



Impact of soil water holding capacity on forest vitality in Swiss plenter forest

ESS 511 Master's Thesis

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Abstract

Forestry in the Swiss Alpine regions is increasingly under pressure due to more frequent heatwaves and dry conditions. These events affect the vitality of plenter forests (uneven-aged mixed stands), which are considered an important part of clear-to-nature silvigenesis. After a prolonged dry period, the soil available water capacity (AWC) becomes a crucial factor for tree water supply. To investigate the effects of AWC on the vitality of the three main tree species (*Fagus sylvatica*, *Abies alba* and *Picea abies*) in Swiss plenter forests, I analyzed long-term data using a linear mixed model. Forest vitality was assessed by focusing on basal area increment (BAI) at the stand level and crown volume growth (DCV) at the individual tree level. The results showed that the BAI of *Fagus sylvatica* and *Abies alba* was not significantly influenced by AWC, whereas *Picea abies* exhibited a positive response. In contrast, all Species displayed reduced DCV with increasing AWC. These contrasting results highlight the importance of the level of observation in forestry, as stand-level does not reflect tree-level DCV. These findings underscore the relevance of considering AWC in adaptive forest management strategies under climate change. Given the drought-sensitivity of *Picea abies*, their extent in dry and warm areas should be reconsidered. Managing *Picea abies* on soils with high AWC results in higher vitality. Furthermore, the complementary effects within plenter forests support the continued presence of *Picea abies* as part of a climate-resilient forest.

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Contents

Abstract	i
Acknowledgements	ii
Figures	v
Tables	vi
Abbreviations	vii
1 Introduction	1
1.1 Challenges in Swiss forests	1
1.2 Plenter forest	2
1.3 Soil and the water household	4
1.4 Forest vitality	6
1.5 Research gap and question	7
2 Materials and methods	8
2.1 Research area	8
2.2 Materials	9
2.3 Available water holding capacity	11
2.4 Selected climatic variables	14
2.5 Forest vitality	14
2.5.1 Basal area increment per stand	15
2.5.2 Crown volume change per tree	15
2.6 Statistical evaluation	17
3 Results	19
3.1 Available water holding capacity	19
3.2 Selected climatic variables	20
3.3 Forest vitality	22
3.3.1 Basal area increment per stand	22
3.3.2 Crown volume change per tree	28

4	Discussion	32
4.1	Forest growth driven by climate, human disturbances and stand structure	33
4.2	Higher vulnerability of <i>Picea abies</i>	35
4.3	Tree crown growth influenced by climatic extreme events and competition	36
4.4	Negative effect of AWC on tree vitality	37
4.5	Forest vitality and its resilience against extreme events	37
5	Conclusion and outlook	39
	References	40
	A Data and figures	46
	B Calculations and statistical evaluations	58
	C Decipherment of historical data	87
	Personal declaration	99

Figures

1	Silvigenesis of a natural forest	3
2	Map of investigated plenter forests in Switzerland	8
3	Material for soil inventory	9
4	Soil drill core	10
5	Soil profile	11
6	The monitoring area and division into subplots for drill cores	12
7	Diagram for the allometric equations for the soil properties	13
8	Two-dimensional shape of a tree crown with two functions	16
9	A model for species-specific homogeneous crown shapes	17
10	Boxplot of the AWC measurements	19
11	Temporal change of mean precipitation	21
12	Temporal change of dry and heat events	21
13	Basal area of the most abundant species	22
14	BAI of different species according to AWC	23
15	BAI _{adj} for <i>Abies alba</i> of 3 plot groups	26
16	BAI _{adj} for <i>Picea abies</i> of 4 plot groups	27
17	Distribution shapes of DCV	28
18	DCV for <i>Picea abies</i> on 4 plot groups	31

Tables

1	Growth dynamics with increasing age for the high forest and the plenter forest.	4
2	Summary statistics of the 20 permanent plots.	9
3	AWC measurements of the 20 plots, the results are graphically represented in Figure 10. . . .	20
4	Estimated BAI_{adj} for given AWC and time values	24
5	Estimated BAI_{adj} for different climatic factors	25
6	Estimated DCV for given AWC and time values	29
7	Estimated DCV for different climatic conditions	30

Abbreviations

<i>AWC</i>	Available water holding capacity of a soil [mm]
<i>ASL</i>	Above sea level [m]
<i>BAI</i>	Basal area increment of a stand [$\text{m}^2/(\text{ha a})$]
<i>BAI_{adj}</i>	Adjusted basal area increment of a stand [$\text{m}^2/(\text{ha a})$]
<i>BAL</i>	Basal area of larger trees of a tree [m^2]
<i>C₃</i>	three-carbon compound photosynthesis
<i>CO₂</i>	Carbon dioxide
<i>cdd</i>	Dry days representing the longest period of consecutive days with daily precipitation <1 mm in a year [d]
<i>DCV</i>	Delta crown volume per year of a tree [m^3/a]
<i>dist</i>	Distance from top of the tree [m]
<i>EFM</i>	Experimental Forest Management project
<i>l</i>	Tree crown length [m]
<i>l_o</i>	Crown length from the tree top to the maximum tree crown radius [m]
<i>Max</i>	Maximum
<i>Min</i>	Minimum
<i>p</i>	P-value
<i>prcp</i>	Total precipitation during growing period from April to October [mm]
<i>QMD</i>	Quadratic mean diameter [cm]
<i>r</i>	Tree crown radius [m]
<i>r₀</i>	Tree crown radius in sunlight [m]
<i>r_u</i>	Tree crown radius in shadow [m]
<i>r_{max}</i>	Maximum tree crown radius [m]
<i>SD</i>	Standard deviation
<i>SE</i>	Standard error
<i>specProp</i>	Respective species proportion of a stand [%]
<i>Tmax</i>	Daily maximum temperature [$^{\circ}\text{C}$]
<i>tmax28</i>	Heatwave days representing the total days with maximum temperature > 28 $^{\circ}\text{C}$ in a year [d]
<i>WSL</i>	Swiss Federal Research Institute for Forest, Snow and Landscape

Units

<i>a</i>	years
<i>d</i>	days
<i>ha</i>	hectares
<i>hPa</i>	hectopascals
<i>mm</i>	millimeters
<i>cm</i>	centimeters
<i>dm</i>	decimeters
<i>m</i>	meters
<i>m²</i>	square meters
<i>m³</i>	cubic meters
<i>°C</i>	degrees Celsius

1 Introduction

Water is one of the most vital resources for trees to thrive. However, its availability is increasingly threatened by environmental changes. Climate change affects many regions regardless of their size and distribution. As precipitation patterns shift, droughts during the growing season become more frequent and intense. A third of the earth's total land area is covered by forest ecosystems (FAO and UNEP, 2020). The same proportion applies to the small area of Switzerland. To keep these large ecosystems vital, water accumulation through roots is essential, especially during dry periods. The forest industry is using most of these ecosystems on a large scale and is responsible for the future of many forest areas. Together with the scientific field of forestry, which studies the dynamics and growth of trees and forests under multiple influences (Pretzsch, 2009), they can contribute to shaping forests into more resilient ecosystems.

1.1 Challenges in Swiss forests

For many years forests' structure, management and requirements have adapted continuously to changing conditions – both human-induced conditions that reshape forest management and environmental shifts that demand responsive management strategies. Because of this, many key transitions become evident within a forest stand – a dynamic entity where trees of varying sizes and other organisms compete for essential resources to grow and survive (Fuentelba et al., 2013). The interests of forestry have shifted from largely even-aged pure stands to diverse mixed stands. Homogenizing thinning regimes are becoming less important as more emphasis is placed on promoting individual trees or groups within a stand. In the last decades, the focus of forestry has evolved from wood production forestry to multipurpose forestry, which relates to many ecological, economic and social services of forests (Pretzsch, 2009).

But has this also been implemented by the responsible forest management institutions? An analysis of the data reveals that clear-cutting practices persisted as the primary management strategy, even though leading scientists suggested a paradigm shift in Switzerland (Ammon, 1995; Schütz, 2001). A speech held by Schütz (1994) in Zurich in front of foresters and scientists recaps the scientific perspective of silviculture in Switzerland in the second half of the 20th century. He emphasizes how the management strategies at the time and in the future should focus on single tree selection – a forestry method based on felling individual trees – and not on clear-cuts, including the principles of the plenter system. This management system relies on mixed stands, including trees of different ages. However, when we look at the management strategies of the last 50 years in Switzerland, there has been only little change: The National Forest Inventory of Switzerland showed in the 1980s that 10 % of the total forest area was specified as plenter and uneven-aged forest, whereas today, in the newest inventory only 7 % is covered by these forests (Abegg et al., 2023a, 2023c). The conventional clear-cutting remained the most commonly used method, although much evidence suggested a change.

What has been challenging to enforce in the last century is widely accepted in science nowadays and is slowly gaining importance in practice. Modern silviculture should be adaptive and diverse to withstand environmental disturbances (Glatthorn et al., 2023). Summerly heatwaves and drought events in Europe are likely to occur more frequently and intensively than today (Grillakis, 2019; Streit et al., 2017). Likewise, insect infestation and wind damage are expected to increase drastically in the near future (Gardiner et al., 2013; Seidl et al., 2007; Thiele et al., 2017), leading to higher tree mortality. Climate change and

environmental aspects require resistant forests that have the ability to change across a range of temporal scales. By enhancing tree diversity, structural diversity, genetic diversity and the resistance of single trees as well as decreasing the rotation period, silviculture can help increase forests' resistance and health (Brang et al., 2016).

1.2 Plenter forest

In Switzerland, 31 % of the total area is wooded. According to the Federal Office for the Environment of Switzerland, the forest area was over a million hectares in 2022 (Schmutz and Gollut, 2023). Of that forest area 60 % is classified as *uniform high forest*, 11.9 % as *non-uniform high forest* and 6.8 % as *plenter forest*, also named *selection type high forest*, making those three the most abundant forest type classes in Switzerland (Abegg et al., 2023b). The non-uniform high forest is an intermediate stage between the uniform and the plenter forest. Those two types are opposed to each other, representing two different principles in silviculture. Firstly, the uniform high forest, which is characterized by an even-aged stand, exhibits a horizontal homogeneous distribution of only one tree generation with a clear temporal and spatial expansion (Bettinger et al., 2017). Secondly, the uneven-aged plenter forest with a high vertical and horizontal diversity of different tree generations within the stand.

In the case of the plenter forest, the silvigenesis – the temporal development of tree communities – occurs in the shadow below the canopy of the surrounding higher and older trees (Bartsch et al., 2020; Schütz, 2001). The idea behind this silvicultural strategy is based on the regeneration of natural mixed forests in temperate zones (Ammon, 1995; Schütz, 1998). Even though the generational change in these untouched forests can take up to 3 times longer, one can notice a phase similar to the silviculture of a plenter forest, which gave it the name plenter phase. As Figure 1 depicts, this phase is relatively short in the ontogenetic forest succession and covers 0 to 14 % of the area in fir-beech natural forests (Schütz, 1998). The fundamental difference between natural and human-influenced plenter forests lies in regeneration. While natural forests have a clear generational succession, plenter forests remain structurally the same over time and undergo continuous, individual regeneration by felling single trees (Ammon, 1995). If the forest stays in the plenter phase, the total wood volume is kept to around 300 m³/ha, which compared to the 400 to 600 m³/ha of a natural beech forest, indicates how important the secondary growth in plenter forests is (Schütz, 1998).

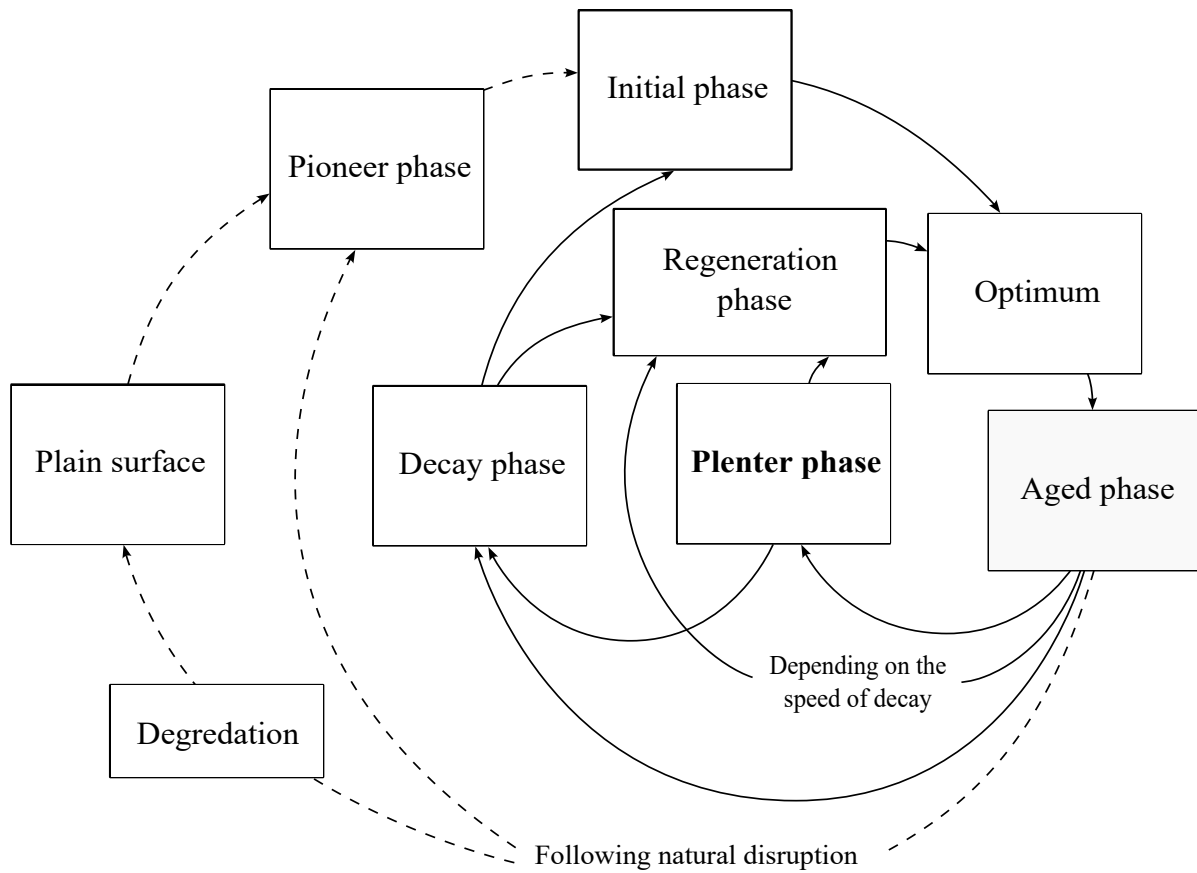


Figure 1: Silvigenesis of a natural forest in a temperate climate, including the plenter phase between the old and optimum stage. This stage is only seen in plenter forests, while uniform forests containing only one species do not include a plenter stage (adapted from Schütz, 1998).

Therefore, an average plenter forest is covered by shadow-resistant tree species. The upper trees build a canopy under which younger trees can grow slowly but steadily to sustain a continuous regeneration (Schütz, 2001). The main differences to even-aged high forests are characterized by the age structure of the trees, as shown in Table 1. In even-aged high forests, trees must be the same age, with a maximum age difference of 20%. A reforested area or a plantation has the characteristics of these forests. At the moment of a generational shift, the new tree community competes for the scarce sunlight, which results in constant growth for an evenly distributed horizontal canopy. Usually, there is only slight variation in tree heights and the diameter distribution represents a bell-shaped curve. Differences in wildlife habitat in high forests vary depending on the trees' structural characteristics and the silvigenesis stage. For example, species can require open spaces with grass or shrubs, only available at the beginning phase of an even-aged forest. Others may require large trees for nesting, which only exists in a mature forest (Bettinger et al., 2017).

