0.182	2141.9	3.015	0.00260 **
sDBH:Pspring	0.744	0.134	2127.2	5.542	3.37e-08 ***
sDBH:Psummer	0.442	0.072	2124.7	6.111	1.17e-09 ***
sDBH:sT	0.135	0.068	2168.8	1.997	0.04599 *

A.Table 18: Results of testing the random variables by comparing with null-model.

Groups	Name	p-value
ID	Intercept	0.004237 **
	Age	< 2.2e-16 ***
	sDBH	0.3967
	sT	0.2903
	Pprev	1
	Pspring	1
	Psummer	1
	sDBH:Pprev	1
	sDBH:Pspring	1
	sDBH:Psummer	0.4561
	sDBH:sT	0.05148 .
Plot	Intercept	1.939e-06 ***
	Age	0.008867 **
	sDBH	1
	sT	0.1105
	Pprev	1
	Pspring	0.006364 **
	Psummer	0.05718 .
	sDBH:Pprev	1
	sDBH:Pspring	1
	sDBH:Psummer	1

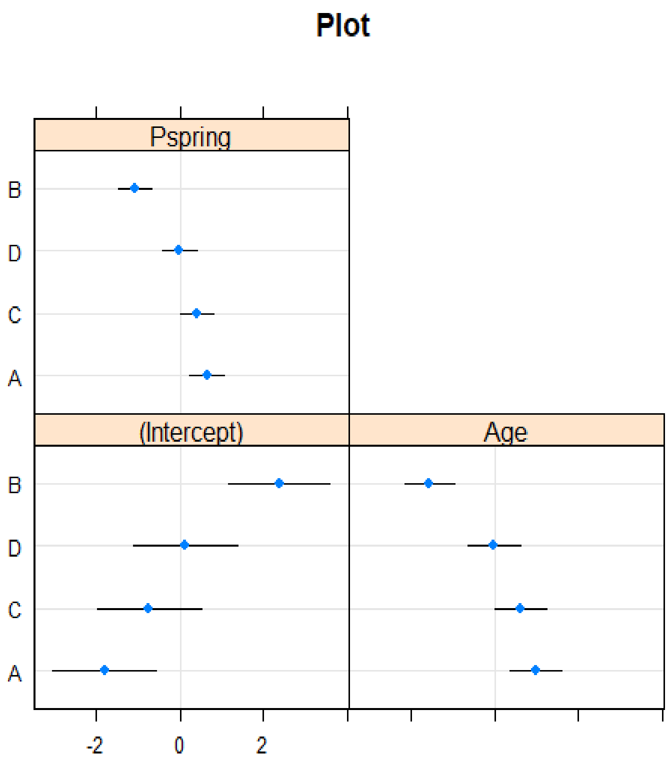
	sDBH:sT	0.9841

A.Table 19: Variance component and standard deviation of the significant random variables.

Groups	Name	Variance	Std.Dev.
ID	Intercept	0.675	0.8216
	Age	2.7031	1.6441
Plot	Intercept	3.7576	1.9384
	Age	1.2402	1.1136
	Pspring	0.4718	0.6869
Residuals		10.7147	3.2733

A.Table 20: Coefficients of the random variables for the four plots.

Plot	Intercept	Age	Pspring
A	-11.16	4.23	3.12
B	-6.98	1.67	1.40
C	-10.10	3.86	2.89
D	-9.23	3.23	2.46



A.Figure 4: Illustrated conditional modes of the random variables for the grouping factor “plot”.