Because of the plenter forest's ability for continuous regeneration, it is less prone to fluctuating changes throughout silvigenesis. On the contrary, tree species with a high need for sunlight are nearly impossible to hold in an uneven-aged stand. In Switzerland, plenter forests consist mainly of the following shade-resistant species: *Picea abies* (Norway spruce), *Abies alba* (European silver fir) and *Fagus sylvatica* (European beech).

However, different types of plenter forests exist, depending on the included tree species, the location, and the individual forestry practices. An approach to assessing plenter forest stands is to analyze the distribution of the tree sizes. If the focus is on the tree vitality, the size of the neighboring trees also matters (Schütz, 2001).

To maintain biodiversity as high as possible in Switzerland’s forests, a complementary approach should be taken, according to Schütz (2001). The biodiversity is highly dependent on the species’ biotopes. Thus, silviculture should include many different management types to generate a possible high number of biotopes. A thrive towards many different forest types standing side by side, with various silvicultural methods containing different tree species, should lead towards a coexistence of different forests. The underrepresented plenter forest should gain importance to support the diversity effect. Silviculture can enhance biodiversity by placing different stands side by side, with varying canopy closure, including both even- and uneven-aged structures, as well as mixed and pure compositions. These may originate from large-scale areas, isolated spots, or even from continuous regeneration, as seen in a plenter forest (Schütz, 2001).

Table 1: Growth dynamics with increasing age for the high forest and the plenter forest.

<i>Development Characteristics</i>	Even-aged Stands	Uneven-aged Stands
<i>Trees per unit area</i>	Decreases with age	Varies
<i>Mortality rate of stems</i>	Decreases with age	Stays relatively constant
<i>Height of canopy</i>	Increases with age, then plateaus	Stays relatively constant
<i>Canopy cover</i>	Ranges from none to full	Ranges from full to one with gaps
<i>Average tree diameter</i>	Increases with age	Fluctuates (harvest entries and mortality)
<i>Diameter distribution</i>	Bell-shaped curve	Reverse J-shaped curve
<i>Basal area</i>	Increases with age, then plateaus	Fluctuates (harvest entries and mortality)
<i>Timber growth rate</i>	Rises, peaks, then declines	Stays relatively constant

adapted from Bettinger et al. (2017)

Despite its small proportion, the plenter forest played an important role in Switzerland’s forestry. It was seen as a traditional management strategy in the canton of Neuchâtel and the canton of Bern. As management strategies caused heated debates within forestry and especially plenter forest were questioned, a project emerged trying to compare different management strategies and their values for forestry. The Experimental Forest Management project (EFM) by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) looks at changes occurring within the forests under certain management types. It is considered one of the oldest ongoing experiments in forestry. The measurements go back until the end of the 19th century (Forrester et al., 2019). In the context of plenter forests, little research has been conducted. To my knowledge, long-term analyses of forest vitality are still largely lacking in the context of the Swiss subalpine and montane area. The relatively stable structure of plenter forests makes long-term vitality analysis possible and comparable.

1.3 Soil and the water household

Most water plants use is accessed through their roots, supplied by the surrounding ground material. Soil is a crucial factor influencing plant distributions, carbon allocation, microbial activity, nutrient cycling and photosynthetic rates (Adhikari and Hartemink, 2016). Its properties determine how much water is available

for plants and control exchange processes between soil, vegetation and atmosphere (Jasper et al., 2006). After a plentiful rainfall, when saturation is reached and the excess water runs off, the soil is at field capacity. In the absence of further precipitation, plants will continue to draw water from the soil storage until the soil reaches the permanent wilting point: At approximately 15 000 hPa, the remaining water is held with such force that most plants are incapable of absorbing it (Rai et al., 2017). The maximum amount of water available to plants is the amount of water stored at field capacity, subtracting the water remaining at the permanent wilting point (Rai et al., 2017; Trasobares et al., 2016). It is referred to as ***soil available water holding capacity*** (AWC) and is influenced by the stone content, the fine earth density, the texture and the humus content (Saxton and Rawls, 2006; Walthert et al., 2004). Under climate change, a reduction in total soil water content is expected due to declining summer precipitation, lower air humidity, and increased evapotranspiration from higher solar radiation, leading to more stressful water conditions for plants (Jasper et al., 2006). In the alpine region, the frequency of droughts during the growing season will likely increase from 15 % to 50 % by the end of the 21st century (Calanca, 2007). Temperature and precipitation extremes are considered two of the most critical impacts of climate change, according to the Intergovernmental Panel on Climate Change (Flato et al., 2013). Droughts and heatwaves will occur more frequently in the near future and will affect vegetation (Miralles et al., 2019).

There are multiple ways to assess climatic effects on trees. Spiecker (1990) showed that dry periods could lead to depression in diameter growth while he looked at Norway spruce stands in the Black Forest region. He further indicated that especially low precipitation acts as a stress factor during the growing season and lowers the diameter increment of spruces, even at higher elevations. A different position takes Stojanovic et al. (2018). They showed that the growth response of trees depends on the precipitation of the current year and the year before and not only on dry periods. Therefore, it can be assumed that the effect of the AWC on trees depends on the amount of precipitation. Nevertheless, precipitation over the growing period is a crucial factor influencing the growth and well-being of trees.

It should be questioned whether the total precipitation per growing season and the length of droughts are directly correlated. The assumption that more precipitation automatically means fewer long droughts would be erroneous. The year 1952 showed that dry periods in Switzerland can even occur when yearly precipitation exceeds the average (Federal Office of Meteorology and Climatology MeteoSwiss, 2025b). The length of droughts should be analyzed independently without relying on total precipitation. Prolonged droughts can still occur even in relatively wet years if rainfall is unevenly distributed or concentrated in short periods.

Heatwaves are very broadly defined as “a period of consecutive days where conditions are excessively hotter than normal” (Perkins and Alexander, 2013). Kong et al. (2024) showed that trees of the same species in a cold environment react more vulnerable to heatwaves than those in warmer regions, making elevated, colder areas more prone to increased temperatures. From a meteorological perspective, heatwave days in Switzerland are defined as days with a maximum temperature higher than 30 °C (Federal Office of Meteorology and Climatology MeteoSwiss, n.d.). However, most temperate C₃ species – representing the standard photosynthesis type of 90 % of all plants, including trees – experience a decline in photosynthesis at leaf temperatures between 26 and 32 °C (Farquhar et al., 1980). Hence, during heatwaves, which can already have an effect at 26 °C, the capacity of soils to retain and store water might become more vital for providing sufficient water to trees than during cold days, when plant activity is considered lower.

Also, the geographical distribution of soil plays a huge role for assessing areas vulnerable to these changes.

The Swiss government is therefore planning a large-scale soil inventory to map the spatial variations in soil characteristics across the country (Federal Office for the Environment FOEN, 2023). It is anticipated that this undertaking will span multiple decades. Moreover, the WSL is repeating their forest soil inventory from 1993 on the 8 x 8 km sub-grid to further specify changes in the soil system and verify the robustness of the grid to the spatial variability of Switzerland (Stephan Zimmermann and Jörg Luster, n.d.). This project should be completed by 2025. Notwithstanding the diversity of the Swiss environment, many combinations of soil formation factors and environmental factors are not covered by this grid. The field site and monitoring plots on plenter forests in the EFM only contain a historical soil inventory conducted at the time of establishment with sparse information. Recent inventories on plenter forest soils in Switzerland are missing, even though the ability of soils to retain water is crucial for root distribution and tree vitality (Smolar et al., 2024).

1.4 Forest vitality

The vitality of trees is a critical element in evaluating the health and well-being of the forest ecosystem. However, because there is no universally accepted definition of forest vitality, there are several different interpretations and approaches (Gehrig, 2004). In this thesis, the focus is laid on Brang’s (1998) definition of tree vitality as the ability of a tree to assimilate carbon, resist stress, respond to a changing environment and reproduce itself. Gehrig (2004) sees tree vitality similarly as a combination of *growth*, *stress tolerance*, *longevity* and *reproduction*. These fundamental components can be assessed using the following indicators: (1) diameter growth, (2) crown clearing and crown shape changing, (3) change in shoot length growth and (4) change in leaf and needle color. Each indicator can only specify a partial aspect of the vitality and cannot be taken as a solitary representative of tree vitality. However, because of the limitations of the long-time available data, this study looks at the growth and stress tolerance of tree vitality by assessing the first two indicators: diameter growth and crown condition.

Growth is a good long-term indicator of vitality (Dobbertin, 2005), which perfectly aligns with the long-term recording of the available data, where the basal area of the stand is used. Also, the tree crown plays an important role in the structural architecture of a forest, as they directly influence the regulation of solar energy, nutrient recycling and moisture retention (Zarnoch et al., 2004). The change in tree crown volume, which is, according to Zhu et al. (2021), an important variable in forest modeling, will be used as a proxy for stress tolerance.

Furthermore, the health of a forest is not only defined by the vitality of individual trees. A community of trees should be able to withstand ecological pressures without significant changes in composition, structure, and processes. Typically, a vital forest contains dead and sick trees (Brang, 1998), but the proportion of vital trees should be predominant for keeping the ecosystem stable. In consequence, forest vitality is connected to the concept of ecological stability, defined by Donohue et al. (2016, p. 1173) as ‘a multidimensional concept that tries to capture the different aspects of the dynamics of the system and its response to perturbations’. Disturbances that alter the structure and dynamics of forests can occur at different time scales. A continuum of their duration, ranging from pulses – short shocks (heatwaves) – to presses – long-term changes (rising temperature or CO₂ fertilization) – can be observed (Donohue et al., 2016).

A single-measure perspective, which many studies include, is criticized by Donohue et al. (2016) for oversimplifying the multidimensional nature of stability and potentially underestimating the actual impact on a system. This thesis emphasizes the long-term presses on plenter forests while also considering the effects of

relatively long pulses, such as heatwaves, high-temperature events, and low precipitation during the growing season.

Furthermore, Walthert (2022) emphasizes the vulnerability of tree species in Swiss plenter forests, highlighting that *Abies alba* is moderately and *Picea abies* and *Fagus sylvatica* strongly affected by droughts. Given these limitations, continued investments in soil inventories and monitoring efforts are crucial for understanding soil dynamics and water acquisition by trees in plenter forests.

1.5 Research gap and question

While many studies showed the influence of longer dry periods on agricultural plants and even-aged managed forests (Calanca, 2007; Frederick and Major, 1997; Spiecker, 1990; Trasobares et al., 2016), there is little research on uneven-aged plenter forests. The higher structural and species diversity suggests greater resilience to water scarcity. Different root lengths and depths allow trees to access water at various soil levels. Furthermore, the stable canopy that keeps most of the area covered by trees moderates the forest microclimate, allows small patches for forest regeneration and therefore reduces degradation and soil drying after harvesting.

The following research question came up:

How does soil water holding capacity affect the forest vitality of plenter forests in Switzerland?

Based on the current state of science, the following hypotheses resulted: (1) There is a positive correlation between the AWC and the vitality of forests and trees because a steady water supply supports vitality. (2) AWC has a stronger effect on forest vitality under conditions of low rainfall. (3) Forests with a high AWC are more resistant to dry events.

2 Materials and methods

2.1 Research area

The study area is located in Switzerland, and the permanent yield plots were repeatedly measured from 1905 to 2022 by the Swiss Federal Institute of Forest, Snow and Landscape Research WSL (Birmensdorf) as part of the EFM project. The study sites are primarily located in the montane and subalpine zones of the Alps, the Jura mountains and the pre-alpine region of the Emmental. These forests are found on steep slopes or mountain valleys shaped by glacial and post-glacial processes. Shallow, stony soils are prevalent, but deeper soils with higher AWC can also occur in colluvial or moraine deposits. The mean temperature during the growing season ranges from 7 to 15 °C (Table 2). Precipitation can exhibit high interannual variability, yet it is typically well distributed throughout the year, with substantial snowfall during the winter months.

The plenter forest plots were selected, based on their very long observation time (older than 1930) and measured at an interval of 4 to 10 years until 2022. The area of the plots was mainly between 10'000 m² and 20'000 m² (1st and 3rd quartile). Only the transition forest plots were much smaller, with a lower size limit of 3,209 m². As they share a similar structure with plenter forests, they were added to increase the number of plots. Most areas were at an elevation of 900 to 1300 meters above sea level (1st and 3rd quartile). 17 plenter forest plots and 3 transition forest plots were used. The transition forest plots are located close to a plenter forest plot. The three plots that include or are transition forest plots are marked with * at the end of their name in the following Figure 2.

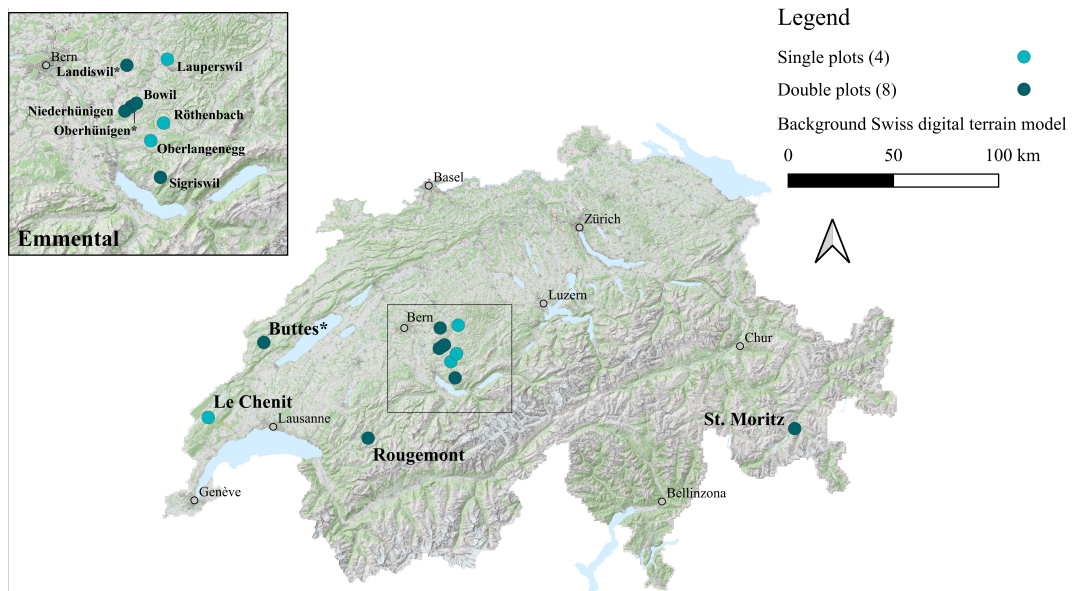


Figure 2: Geographical distribution of the plenter plots of the Experimental Forest Management project in Switzerland. Plots that include a transition forest plot are marked with *. For a clearer view, areas with two nearby plots are depicted together and named *double plots*. On the contrary *single plots* contain only one plot. For further information on the plot names and their respective ID see Table 3 (own figure with a digital terrain model by the Federal Office of Topography swisstopo, 2022).

Table 2: Summary statistics of the 20 permanent plots.

Variable	Mean	SD	Min	Max
Number of inventories	15.2	2.63	11	19
Stand installation	1918	8.53	1905	1931
Basal area (m ² /ha)	34.64	6.06	14.92	42.51
Stem number	455.2	122.88	112.2	618.7
Altitude (m)	1137	283.41	861	1810
Mean temperature (April-October; °C)	11.1	0.66	6.76	15.8
Precipitation (April-October; mm)	921	141	479	1351

2.2 Materials

The soil group of the WSL provided materials for the soil inventories. They included a hand auger, a spade, a folding rule, soil color charts for evaluating humus content, and a knife for measuring soil density, as shown in Figure 3. The AWC calculation of the soil inventories was the only primary measurement assessed in this thesis.

After the drill core was evenly laid out, as in Figure 4, it was analyzed with the help of the tools and the small soil protocol provided by the WSL.



Figure 3: Material used for the soil inventories. Image taken in St.Moritz at plot 1033000, while conducting the second drill core (own photograph).



Figure 4: The drill core was evenly laid out on the forest floor, using the folding rule and a handle of the spade or the auger as straight boundaries. This drill core was carried out at plot 2035000 in Buttes (first measurement, own photograph).

A similar inventory procedure was followed for a soil profile, but additionally, the density was determined by using a soil knife.



Figure 5: The soil density can be determined by assessing the resistance to penetration in different soil horizons in the profile using a knife. The soil profile was dug at plot 2035000 as the third measurement (own photograph).

2.3 Available water holding capacity

At each forest monitoring plot, the soil properties were determined from one historical soil profile combined with the results of 3 conducted soil recordings. The historical soil profiles were conducted by the WSL at the installation point of each monitoring between 1905 and 1931, depending on the field site. The information was found in the WSL archive and was mostly preserved. A default value was taken for values that could not be extracted from the documents. Subsequently, three soil recordings were made to check and compare with the historical data. These consisted of two drill cores and one soil profile. A third drill core was taken

where the terrain did not allow a soil profile to be dug. To obtain the soil variability of a plot, the area was divided into three subplots of equal size, as shown in Figure 6. The transect for the subdivision was determined based on the superficial variation of the field plot, which was analyzed approximately on the day of the field survey. Elevation was usually the dominant variation factor, but other terrain factors, such as dells, which can occur horizontally, had to be considered where appropriate. Each subplot consists of one soil record. The specific location of the soil records was chosen to represent the variation within the subplot. The location of the soil profile was selected based on a balance between ease of access and representativeness, with the condition that it had to be within a subplot. When multiple options were available, the location was chosen randomly. From the four soil records (one historical and three newly generated), the average soil properties were derived from which the AWC was estimated.

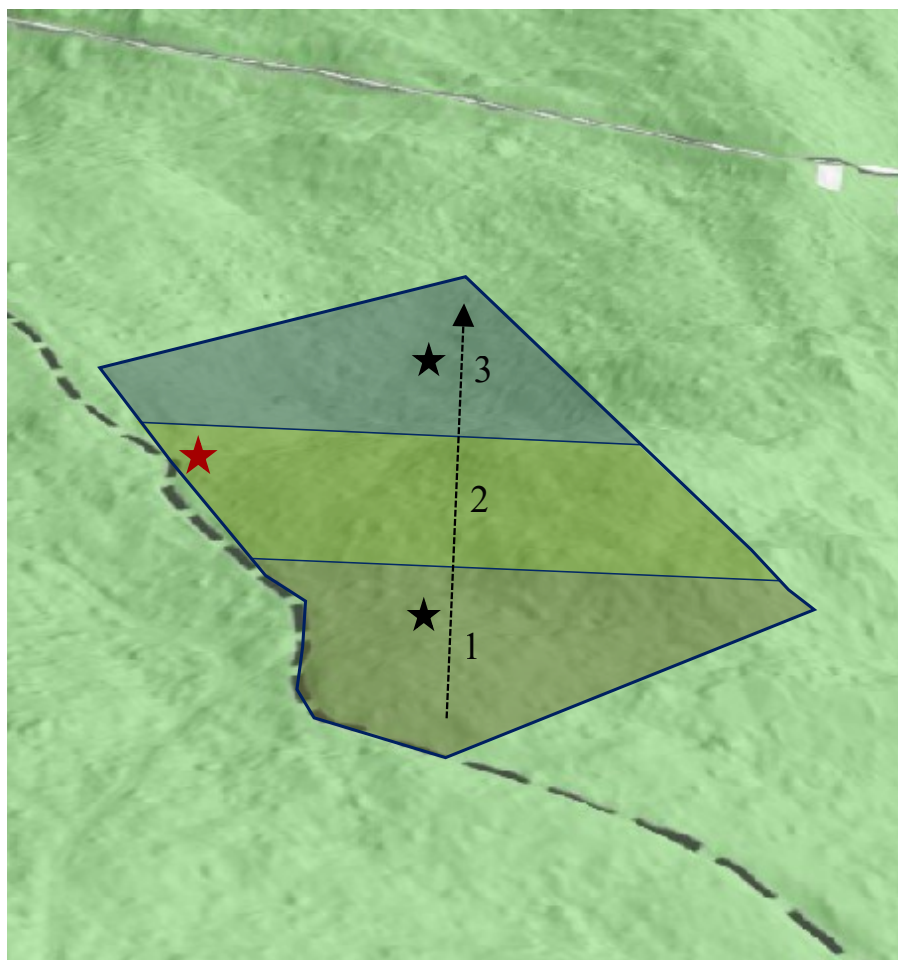


Figure 6: The monitoring area of Rougemont has a diverse terrain, according to the digital terrain model (Federal Office of Topography swisstopo, 2022). The transect was chosen so that it includes the main elevation path and two smaller horizontal dells. The black arrow represents the transect, the black stars the drill cores and the red star the soil profile, which was made near the hiking path (own figure).

The AWC was calculated for a depth of 100cm. Where the rooting system was limited above 100cm depth by parental rock or water conditions, the AWC was calculated only to the respective rooting depth. Where organic layers were present, they were considered using the method by Zuber (2007), which proposes using 27.4 % for F horizons and 35.7 % for H horizons for the AWC. For the soil horizons, the pedotransfer functions by Teepe et al. (2003) were used. The AWC, air capacity, and the permanent wilting point of each horizon were estimated. Figure 7 depicts the calculating process with the required soil properties: *fine earth density* (5 classes), *texture* (10 classes) and *humus content* (%). Detailed tables for the calculations are attached in the appendix. After adjusting each horizon for its thickness and stone content, the values were summed to a total depth of 100cm.

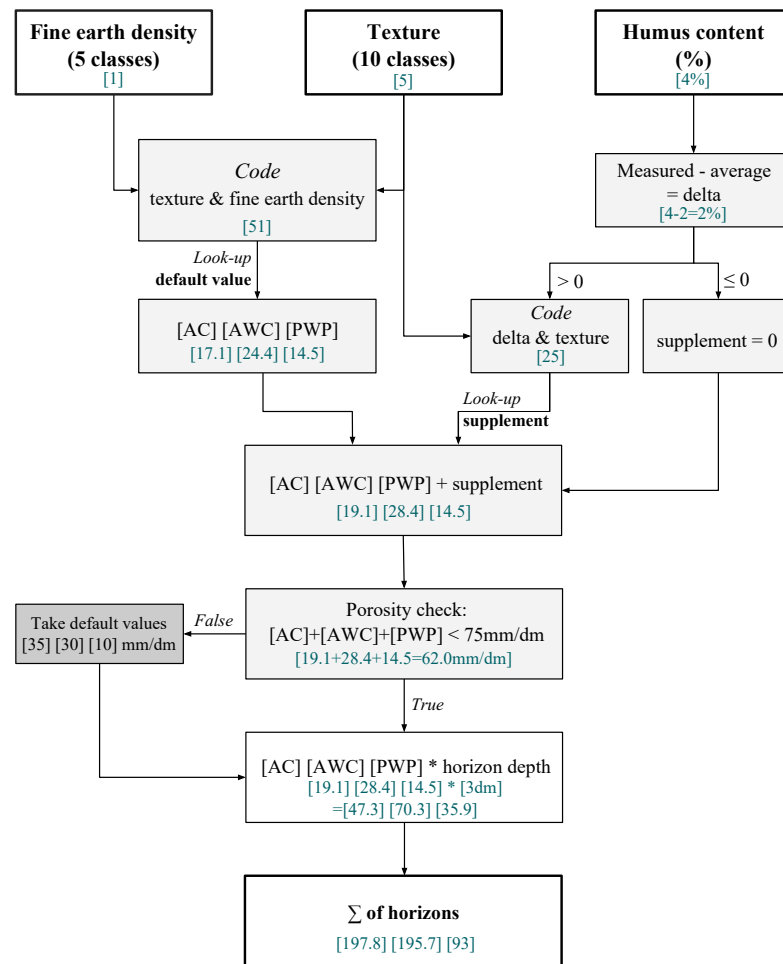


Figure 7: The method by Teepe et al. (2003) was executed step by step using the three main soil properties for the allometric equations. *Code* defines a combination of two previous steps, *Look up* represents a look-up table where the code is transformed to a value (see appendix for detailed tables). In green brackets, an example from a B horizon in Rougemont has been added (own figure).

2.4 Selected climatic variables

The climatic parameters for the statistical evaluation are based on the daymetCH dataset. It was calculated by the Land Change Science group of the WSL with the methodology by Thornton et al. (1997) and the primary data available from the Federal Office of Meteorology and Climatology MeteoSwiss. The variables (temperature and precipitation) are provided daily with a spatial resolution of 100m and cover the time frame from 1930 to 2022. The temperatures represent the given 2-meter air temperature, and the precipitation includes all forms converted to water equivalent.

A feasible way of including a long-term precipitation effect on the growth of trees was conducted by calculating the total **precipitation** during the growing period in a year (prcp), which lasts from the beginning of April until the end of October.

A straightforward method of incorporating drought effects is calculating the maximum number of consecutive **dry days** (cdd) per year, where daily precipitation does not exceed 1mm (Frich et al., 2002). It was used to describe the likelihood of experiencing droughts in a given year and represents the longest drought in a year.

In Switzerland, heatwave days are typically defined when the daily maximum temperature exceeds 30 °C (Federal Office of Meteorology and Climatology MeteoSwiss, n.d.). However, because the monitoring plots lie at an increased elevation of 861 m to 1810 m above sea level, which is a colder environment than considered normal, the threshold was lowered to 28 °C. The **heatwave days** (tmax28) are the total number of days within a year where the maximum temperature exceeds 28 °C.

As the inventories were conducted several years apart, all climatic parameters were averaged between two consecutive inventories to obtain a single value for each inventory. Over the whole observing period, three climatic extreme periods were detected, each lasting about 20 years. The climatic extreme periods are used to quantify the effects of low precipitation and high numbers of dry and heatwave days on forest vitality.

2.5 Forest vitality

The data used for the forest vitality assessment is provided by the EFM project. The large-scale experiment supplies data on tree and stand-related growth parameters. Since the beginning of the 20th century, the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, has been collecting growth and yield data on forest and tree dynamics. The EFM project, whose concept has altered little to date, provides empirical data to study forest development. To cover many different management strategies, 495 monitoring plots are active and maintained by the WSL (Forrester et al., 2019).

The plots are measured every five to twelve years, recording growth rate, stand age and research objectives. Usually, all plots are installed on relatively homogeneous site conditions without forest roads or paths. All trees above the caliper cut-off size of 7.5 cm within the plot area and the surrounding buffer of 5 m are identified and measured, including species, diameter at breast height, relative crown length, social position within the stand and more. From the diameter at breast height the **basal area increment** (BAI) has been derived by the EFM team. Similarly, the quadratic mean diameter (QMD), the average tree basal area, was used to characterize the tree size distribution within a stand (Bettinger et al., 2017). For the single tree crown analysis, the basal area of larger trees (BAL) indicated the size of that tree in comparison with the

other trees of that stand and was calculated explicitly for each single tree as the sum of the basal area of all larger trees of the entire plot.

The long-term project’s thinning events have a major impact on the data. Thinning within the plots is always selective, based on tree criteria rather than geometric. It takes into account the tree’s social status, the vitality of the crowns, and the stem quality. Crop trees are evenly spread over the plot. The BAI of the thinned trees is accounted for in the stand’s BAI.

2.5.1 Basal area increment per stand

The basal area increment (BAI) per stand, is defined as the sum of the increments of all trees during the period divided by the length of the period and scaled to a per-hectare basis (Forrester et al., 2019). The EFM team calculated the basic measurement, including the measurements from all trees with a diameter at breast height higher than 7.5 cm for each plot and each species separately. The dataset consists mainly of the two species *Picea abies* and *Abies alba*. Because of the poor data size, *Fagus sylvatica* has not been further investigated. For the two other species, the adjusted basal area increment (BAI_{adj}) has been calculated by adjusting the BAI according to the proportion of the respective species (specProp) in the stand. In other words, it represents the BAI of a simulated stand consisting solely of the focused species, with no other species present. The purpose was to make stands with different species proportions more comparable.

2.5.2 Crown volume change per tree

For the crown volume, the calculations were likewise made using tree data from the EFM project. Within the project, they used allometric equations to estimate the crown radius and length. Using the species-specific parameters (a, b, c and d) and the species-specific equations proposed by Pretzsch (2009) the different crown shapes have been calculated. The crown volume was derivated with the help of integral equations of the two crown shape functions (Equation 3). Crowns are not always circular and their structure depends on site characteristics. The position within the forest, solar exposure, wind conditions and slope influence the shape of a crown. Nevertheless, for simplicity, the individual shapes were neglected and a uniform round shape for the crown was assumed for all trees. According to Pretzsch (2009), the tree crown was separated into an upper, sunlit part and a lower, shaded part. Each contains its separate function. The biometric reproduction of the crown parameter is done using a function that depends on the crown radius. The crown radii (r_0) for the sunlit part are calculated as a function of the distance ($dist$) from the top of the tree, with the individual tree parameter a and the species-specific exponent b :

$$r_0 = a \cdot dist^b \quad (1)$$

The shaded crown radii (r_u) were calculated using a linear equation based on the distance ($dist$) from the top of the tree with the individual tree parameters c and d :

$$r_u = c + dist \cdot d \quad (2)$$

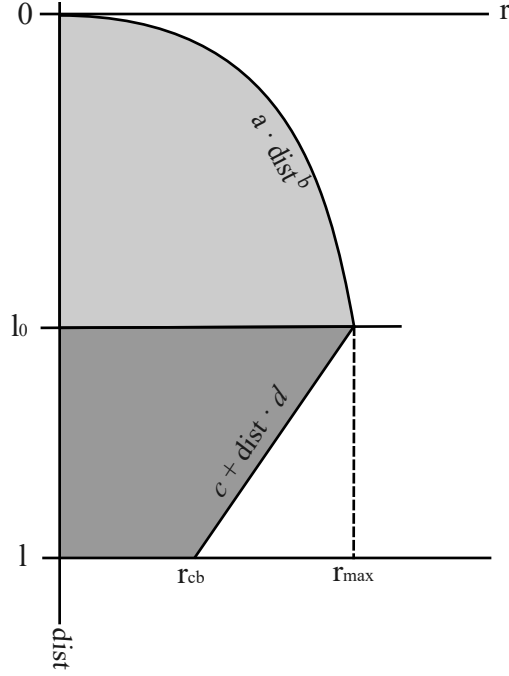


Figure 8: Visual representation of the sunlit crown function 1 and the shaded crown function 2, that give us the vertical half of the two-dimensional shape of a tree crown. For a more precise visualization, the diagram was flipped by 90° following the shape of a standing tree. Keep in mind that the response variable is r and the explanatory variable is $dist$ (adapted from Pretzsch, 2009).

In Figure 8, the two functions meet at the radius maximum l_0/r_{max} . The volume was calculated by adding the two integral, from 0 to l_0 and l_0 to l , of the rotational body spanned by the respective functions, with the $dist$ axis:

$$V = \int_0^{l_0} \pi \cdot (a \cdot dist^b)^2 d dist + \int_{l_0}^l \pi \cdot (c + dist \cdot d)^2 d dist \quad (3)$$

The species-specific parameters determine the shape of the crown. The shape is given in Figure 9 for the six most important tree species. The shape and volume have been calculated with the given parameters and equation 3.

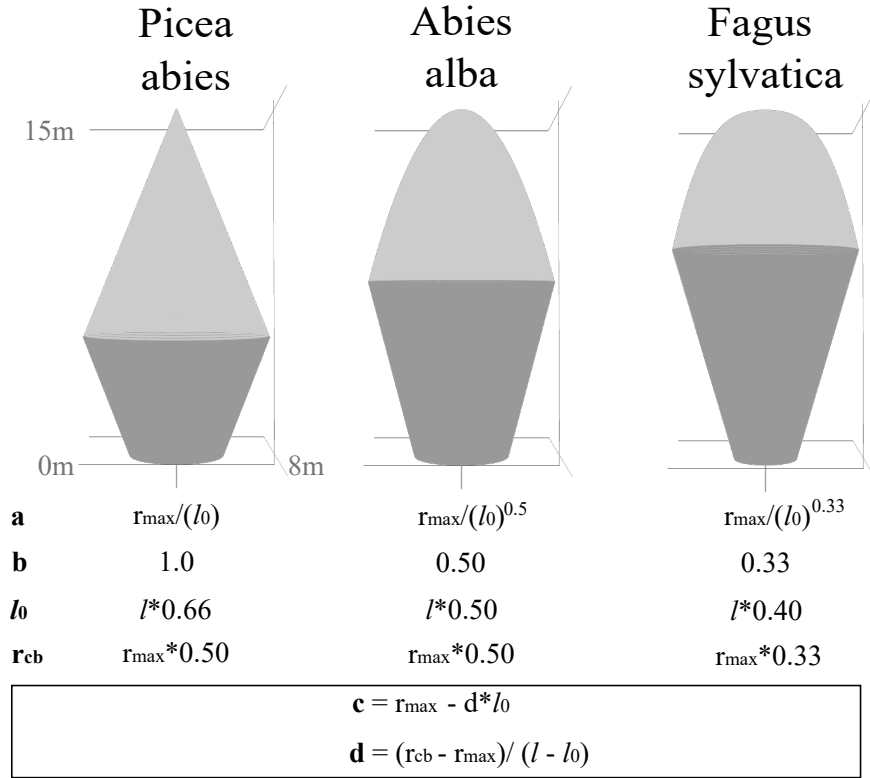


Figure 9: The shapes and the parameters according to Pretzsch (2009) of the three most important tree species in Swiss plenter forests, with decreasing abundance from left to right (Abegg et al., 2023e). Each shape was calculated using a crown length of 15m and a crown diameter of 8m to represent the individuality of the different species (own figure).

The **delta crown volume** per year (DCV) has been calculated from the crown volume. It can be derived by dividing the crown volume of a specific tree by the length of the observation period. There were many data points for DCV (155088). To show the differences between plots and AWC, distribution shapes were visualized. The shapes were calculated using the ggridges package (Wilke, 2017) and represent the number of trees with a certain DCV for a given AWC. The package uses kernel density estimation to visualize the probability density function of a continuous variable.

2.6 Statistical evaluation

Like the distribution shapes, all other visualizations, calculations, and modeling procedures were done using the R software v4.3.1 (R Core Team, 2024). The data was manipulated with the dplyr package (Wickham et al., n.d.) and then edited with the ggplot2 package (Wickham, 2016) to obtain graphs.

To ensure data quality, values identified as outliers were excluded from the analysis. The two plots in Sigriswil (21293001 and 21293002) had extreme values due to very high stone content, which made their AWC calculations extraordinarily low and incomparable.

Due to time constraints, the plot in Le Chenit (21294000) was not inventoried. To use only the historical measurement was discarded, as the AWC value was unrealistically high and was therefore considered unreliable. So, it was excluded from the dataset. From the original 20 plots, 17 were used for the analysis.

The fixed effects and interactions were selected based on the contemporary scientific background. The significance of variables was tested using the analysis of variance (ANOVA) with a chi-square (χ^2) test to determine their association with the respective vitality variable. The p-value was used as an indicator of significance. Additionally, the standard error was calculated for the fixed effects, except for the interaction terms where only the χ^2 test has been done. The mixed linear model (Equation 4) used the adjusted BAI (BAI_{adj}) as the response variable, representing the growth rate of a plot over time. As fixed effects were used, the AWC, the *time* variable, the interaction of *precipitation* (prcp) with AWC, the interaction of *dry days* (cdd) with AWC, and the *heatwave days* (tmax28). Secondary factors – the respective *species proportion* (specProp), the *elevation* and the *quadratic mean diameter* (QMD) – were also included. The random effects were on the plot level. For the *Picea abies* model, plots that had a smaller *Picea abies* proportion than 20 % were neglected for the modeling because of a disturbing sample size effect, as the variability of growth was regarded high within plots of smaller proportion. All plots have been used for the *Abies alba* model, as no sample size effect was detected with a lower proportion.

$$BAI_{adj} = \beta_0 + \beta_1 \text{time} + \beta_2 \text{QMD} + \beta_3 \text{specProp} + \beta_4 \text{elevation} + \beta_5 \text{tmax28} \\ + \beta_6 (\text{AWC} \times \text{cdd}) + \beta_7 (\text{AWC} \times \text{prcp}) + u_{\text{plot}} + \epsilon \quad (4)$$

The linear mixed effect models were fitted using a Gaussian distribution, a log-link function and the R package glmmTMB (Brooks et al., 2017). The model correctness and distributional assumptions were validated using the R package DHARMA (Hartig, 2024).

The linear mixed effect models for the DCV analysis were based on the same fixed effects as the BAI model, but instead of the QMD, the basal area of larger trees (BAL) was used. For the tree-specific analysis of *Fagus sylvatica* specProp was neglected due to missing data. Further, for the analysis of *Abies alba*, plot 21290000 was excluded as it was a transition forest plot with mainly *Picea abies* on it. The DCV distribution was not normal but right-skewed. As glmmTMB could not handle a right-skewed normal distribution, a Gaussian normal distribution was used, aware of the deficiency.

$$DCV = \beta_0 + \beta_1 \text{time} + \beta_2 \text{BAL} + \beta_3 \text{specProp} + \beta_4 \text{elevation} + \beta_5 \text{tmax28} \\ + \beta_6 (\text{AWC} \times \text{cdd}) + \beta_7 (\text{AWC} \times \text{prcp}) + u_{\text{plot}} + u_{\text{TreeNo}} + \epsilon \quad (5)$$

3 Results

3.1 Available water holding capacity

Altogether, in the 1 m deep soil, the AWC calculations reached from 124.1 mm to 260.3 mm. The plots 21293001, 21293002 and 21294000 stand out through strongly differing values and were therefore neglected for further analysis (see Section 2.6 and Figure 10). The average within-plot standard deviation was 34.4 mm and the between-plot standard deviation was 29.7 mm.

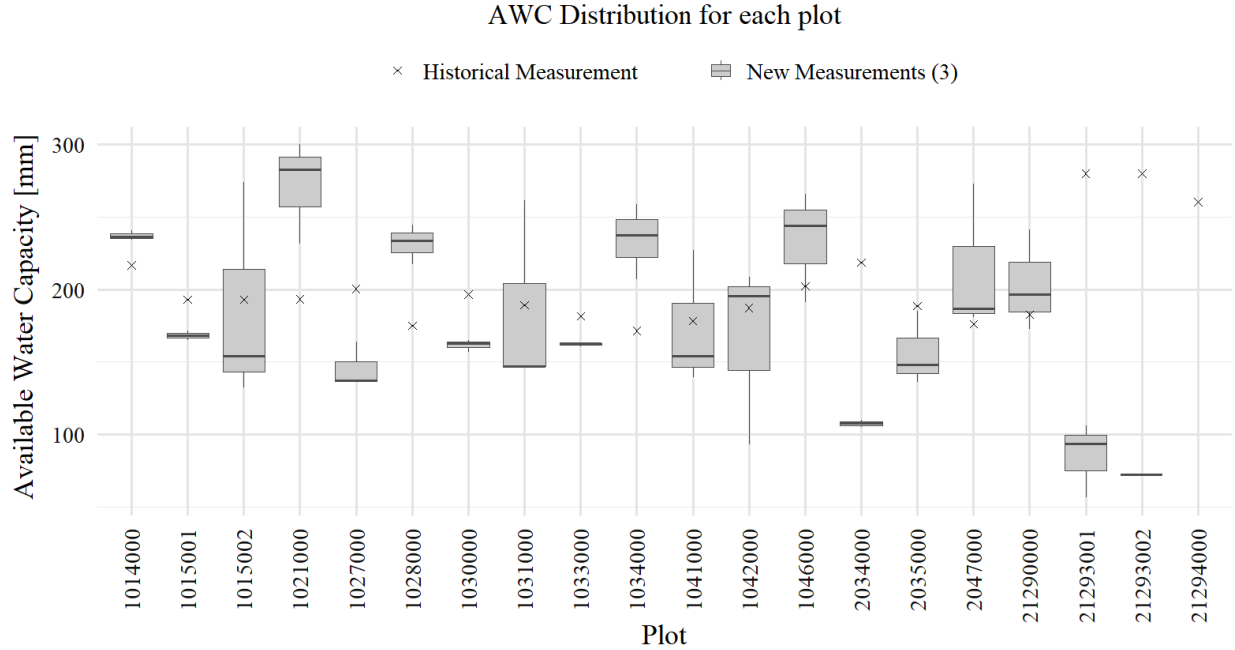


Figure 10: The variation of the three measurements per plot in a boxplot. Additionally, the star shows the historical measurement at the beginning of the 20th century. The standard deviation within a plot, including all measurements, reaches from 10.6 in 1014000 to 147 in 21293002 (own figure).

Table 3: AWC measurements of the 20 plots, the results are graphically represented in Figure 10.

Name	Plot	Historical	Measurement 1	Measurement 2	Measurement 3	Mean
*Oberhuenigen 1	1014000	217	235	241	237	233
Niederhuenigen 1	1015001	193	165	169	172	175
Niederhuenigen 2	1015002	193	133	154	274	189
Oberhuenigen 2	1021000	194	301	283	232	252
Bowil 1	1027000	201	164	137	138	160
Bowil 2	1028000	176	218	234	245	218
Lauperswil	1030000	197	163	157	165	171
Landiswil 1	1031000	190	262	147	147	187
St. Moritz 1	1033000	182	163	161	163	167
St. Moritz 2	1034000	172	259	238	208	219
Rougemont 1	1041000	179	154	140	228	175
Rougemont 2	1042000	188	196	209	92	171
Oberlangenegg	1046000	203	245	266	192	226
*Buttes 1	2034000	219	105	111		145
Buttes 2	2035000	189	186	149	137	165
Röthenbach	2047000	177	273	181	187	205
*Landiswil 2	21290000	183	242	173	197	199
**Sigriswil 1	21293001	280	94	57	107	134
**Sigriswil 2	21293002	280	73			177
**Le Chenit	21294000	261				261

The plots marked with a * are transition plots

The plots marked with a ** are not used for the statistical analysis

3.2 Selected climatic variables

Over the whole study period from 1930 to 2020, no clear overall trend was observed in the climatic factors. While mean precipitation has slightly decreased since the 1990s, its fluctuating pattern stayed relatively constant over the whole period (Figure 11). However, the number of dry days followed a cyclic pattern, repeating every 30 years, whereas the number of heatwave days did not exhibit a specific trend.

When the three parameters overlap, they can cause periods of extreme climatic conditions. Between 1945 and 1960 (period '45), the parameters reached their most extreme values, with cdd over 35 d and tmax28 reaching nearly 20 d. During the same time, very low precipitation values were recorded, with the lowest being under 600 mm. A similar pattern is visible in the years 1975 to 1990 (period '75) and again from 2003 to 2023 (period '03).

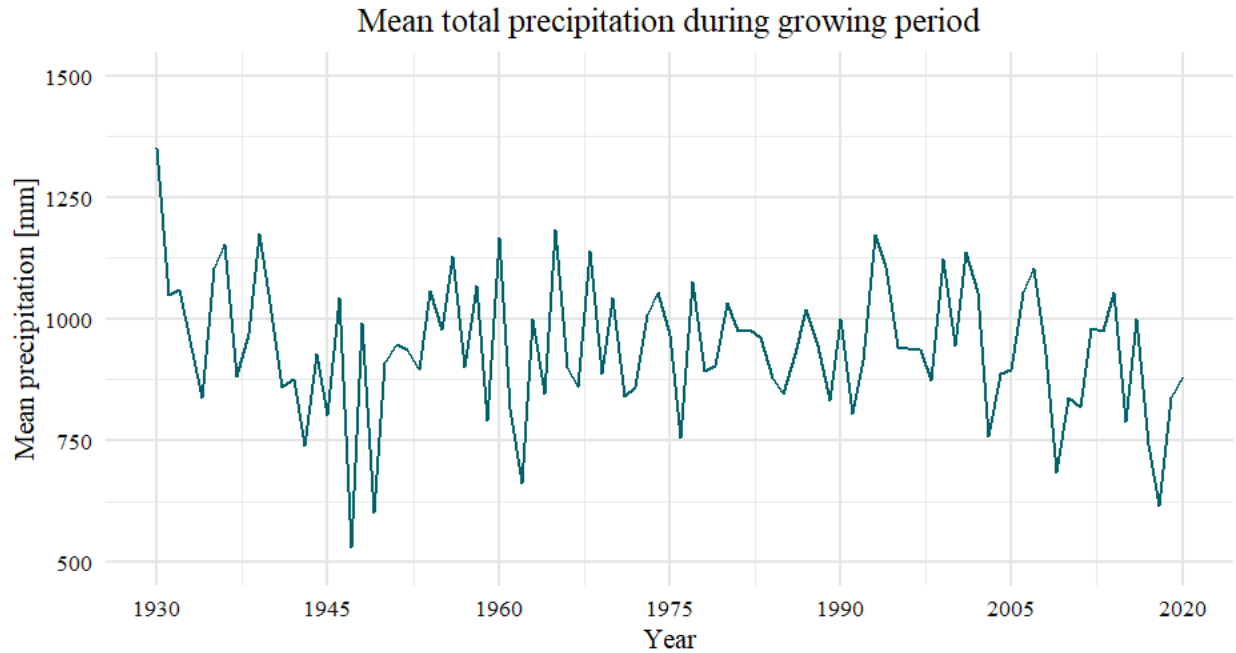


Figure 11: Mean total precipitation across all plots during the growing season, from April to October (overall mean = 947mm). It shows highly fluctuating differences between most consecutive years (own figure).

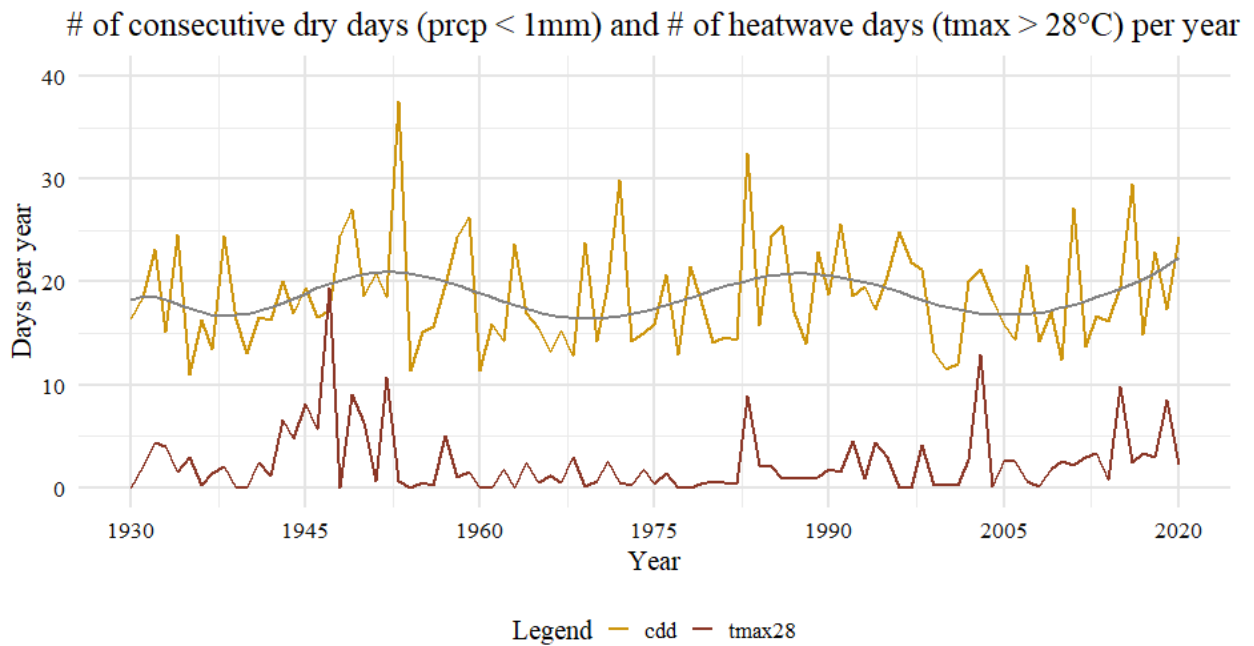


Figure 12: Mean total number of heatwave days (tmax28) and the mean maximum number of consecutive dry days (cdd) per year across all plots (overall mean: tmax28 = 3 d, cdd = 18 d). A trend line was added to the pattern of cdd, revealing a 30-year recurring cycle (own figure).

3.3 Forest vitality

3.3.1 Basal area increment per stand

The stands had more or less the same basal area, except plot 1030000, which showed 3 times higher basal area per hectare because of its giant trees and special management. *Picea abies* was the most abundant species, followed right after by *Abies alba* and *Fagus sylvatica*, which had a very low proportion compared to the other two main species (Figure 13).

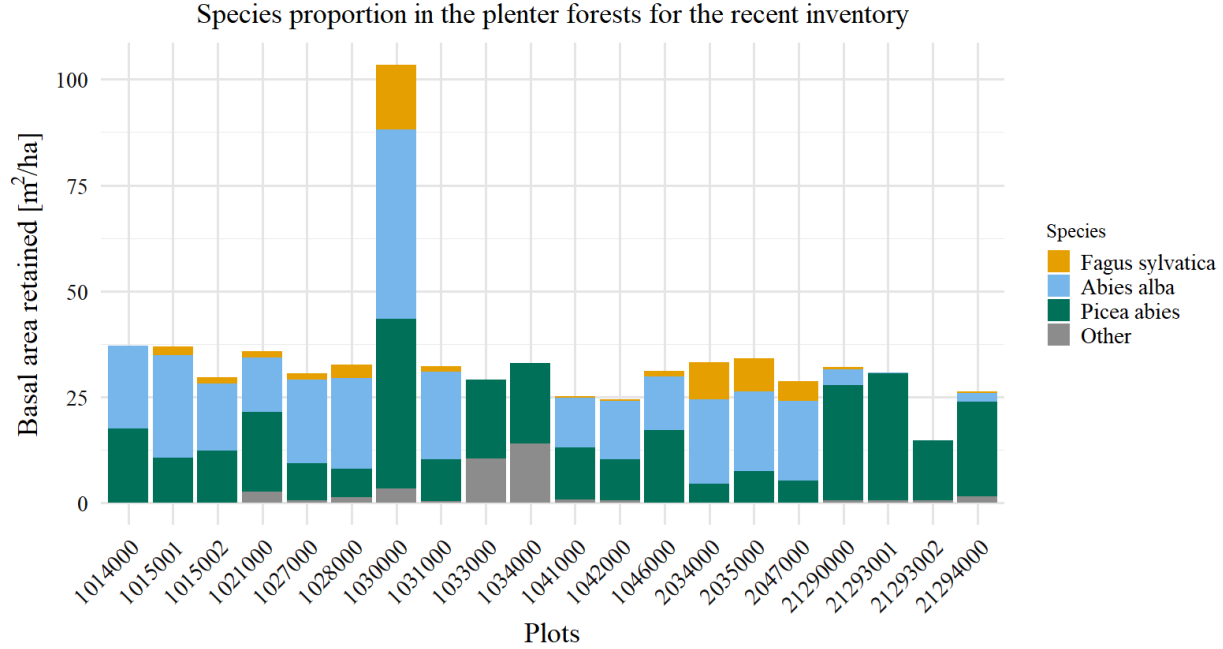


Figure 13: The basal area per hectare of each species in the respective plots from the last monitoring period 2013-2022 (except 1014000, last measured in 1977). The main species were *Picea abies*, *Abies alba* and *Fagus sylvatica* (own figure).

Model

The data points in Figure 14 did not give any visual hint on a specific pattern regarding the interaction between BAI_{adj} and AWC. From the fitted models (one for each species according to Equation 4), predicted values for BAI_{adj} were calculated for three input-values of respectively AWC (150, 200 and 250) and time (1940, 1975, 2010), while the other covariates were held constant at their mean values and the species proportion was set to 50 %. The BAI increased for both species with higher time and AWC values (Table 4). The AWC calculations were not significant in terms of p-value. Likewise, the covariable elevation was also not significant.

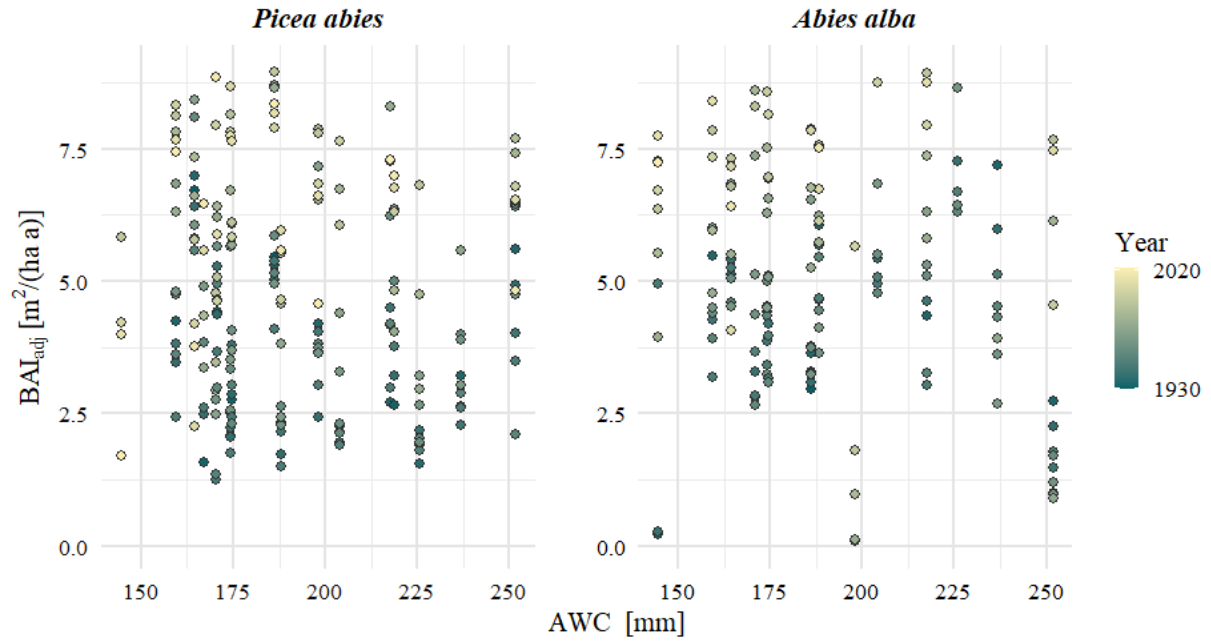


Figure 14: Each species and its respective BAI_{adj} values for each AWC over time. A BAI increase over time is observed (own figure).

Table 4: Estimated BAI_{adj} for given AWC and time values

Year	AWC [mm]	BAI _{adj} [m ² /(ha a)]	
		<i>Picea abies</i>	<i>Abies alba</i>
1940	150	3.19	2.93
	200	3.43	3.91
	250	3.68	4.89
1975	150	5.33	5.53
	200	5.58	6.51
	250	5.82	7.49
2010	150	7.48	8.13
	200	7.72	9.11
	250	7.97	10.09

Other covariates were set to the mean:

prcp = 947 mm , tmax28 = 3 d, cdd = 18 d,
elevation = 1064 m ASL, QMD = 27.05 cm,
specProp = 50 %

Significant covariables were species proportion, quadratic mean diameter (QMD), and time. Both models showed the same results. The p-value (p) and standard error (SE) for the respective species model are shown in brackets. They indicated for species proportion (*Abies* p = 0.04, SE = 0.035; *Picea* p = 0.10, SE = 0.016), a BAI increase with increasing *Abies alba* abundance, respectively decreasing *Picea abies* abundance. Also, smaller QMD (*Abies* p < 0.001, SE = 0.029; *Picea* p = 0.01, SE = 0.017) led to an increase in BAI. The significant covariable time (*Abies* p < 0.001, SE = 0.006; *Picea* p < 0.001, SE = 0.005) showed a clear temporal BAI increase, which was visible in Figure 14.

The climatic factors were different for the two models. The heatwave indicator tmax28 was not significant at all. Adding the interaction between prcp and AWC was only significant for *Picea abies* (p = 0.008) and showed that BAI increases with increased precipitation. Under low precipitation, the effect of AWC on BAI was smaller than under high precipitation. However, there was only a slight difference in the interaction of different AWC values. Adding the interaction between cdd and AWC was not significant. However, it suggested for *Picea abies* (p = 0.17) a trend in an unexpected direction, that with higher cdd, the effect of AWC was negative on the BAI_{adj}, as with low cdd, it is positive. Nevertheless, overall BAI_{adj} increased with higher precipitation, but curiously for *Picea abies* BAI_{adj} decreased with higher AWC (Figure 5).

Table 5: Estimated BAI_{adj} for different climatic factors

AWC	prcp	cdd	BAI_{adj} [$\text{m}^2/(\text{ha a})$]	
[mm]	[mm]	[d]	<i>Picea abies</i>	<i>Abies alba</i>
150	600	15	3.10	3.17
250	600	15	3.76	6.16
150	1200	15	6.14	6.64
250	1200	15	6.90	7.81
150	600	35	6.01	5.34
250	600	35	5.27	8.44
150	1200	35	9.05	8.81
250	1200	35	8.41	10.10
Other covariates were set to the mean as before and the year to 1975				

The following two figures present four plot groups, each containing the temporal change in BAI_{adj} for two neighboring plots with different AWC (except Rougemont, which has very similar AWC). Each plot group had a different change in BAI_{adj} and reacted differently during the three extreme periods. The BAI_{adj} change showed no clear difference between two neighboring plots for *Abies alba*, but *Picea abies* plots with higher AWC showed higher BAI_{adj} . Plots with higher AWC had a less severe decline during the visible extreme periods ('45, '75, '03). During period '45, three out of four plot groups had a substantial reduction in BAI_{adj} for *Picea abies*. In the two plot groups Hünigen (Ober- and Niederhünigen) and St. Moritz, the plot with higher AWC (marked with blue triangles) had less reduction in BAI_{adj} during the period '45. Thirty years later, the extreme period '75 reduced BAI_{adj} in St. Moritz and Bowil, while Hünigen showed an increase and Rougemont stayed constant. In period '03, all except for St. Moritz had a decrease in BAI_{adj} , whereas St. Moritz has shown a flattening curve over the last twenty years. The two plots in Rougemont, with only minor AWC differences, showed a similar BAI_{adj} .

Abies alba

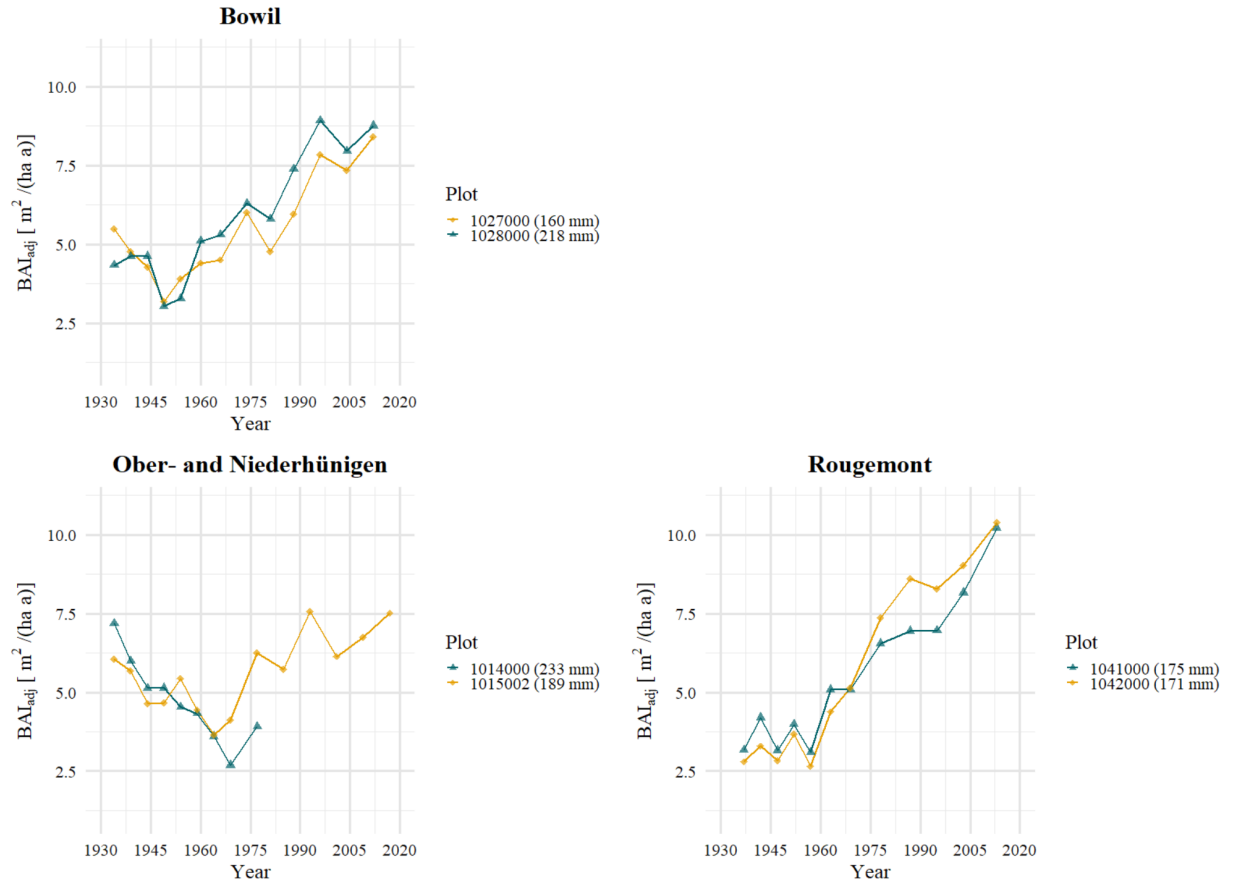


Figure 15: The change of BAI_{adj} of *Abies alba* for comparable plots. *Abies alba* is absent in St. Moritz. Blue triangles mark plots with high AWC and yellow squares with low AWC. The respective AWC values are in parentheses. The plot groups are ordered according to their AWC differences in decreasing order (own figure).

Picea abies

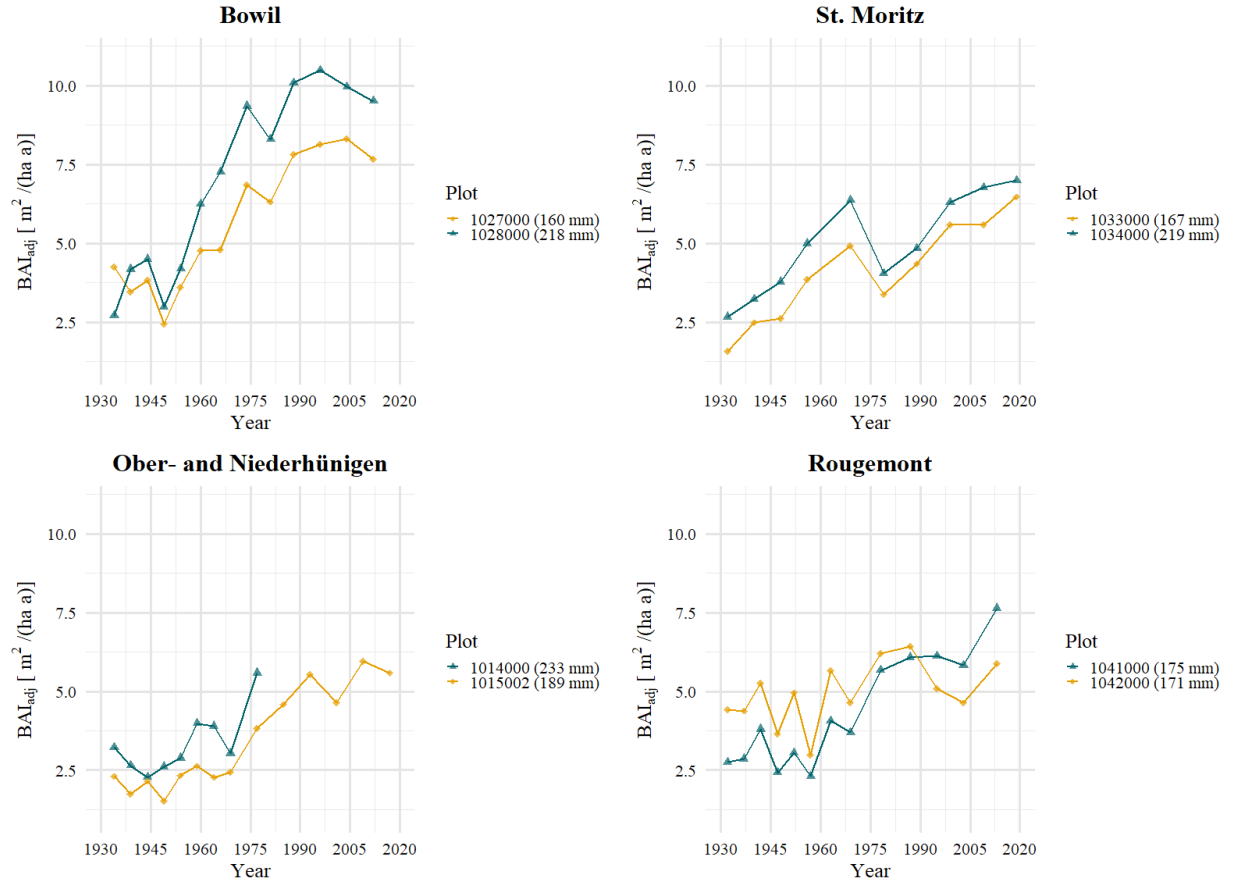


Figure 16: The change of BAI_{adj} of *Picea abies* for comparable plots. The plot with high AWC is marked with blue triangles, while the lower AWC is represented in yellow squares. The respective AWC values are indicated in parentheses (own figure).

3.3.2 Crown volume change per tree

The change in tree crown volume (DCV) ranged between positive and negative. In Figure 17, DCV is depicted for all stands, which are shown according to their AWC on the y-axis and for each species. There were only slight differences in DCV, and in contrast to BAI_{adj} , no temporal change can be seen. Whereas *Abies alba* and *Fagus sylvatica* did not show significant changes in DCV, *Picea abies* indicated a slight increase in DCV with higher AWC.

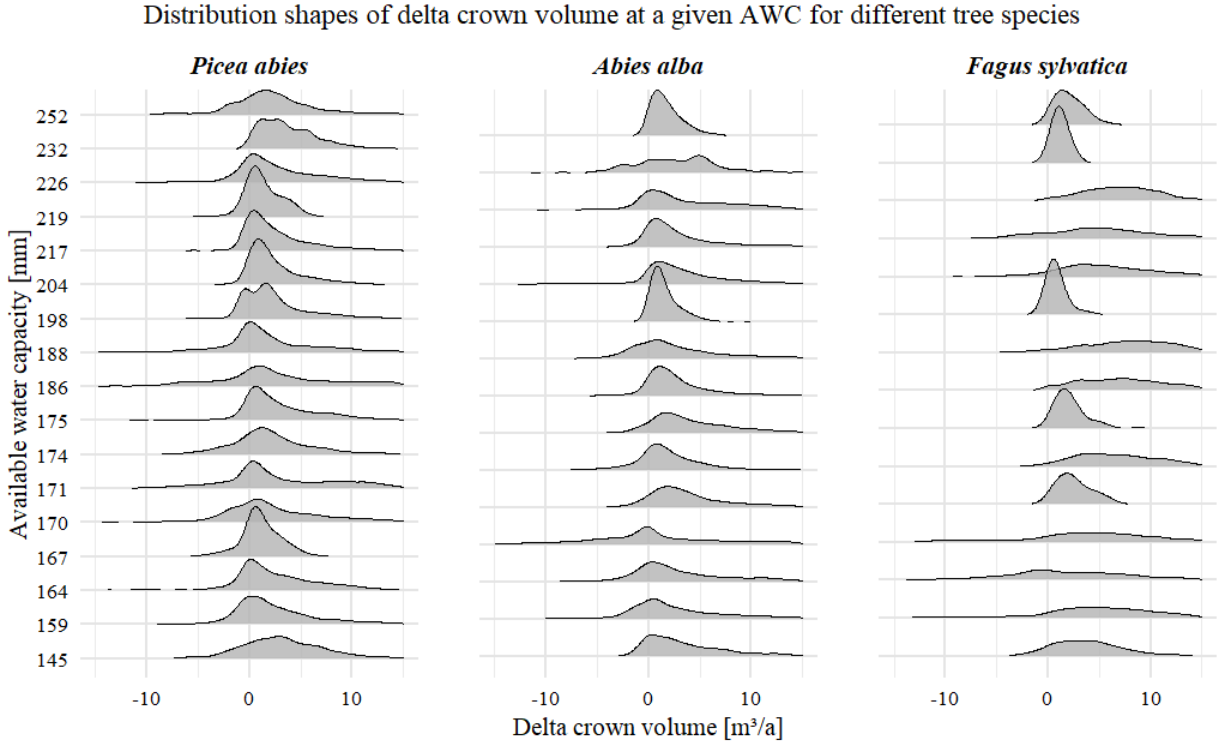


Figure 17: The Distribution shapes of DCV for the three main tree species in plenter forests (own figure).

Model

Similarly to BAI_{adj} , the DCV values were estimated using the species-specific models (according to Equation 5). The model showed a decrease of individual tree DCV with increasing AWC (*Fagus* $p = 0.004$; *Abies* $p < 0.001$; *Picea* $p < 0.001$). But over time (*Abies* < 0.001 , $SE = 0.001$; *Picea* $p < 0.001$, $SE =$) DCV increased similarly to BAI_{adj} for *Picea abies* and *Abies alba*. *Fagus sylvatica* was not significant in terms of temporal change (Table 6).

The other covariables – BAL, species proportion and climatic factors – were significant for *Picea abies*, whereas the other two species had exceptions. The principal factor was BAL, as it indicated the highest significance for all species (*Fagus* $p < 0.001$, $SE = 0.008$; *Abies* $p < 0.001$, $SE = 0.001$; *Picea* $p < 0.001$, $SE = 0.001$). A higher BAL value caused a decrease in DCV. Regarding species proportion (*Picea* $p = 0.053$, $SE = 0.024$), it was determined that there was a significant increase in DCV with increasing *Abies alba* abundance and decreasing *Picea abies* abundance. It was significant only for *Picea abies* (no species proportion was included in the *Fagus sylvatica* model). Also, the elevation was significant for *Picea abies* ($p = 0.009$, $SE =$

Table 6: Estimated DCV for given AWC and time values

Year	AWC [mm]	DCV [m ³ /a]		
		<i>Picea abies</i>	<i>Abies alba</i>	<i>Fagus sylvatica</i>
1940	150	1.40	3.69	8.14
	200	1.11	1.63	4.06
	250	0.81	-0.42	-0.02
1975	150	2.06	4.71	8.08
	200	1.77	2.65	4.00
	250	1.48	0.60	-0.08
2010	150	2.73	5.73	8.02
	200	2.43	3.67	3.94
	250	2.14	1.61	-0.14

Other covariates were set to the mean:

prcp = 946 mm , tmax28 = 3 d, cdd = 18 d,

elevation = 1052 m ASL, BAL = 51.41 m², specProp = 50 %

0.001) and showed that with increasing elevation, DCV decreases. Elevation for *Fagus sylvatica* and *Abies alba* was not significant.

The *Picea abies* model is more affected by climatic factors than the *Abies alba* or the *Fagus sylvatica* model. The average precipitation per growing season showed an increase in DCV for all species with increasing precipitation ($p < 0.001$). For the *Picea abies*, higher AWC showed an increase in DCV during low prcp, whereas during high prcp it showed a decrease. For *Fagus sylvatica* the effect of AWC was also higher under high prcp, but *Abies alba* showed no clear differences. The cdd term was significant for all species (*Fagus* $p = 0.06$; *Abies* and *Picea* $p < 0.001$), it showed a decrease for *Fagus sylvatica* and an increase for the other two species in DCV, with increasing cdd.

The heatwave days factor was not significant for *Abies alba* ($p = 0.61$, $SE = 0.016$), but for *Fagus sylvatica* ($p < 0.001$, $SE = 0.048$) and *Picea abies* ($p < 0.001$, $SE = 0.013$). While the DCV of *Picea abies* decreased, the DCV of *Fagus sylvatica* increased with more heatwave days.

The effect of AWC was the highest during high precipitation (1200mm) and high cdd (35), as you can see in Table 7 rows 7-8 and 15-16.

Table 7: Estimated DCV for different climatic conditions

AWC	prep	cdd	tmax28	DCV [m ³ /a]		
[mm]	[mm]	[d]	[d]	<i>Picea abies</i>	<i>Abies alba</i>	<i>Fagus sylvatica</i>
150	600	15	3	-0.52	2.61	-0.17
250	600	15	3	4.30	2.68	-2.89
150	1200	15	3	2.80	4.35	17.06
250	1200	15	3	0.60	4.39	4.43
150	600	35	3	3.50	9.31	-10.30
250	600	35	3	0.01	-16.10	-11.35
150	1200	35	3	6.82	11.05	6.93
250	1200	35	3	-3.68	-14.39	-4.03
150	600	15	9	-2.25	2.66	1.33
250	600	15	9	2.57	2.73	-1.39
150	1200	15	9	1.07	4.40	18.57
250	1200	15	9	-1.12	4.44	5.93
150	600	35	9	1.78	9.35	-8.80
250	600	35	9	-1.71	-16.05	-9.84
150	1200	35	9	5.09	11.10	8.44
250	1200	35	9	-5.41	-14.34	-2.52

Other covariates were set to the mean as before and the year to 1975

To have a clearer look at the spatial and temporal patterns, the changes within the plot groups for each measurement period are depicted for the DCV for *Picea abies* in Figure 18.

The two plots in St. Moritz and Rougemont did not differ. At the sites in Bowil, plot 1028000 (higher AWC) had a slightly higher DCV between 1930 and 1954. In the following measurements, the two plots have nearly the same DCV. In Ober- and Niederhünigen, plot 1014000, which was measured only until 1977, showed a higher DCV in seven out of nine observations compared to plot 1015002, which has a smaller AWC.

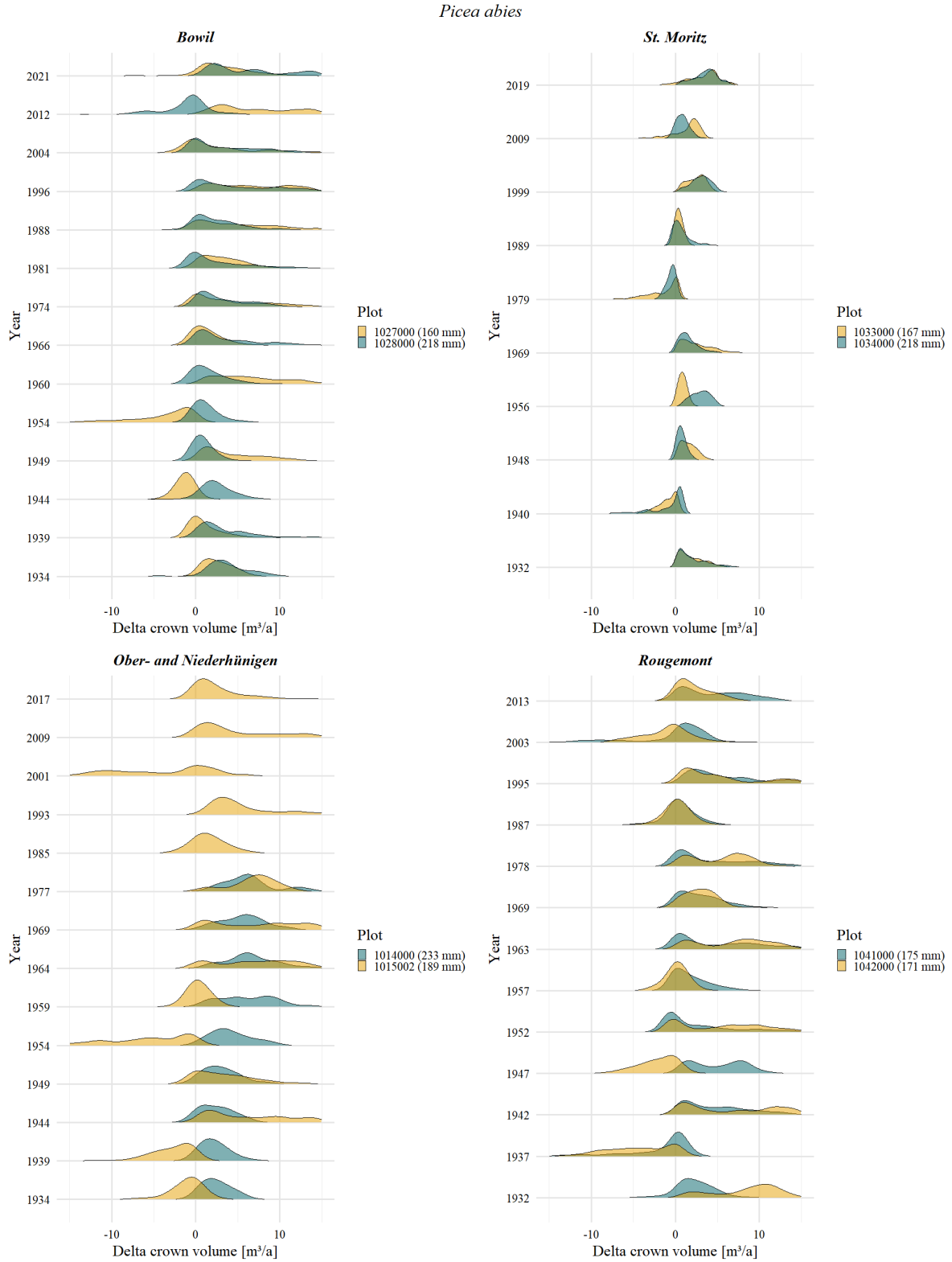


Figure 18: The Distribution shapes of the DCV for *Picea abies* on different plot groups (The plots for *Abies alba* and *Fagus sylvatica* are in the appendix as they did not show significant differences, own figure).

4 Discussion

According to the first geographic law by Tobler (1970) – ‘[...] near things are more related than distant things’ – neighboring plots seem to have more similar site conditions, such as elevation, climatic conditions, species composition, tree size distribution and change over time, than distant plots. All of the above-mentioned factors have been considered in the modeling. However, many other important environmental aspects could not be implemented into the modeling procedures because of time constraints and limitations. These include, among others, wind exposure, nutrient availability, slope gradient and aspect, terrain position, hydrological factors, such as proximity to streams or wetlands and disturbances like windthrows, forest fires, avalanches or diseases. Each would be a natural factor that can greatly impact the forest ecosystem and vitality when occurring.

Additionally, human-driven factors tend to be less variable across neighboring plots. The same forestry district typically manages neighboring plots. Therefore, differences in management strategies are relatively low and the plenter principles have been implemented similarly. Based on scientific principles, every plenter forest should have the same structure (Schütz, 2001), but there are still significant differences in how individual foresters handle plenter forests. Management differences between foresters can occur and influence silvigenesis. Furthermore, neighboring plots are measured by the same scientific team within the same year, which minimizes experimental variability and reduces potential bias. The management design alters the silvigenesis and the forest structure.

The naturally diverse setting and the human-driven aspects are likely the reasons the modeling approach reached its limits. The high heterogeneity of the plots explains the very low significance of the variables in the BAI models. The differences between the plots are too high within the model, leading to less meaningful results for the important factors. It is doubtful that the difference in forest vitality would be too small to be noticed by the model, as the differences between the plot groups in Figure 16 are visible for *Picea abies*. On the neighboring plots, different vitality developments seem plausible, based on AWC, as other factors are very similar. To pursue this further, a paired t-test would quantify the differences between the plots in each plot group, even though it cannot account for variation at the plot level.

Besides the naturally diverse setting, the model assumptions could also be a source of error. For the DCV analysis, the crown volume calculation was too simplified and the distribution deviated from the model assumptions, following a right-skewed distribution instead of a normal distribution. But, it had to be modeled with a normal distribution, leading to certain errors. Further, to improve the selection of covariables a principal component analysis would have reduced complexity and compressed redundant variables.

Variation also plays a role in the AWC calculations, as the standard deviation within plots was higher than between plots. AWC varies considerably within individual plots. The study by Longchamps et al. (2015) demonstrated that even in leveled, homogeneous agricultural areas, soil water content has a very high spatial variability on a small scale, especially near the surface. They state that 87 % of locations within a plot have a soil water content that differs significantly from the mean of that plot. In essence, relatively small and seemingly homogeneous areas can already have a heterogeneous distribution of soil water content. The obtained AWC values may not accurately represent the water availability, as the skeleton content was difficult to determine. Also, the plots were heterogeneous and only a single, relatively small soil profile was dug. More frequent and denser measurements containing more soil profiles at each plot would be necessary to better quantify AWC and its distribution on the plot level.

4.1 Forest growth driven by climate, human disturbances and stand structure

Forest growth and vitality have increased over time, driven by various environmental factors. Similar to the findings by Van Der Bauwhede et al. (2024), a significant increase in BAI has been observed over the last five decades for *Picea abies* and *Abies alba*. According to Cienciala et al. (2018), the most important environmental factors influencing tree growth are spring air temperature, precipitation, CO₂ concentration, and nitrogen deposition during the growing period. Since the pre-industrial period in the 19th century, the mean temperature in Switzerland has increased by approximately 2.9 °C as of 2025 (Federal Office of Meteorology and Climatology MeteoSwiss, 2025a). Mountain areas are strongly affected by the changes. A 3.5 times larger temperature rise than the corresponding northern hemisphere temperature rise was observed in the European Alps (Lamprecht et al., 2018). Climate change has increasingly affected environmental conditions and has, in some ways, improved tree growth conditions.

As the BAI model included the precipitation, the other three factors – spring air temperature, CO₂ concentration and nitrogen deposition – play a crucial role in explaining the effect of the time covariable. Even though temperature indicators have already been added to the model in the form of heatwave days, a suitable temperature index for the spring season, which also includes temperatures below the freezing point, has not been implemented. The same holds for a prolongation of the growing season, which was not included. Further CO₂ fertilization and nitrogen deposition are decisive factors that increase photosynthesis and C-fixation, resulting in higher basal growth (Etzold et al., 2020; Silva et al., 2016). The increase in BAI over the last century is most likely related to higher temperatures, longer growing seasons, CO₂ fertilization and nitrogen deposition.

Besides the natural impacts, the anthropogenic pressure changed over time and affected forest growth. Overall, the exploitation of forests decreased enormously in the last century. Particularly during harsh years of the Second World War or longer dry periods, food and forage for livestock were limited, and people increasingly used the resources provided by the forest. Foliage, fir cones, branches and everything else the forest could offer were used and extracted from the forest. The forest ecosystem was disturbed and nutrient cycles were slowed, limiting availability. In the second half of the 20th century, the Swiss population's pressures decreased, contributing to the BAI (Stuber and Bürgi, 2012).

The modeling output for BAI showed that a stand's overall tree size distribution plays a crucial role in its BAI. A low quadratic mean diameter (QMD) indicates a higher BAI. Consequently, stands with many small trees grow more in the basal area than stands with many large trees. Although the scientific principles of plenter forest dynamics dictate similar tree age and size distribution per area across time, the current state reveals discrepancies. A study of uneven-aged forests in Romania has reached a similar conclusion, that the QMD of a stand influences its BAI by showing that trees with a smaller diameter at breast height experience a higher BAI (Ciceu et al., 2022). This phenomenon is attributed to increased relative resource allocation and reduced hydraulic limitations in smaller trees because of higher resource investment into growth and easier water transport (Rötzer and Pretzsch, 2013; Ryan and Yoder, 1997).

Paluch and Jastrzębski (2023) found the opposite in natural stand dynamics, where increased BAI on a single tree level for *Picea abies* with larger diameter at breast height was documented. When young trees do not have sufficient space, their growth is limited (Drobyshev and Nihlgård, 2000). Only through waiting and years of development do they attain the required space and, consequently, begin to exhibit accelerated growth in response to sunlight exposure (Collet et al., 2001). The difference between BAI on the observed plenter

stands with different quadratic mean diameters is due to the number of trees and tree size distribution, which depends on the canopy opening. A given area can fit more small trees than large trees. The number of trees outplays the single tree basal area. Therefore, stands with smaller trees and a well-balanced canopy experience more growth. The stand differences align with Forrester (2019), who emphasized the crucial role of tree size distribution on forest growth.

Apart from tree size, the tree species is important for the BAI. The species composition showed lower growth rates with a high *Picea abies* abundance and a low *Abies alba* abundance. *Abies alba* had a higher diameter growth on the plenter forest plots. In old forests driven by natural stand dynamics, *Abies alba* grows slightly faster than *Picea abies*. It reached the upper canopy with a diameter at breast height of 40 cm after 137 years, 13 years earlier than *Picea abies* according to a study in the Western Carpathians (Paluch and Jastrzębski, 2023). However, they also state that the history of release events through canopy opening is the primary reason for tree growth, not tree age. The lower growth of *Picea abies* in Swiss plenter forests could be related to another reason.

Lebourgeois (2007) showed that the growth variation of the two species is different. A decrease in diameter growth of *Picea abies* is related to summer water deficits during the current growing season, suggesting that its growth responds directly to current moisture availability. In contrast, *Abies alba* is more influenced by weather conditions from the previous growing season, indicating a lagged growth response. These sensitivity differences result in different growth phases for *Picea abies* and *Abies alba* over the observed period. Overall, the temporal growth variations of the two different species are more important than overall spatial and weather variations (Lebourgeois, 2007).

Even though the BAI model shows significant results for only a single climatic covariable (precipitation), the others might still influence forest growth. As shown in Figure 16, the BAI for *Picea abies* stands on eight plots showed an apparent decline during the respective extreme climatic periods ('45, '75, '03,) including heatwaves and dry periods. The BAI decline during the extreme climatic period showed itself in different years with varying intensity for each plot group. Unlike the other plot groups, the plots in St. Moritz showed a relatively stable BAI, declining only in period '75.

In contrast, the other groups only slightly declined during that period. The reason behind the different vitality at the plots in St Moritz is because St. Moritz was the highest location in the study at an elevation of 1810 m in a high mountain-influenced area, which was spared from challenges provoked in the rest of the country.

Another reason is the location in the Eastern Alps of Switzerland. St Moritz was the only plot group measured in eastern Switzerland, whereas the other plot groups were located in western regions. Further, St. Moritz consists of only *Picea abies* and other high-alpine tree species like *Pinus cembra* (Swiss stone pine), while *Abies alba* and *Fagus sylvatica* are missing. As other high elevated plots for those species are missing, no statistical effect of elevation on *Abies alba* and *Fagus sylvatica* is explained. Given the considerable variation in weather conditions within Switzerland and between different elevations (Brugnara, 2020), BAI can have individual trends. Despite the individual changes, each extreme climatic period can be identified by the temporal trend of BAI, which influences its dynamics.

4.2 Higher vulnerability of *Picea abies*

When we neglect the analysis of all plots and focus on differences within plot groups, a clear pattern can be seen: Each plot group showed for *Picea abies* a higher forest vitality on the plot with higher AWC (Figure 16). The first hypothesis states that AWC positively affects forest vitality through a steady water supply. This holds for the BAI of *Picea abies* when comparing two plots with identical site conditions. As soon as we want to compare more plots and neglect the plot group level, the differences in BAI are due to other untracked site conditions. For *Abies alba* (Figure 15), the differences between the high and low AWC plots are less clear, as only one plot group with significantly different AWC was observed over the whole period. Like *Picea abies*, the plot in Bowil with higher AWC showed higher BAI but less clear differences. Thus, *Picea abies* is more dependent on the soil AWC than *Abies alba*, which on soils with low AWC can still have a relatively high BAI.

The logical inference to be drawn is that precipitation, as the primary contributor to water availability, also influences growth. For *Picea abies*, rainfall had a strong positive effect on its BAI, while for *Abies alba*, the water availability was less important. The second hypothesis, that AWC has a stronger effect on forest vitality under low rainfall, applies to *Picea abies*. While the precipitation was not significant for the vitality of *Abies alba*, it plays a crucial role in the vitality of *Picea abies*.

As follows, *Picea abies* encounters higher AWC and precipitation dependency than *Abies alba*. Due to its shallow rooting system in subalpine and alpine areas (Polonski and Kuhn, 1998), *Picea abies* is more dependent in water acquisition on the upper soil layers than *Abies alba* (Rudow et al., 2024). With its deep-going tap roots, *Abies alba* can reach water reserves less affected by droughts (Potępa et al., 2018). Moreover, other disruptive events like windthrows and bark beetle infestation are increasingly observed for *Picea abies* (Glatthorn et al., 2023). Due to their vulnerability during dry periods, *Picea abies* exhibit higher mortality rates. As a consequence, the *Picea abies* population has declined in the Swiss Central Plateau by a third between 1995 and 2015 and is shifting towards its original habitat in the mountains and foothills, where its population is steadily growing (Bolliger et al., 2000; Cioldi and Leuch, 2020). Nevertheless, *Picea abies* remained the most abundant tree species in the Swiss Central Plateau (Abegg et al., 2023d). Since the decline of *Picea abies* is expected to accelerate in the near future as a consequence of climate change (Cioldi and Leuch, 2020), opportunities arise for integrating close-to-nature silviculture. By introducing different naturally occurring tree species, *Picea abies* can be substituted.

In lower regions, like the Swiss Central Plateau, the species composition in plenter forests should be reconsidered. A plenter method should be implemented without *Picea abies* but based on *Abies alba* and *Fagus sylvatica*. In the Thuringian Basin exist many pure *Fagus sylvatica* plenter forests, which can function as an example, as the Swiss Plateau is the natural habitat of *Fagus sylvatica* (Schütz, 2001). Since pure stands are less adaptable to climate change (Glatthorn et al., 2023), mixed stands should be considered, as they increase the biological diversity and resistance (Kolář et al., 2017). Forests, consisting of *Fagus sylvatica* with admixed *Abies alba* and other naturally occurring species, can have high vitality and resilience within the Swiss Plateau. In more alpine-influenced regions, the vitality of *Picea abies*, which is naturally occurring in these areas (Cioldi and Leuch, 2020), is not harmed and can be managed within the plenter system. Therefore, the location, the associated site conditions and the climatic setting decide which species are best used for the plenter system.

4.3 Tree crown growth influenced by climatic extreme events and competition

Over the observation period, coniferous trees experienced an increase in crown growth. Similar reasons that accelerated the BAI over time (higher spring temperatures, CO₂ concentration, nitrogen deposition and easing of anthropogenic disturbances) can be responsible for the DCV increase. The DCV analysis focuses on single trees, where the competition between neighboring trees is important. The basal area of larger trees (BAL) indicates the pressure of larger trees, which is considered essential for the growing capacity of a tree. Monserud and Sterba (1996) showed that the growth variability of *Abies alba* and *Picea abies* was, on average, described by 10 % through competition measured by BAL, similar to the model output of this thesis, which indicated for all three species that lower BAL relates to higher DCV. As a consequence, larger trees experience higher crown growth rates.

Contrary to the BAL covariable, which did not show any differences between species, the results showed that for species composition, DCV was higher for plots with fewer *Picea abies*. Again, plots with more *Abies alba* have higher growth rates on Swiss plenter forests than plots with *Picea abies*. There are many studies indicating a complementary effect in mixed stands, which leads to higher biomass productivity than in monocultures under favorable conditions (Forrester, 2014; Forrester and Albrecht, 2014; Pretzsch et al., 2010). Even though interactions between different species change temporally as stands develop (Forrester and Albrecht, 2014), the complementary effects of *Picea abies* and *Abies alba* could be connected with the reduced competition for water (Lebourgeois et al., 2013). As previously mentioned, *Abies alba* can form independently of site conditions, the deepest tap roots regarding coniferous trees (Polomski and Kuhn, 1998). This root structure influences the DCV and the BAI of *Picea abies* more than *Abies alba*. Intra-specific competition for water among *Picea abies* trees in the upper soil horizons is higher than the inter-specific competition with *Abies alba*, as *Abies alba* can access deeper water sources. Consequently, the complementary effect on water use is particularly important for *Picea abies* and can enhance its vitality, while it is neglectable for *Abies alba*.

As the plant-available water content can be interpreted as a snapshot, it fluctuates over the year depending on the selected climatic variables. The average precipitation per growing season influenced the DCV of all three species positively, making their vitality directly dependent on rainfall. Differently, the number of dry days (cdd) showed solely for *Fagus sylvatica* a decrease in DCV with increasing cdd. *Fagus sylvatica* is considered very susceptible to droughts because of its high transpiration rate during warm and dry conditions (Lorenz Walthert, 2022; Nalevanková et al., 2018). However, as explained before, the other two species experience an increased DCV with higher cdd, possibly due to the competition between trees. Another reason for the two conifers is that cdd is linked with reduced cloud cover and, thus, increased solar radiation, which can enhance crown growth, whereas for *Fagus sylvatica*, cdd is coupled with low water availability.

Differently, heatwave days (tmax28) positively affected the DCV of *Fagus sylvatica*. As the study sites were selected on higher altitudes, the probability of harsh winter conditions and late frosts during spring is high, which reduces the vitality and growth of *Fagus sylvatica* (Kolář et al., 2017). More heatwave days is connected with a lower probability of late frosts, which enhances the vitality of *Fagus sylvatica*. On the contrary, *Picea abies* has a reduced DCV with more heatwave days. A warmer and dryer climate can increase the intensity of bark beetle infestation (Vakula et al., 2015), which decreases the vitality of *Picea abies* and increases its mortality. In montane and subalpine zones, more heatwave days will increase the vitality of *Fagus sylvatica* due to fewer late frosts, whereas *Picea abies* will suffer from increased pest incidents.

4.4 Negative effect of AWC on tree vitality

DCV behaved similarly to BAI during growing periods with very low precipitation for the two coniferous tree species. In those periods, plots with higher AWC could provide trees with more water and had higher crown growth. Again, *Picea abies* showed a stronger dependency on AWC than *Abies alba*. In contrast, when precipitation was above the annual average, the crown of *Abies alba* and *Picea abies* trees developed worse with higher AWC. The same holds for *Fagus sylvatica*, which was negatively affected by AWC, independently from other factors. Overall, the first hypothesis does not apply to tree crown growth, as the DCV decreased with higher AWC, which seems counterintuitive, as water availability was thought to be coupled with vitality.

The reduction of DCV could be due to higher competition with increasing water availability. As water is less limiting, higher stand density occurs. The increased competition for light, nutrients, and space reduces crown expansion. Also, the competition for light leads to shading effects, where lower branches and smaller trees would experience decreased crown growth. Trees invest their resources in height growth rather than lateral crown growth in such areas. For this reason, the basal area also increases as diameter increment is dependent on height increment (Tanovski et al., 2023). This phenomenon aligns with the stand results, where increased BAI is observed on plots with higher AWC.

The second hypothesis, does apply for *Fagus sylvatica* and *Picea abies* as it showed for *Fagus sylvatica* a less negative influence in DCV, and for *Picea abies* even a positive influence on DCV under low prcp. *Abies alba* showed no clear differences. In plenter forests, AWC is important for trees of all size of drought-prone species in years of low precipitation during the growing season.

Furthermore, tree distribution in a plenter forest stand follows the shape of a reverse J-curve, where the majority of trees are relatively small and compete with a few large trees for resources (Coomes and Allen, 2007). Those small trees experience a higher reduction in crown volume when larger trees are growing well. When they experience suboptimal growth conditions, smaller trees, representing the majority, gain a higher DCV. For smaller trees, the resource availability is therefore less important than the influence of the canopy by larger trees. Therefore, most trees experience higher crown volume growth during unfavorable climatic conditions, when the growth of larger trees is increasingly inhibited. A recent study by Beauchamp et al. (2025) highlights that crown and overall tree growth depend on light competition. They highlighted that trees in shade experience more growth during colder and drier periods, which are less optimal for trees in full sun in the upper canopy. Therefore, the majority of trees receive higher DCV values to some extent during unfavorable soil or climatic conditions.

4.5 Forest vitality and its resilience against extreme events

The results of the DCV analysis have uncertainties. The allometric calculation for the crown length can produce misleading results. For a small proportion of trees, the crown diameter was measured. Comparing the measured and calculated values reveals differences, which are transferred to the crown volume calculations and can impact several observing periods. In further studies, it is suggested to measure crown length instead of calculating it with allometric equations to better quantify DCV. Also, the results should be handled with care due to deviations from model assumptions – specifically the DCV distribution exhibits a right-skewness rather than normality. Even though there are some restrictions, the results are considered liable.

Since tree vitality (DCV) decreases with higher AWC, contrasting to stand vitality (BAI), the question arose whether the gain in crown volume of larger trees outweighs the crown loss experienced by smaller trees. To test this further, one could compare the 100 largest trees on a plot with the rest of the trees. Furthermore, a stand crown volume could be calculated. As time went by, no such test was executed.

As AWC has different effects on BAI and DCV, forest vitality measured through diameter growth on a stand level does not represent the vitality of individual trees based on their crown growth. Even though mixed uneven-aged forests on soils with high AWC can be more resilient against extreme weather conditions with respect to BAI, the crown growth of single trees is higher when AWC is low. In the case of the species *Picea abies*, the extreme weather conditions press severely on the vitality, whereas *Abies alba* and *Fagus sylvatica* experience less influence on their resilience.

The third hypothesis, that AWC can contribute to more resistant forests under the pressure of dry events, does not hold for *Abies alba*. The influence of AWC is too small to determine or does not exist. Other factors like site conditions or climatic setting are more important for the vitality of *Abies alba* in Swiss plenter forests. The same holds for *Fagus sylvatica*, which is more influenced by surrounding trees and climatic conditions like droughts and heatwaves and does not have a supporting effect through AWC. In contrast, *Picea abies* relies on soils with high AWC, as it is susceptible to water availability. Its resilience to extreme climatic conditions is enhanced in areas with higher AWC, which can support their long-term health.

In the future, a comparison of uneven-aged forests to even-aged forests on their vitality and water household usage should be considered. A study already conducted by Trasobares et al. (2016) analyzes even-aged beech forests in the central valley of Switzerland over the same period. But, the findings of my study indicate that the heterogeneity of plots from different sites hinder the identification of differences related to AWC. To compare stands of different management strategies they have to lie nearby. Therefore, it would be beneficial to keep neighboring plots, and it is even suggested to introduce new plots near already existing ones. Including different management strategies in the same area would enhance the experimental design and the comparability of different plots.

Despite the many limitations and error-prone nature of the calculations, it can be summarized that the vitality of a plenter forest is dependent on climate change, extreme weather events, anthropogenic influences, competition and AWC. The effect of AWC depends on the observation scale (stand or tree) and the species. Unlike the other species, *Picea abies* shows a clear dependence of its vitality on AWC at the stand level. Since AWC can support the water balance, especially during dry periods, the shallow-rooted *Picea abies* can be supplied with sufficient water and experience higher vitality. The opposite is true for the tree level. For the three species, tree vitality is lower when the soil has a high AWC. Competition for space limits the growth of the majority of trees.

5 Conclusion and outlook

The most important factor in forest vitality is time, which includes many subfactors that could not have been added to the analysis. Over the last 100 years, the anthropogenic effects have influenced forest growth enormously. Although understanding of forest management has grown and close-to-nature silviculture has gained importance, human activity will continue to influence the vitality of forests in the future – directly through management strategies and indirectly through the effects of climate change. As temperatures in the Swiss climate are rising steadily with no sign of reduction, extreme climatic periods are expected to become more frequent (Calanca, 2007) and will put further pressure on the forest ecosystems. More than ever, resilient silviculture is needed to preserve agile forests that can respond to diverse environmental shocks and pressures.

When managed adequately with suitable tree species, mixed, uneven-aged forests show high adaptability, resilience, biodiversity and resource-use efficiency. Compared to uniform high forests, they provide a more persistent ecosystem functioning, balanced within the surrounding environment (Schütz, 2001). The current proportion of plenter forests below 10 % of the total forest area of Switzerland (Abegg et al., 2023b) is too low and does not represent the silvicultural value of plenter forests. A transition to more plenter forests at the expense of uniform high forests is proposed.

Picea abies is encountering the largest decline in the Swiss Central Plateau since the beginning of modern silviculture. Nonetheless, it is still the most widely used wood and thus plays an important role in Swiss forestry. The advantages of plenter forests managed on deep and healthy soils with high AWC can help to keep a steady but small *Picea abies* abundance in montane regions vulnerable to dry periods and other disruptions. In warmer areas, the abundance of *Picea abies* should be decreased in favor of *Abies alba*, *Fagus sylvatica* and other naturally occurring species to increase forest vitality.

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Appendix A

Data and figures

A.1 Available Water Holding Capacity

Detailed table with primary data on next page

Table 8: The AWC was calculated for 3 soil recordings per plot. The total AWC represents the AWC for a soil depth of 1 m.

Plot	Measurement	Rooting depth [cm]	Horizon	Thickness [cm]	Skeleton content [%]	AKSK 2003	Code soil *	Soil density	Code density *	Code final*	Plenter plots					AWC total [mm/dm]
											AWC [mm/dm]	Corg [%]	Supplement by Corg [mm/dm]	AWC + supplement [mm/dm]		
1015001	0	200	Ah	8	10	SI3	2	0	20	25.2	10.0	7.5	30.0	21.6	192.9	
1015001	0	200		22	10	SI3	2	0	20	25.2	4.0	0	25.2	49.9		
1015001	0	200		70	15	SI3	2	1	21	20.4	1.0	0	20.4	121.4		
1015001	0	200		50	30	SI3	2	2	22	20.9	0.0	0	20.9	73.2		
1015001	1	150	C	10	37.5	Ls3	5	dense	53	22.5	0	0	22.5	14.1		
1015001	2	150	F	5						27.4	0	0	27.4	13.7	168	
1015001	2	150	A	5	37.5	Ls3	5	loose	50	29.2	8	6	30	9.4		
1015001	2	150	B	95	37.5	Ls3	5	medium	51	24.4	0	0	24.4	144.9		
1015001	3	150	F	8						27.4	0	0	27.4	21.9	171.2	
1015001	3	150	A	3	37.5	Ls3	5	loose	50	29.2	8	6	30	5.6		
1015001	3	150	B	87	37.5	Ls3	5	medium	51	24.4	2	0	24.4	132.7		
1015001	3	150	B2	10	37.5	SI4	2	dense	23	17.5	0	0	17.5	10.9		
1015002	0	200	Ah	8	10	SI3	2	0	20	25.2	10.0	7.5	30.0	21.6	192.9	
1015002	0	200		22	10	SI3	2	0	20	25.2	4.0	0	25.2	49.9		
1015002	0	200		70	15	SI3	2	1	21	20.4	1.0	0	20.4	121.4		
1015002	0	200		50	30	SI3	2	2	22	20.9	0.0	0	20.9	73.2		
1015002	1	150	F	6						27.4	0	0	27.4	16.4	132.2	
1015002	1	150	A	4	37.5	Ls3	5	loose	50	29.2	8	6	30	7.5		
1015002	1	150	B	71	37.5	Ls3	5	medium	51	24.4	2	0	24.4	108.3		
1015002	2	150	A	4	37.5	Ls3	5	loose	50	29.2	8	6	30	7.5	153.9	
1015002	2	150	B	96	37.5	Uls	5	medium	51	24.4	2	0	24.4	146.4		
1015002	3	150	F/H	10						27.4	0	0	31.55	31.6	273.8	
1015002	3	150	Ah	16	1	Ls3	5	loose	50	29.2	13	16	30	47.5		
1015002	3	150	B	84	5	Ls3	5	medium	51	24.4	2	0	24.4	194.7		
1021000	0	160	Ah	30	5	SI3	2	loose	20	25.2	2.5	0	25.2	71.8	193.2	
1021000	0	160		70	15	SI3	2	loose	21	20.4	1.0	0	20.4	121.4		
1021000	0	160		60	25	SI3	2	loose	22	20.9	0.0	0	20.9	94.1		
1021000	1	150	F/H	20						27.4	0	0	31.55	63.1	300.1	
1021000	1	150	Ah	8	1	Ls3	5	loose	50	29.2	13	16	30	23.8		
1021000	1	150	B	92	5	Ls3	5	medium	51	24.4	2	0	24.4	213.3		
1021000	2	150	F/H	15						27.4	0	0	31.55	47.3	282.4	
1021000	2	150	A	5	1	Ls3	5	loose	50	29.2	8	6	30	14.9		
1021000	2	150	B	95	5	Ls3	5	medium	51	24.4	2	0	24.4	220.2		
1021000	3	150	F/H	10						27.4	0	0	31.55	31.6	231.5	
1021000	3	150	A	6	1	SI4	2	loose	20	25.2	8	4.5	30	17.8		
1021000	3	150	B	89	5	SI4	2	medium	21	20.4	2	0	20.4	172.5		
1021000	3	150	B	5		SI4	2	medium	21	20.4	0	0	20.4	9.7		
1027000	0	200	A	30	10	SI3	2	loose	20	25.2	4.0	0	25.2	68.0	200.3	
1027000	0	200		70	25	SI3	2	loose	20	25.2	1.0	0	25.2	132.3		
1027000	0	200		100	50	SI3	2	loose	22	20.9	0.0	0	20.9	104.5		
1027000	1	150	F	3						27.4	0	0	27.4	8.2	163.6	
1027000	1	150	A	3	17.5	Ls3	5	loose	50	29.2	8	6	30	7.4		
1027000	1	150	B	97	37.5	Ls3	5	medium	51	24.4	0	0	24.4	147.9		
1027000	2	150	F	5						27.4	0	0	27.4	13.7	136.2	

Plot	Measurement	Rooting depth [cm]	Horizon	Thickness [cm]	Skeleton content [%]	AKSK 2003	Code soil *	Soil density	Code density *	Code final *	AWC [mm/dm]	Corr [%]	Supplement by Corr [mm/dm]	AWC + supplement [mm/dm]	AWC per horizon [mm/dm]	AWC total [mm/dm]
1027000	2	150	B1	35	37.5	Ls3	5	loose	0	50	29.2	2	0	29.2	63.9	
1027000	2	150	B2	53	62.5	Ls3	5	medium	1	51	24.4	0	0	24.4	48.5	
1027000	3	150	C	12	62.5	Ls3	5	dense	3	53	22.5	0	0	22.5	10.1	
1027000	3	60	B	90	37.5	Ls3	5	medium	1	51	24.4	0	0	24.4	137.3	137.25
1028000	0	200	A	30	10	Lt2	9	medium	3	93	13.0	4	6	19.0	51.3	175.0
1028000	0	200		55	15	SI3	2	medium	1	21	20.4	1.0	0	20.4	95.4	
1028000	0	200		65	25	SI3	2	loose	0	20	25.2	1.0	0	25.2	122.9	
1028000	0	200		50	35	SI3	2	loose	0	20	25.2	0.0	0	25.2	81.9	
1028000	1	150	A	8	5	Lt2	9	medium	1	91	24.3	4	3	27.3	20.7	217.4
1028000	1	150	B	92	5	Ls3	5	dense	3	53	22.5	0	0	22.5	196.7	
1028000	2	150	A	5	1	Lt2	9	loose	0	90	28.4	4	0	28.4	14.1	233.4
1028000	2	150	B	95	5	Lt2	9	medium	1	91	24.3	0	0	24.3	219.3	
1028000	3	150	A	5	1	Ls3	5	loose	0	50	29.2	13	16	30	14.9	244.3
1028000	3	150	B	95	1	Ls3	5	medium	1	51	24.4	0	0	24.4	229.5	
1030000	0	150	A	30	5	Ls4	3	loose	0	30	24.7	2.5	0	24.7	70.4	196.5
1030000	0	150		70	15	Ls4	3	medium	1	31	21.2	1.0	0	21.2	126.1	
1030000	0	150		50	25	Ls4	3	dense	3	33	22.4	0	0	22.4	84.0	
1030000	1	150	A	5	1	Ls3	5	medium	1	51	24.4	8	12	36.4	18	162.9
1030000	1	150	B	95	37.5	Ls3	5	medium	1	51	24.4	0	0	24.4	144.9	
1030000	2	150	A	2	1	Ls3	5	medium	1	51	24.4	8	12	36.4	7.2	156.7
1030000	2	150	B	98	37.5	Ls3	5	medium	1	51	24.4	0	0	24.4	149.5	
1030000	3	150	F	5	37.5	SI4	2	loose	0	20	27.4	0	12	27.4	13.7	164.7
1030000	3	150	A	4	37.5	SI4	2	medium	1	21	25.2	13	0	30	7.5	
1030000	3	150	B1	46	37.5	SI4	2	medium	1	21	20.4	4	3	23.4	67.3	
1030000	3	150	B2	50	37.5	Ls3	5	medium	1	51	24.4	0	0	24.4	76.3	
1031000	0	150		30	5	Ls4	3	loose	0	30	24.7	2.5	0	24.7	70.4	189.1
1031000	0	150		70	20	Ls4	3	medium	1	31	21.2	1.0	0	21.2	118.7	
1031000	0	150		50	30	Ls4	3	medium	1	31	21.2	0.0	0	21.2	74.2	
1031000	1	150	F/H	12												
1031000	1	150	A	4	5	Ls3	5	medium	1	51	27.4	0	12	31.55	37.9	261.6
1031000	1	150	B	96	17.5	Ls3	5	dense	3	53	24.4	8	4	36.4	13.8	
1031000	2	150	F	6	4						22.5	2	26.5	209.9		
1031000	2	150	A	4	37.5	SI4	2	medium	1	21	27.4	0	9	27.4	16.4	146.9
1031000	2	150	B	96	37.5	SI4	2	dense	3	23	20.4	8	30	30	7.5	
1031000	3	150	F	7	37.5						17.5	2	20.5	123	123	
1031000	3	150	B	100	37.5	SI4	2	medium	1	21	27.4	0	3	27.4	19.2	146.7
1031000	3	150									20.4	2	0	20.4	127.5	
1033000	0	100	Ah	7	0	SI2	1	loose	0	10	26.8	10.0	2.5	30.0	21.0	181.6
1033000	0	100		8	0	SI2	1	medium	1	11	21.2	1.0	0	21.2	17.0	
1033000	0	100		30	0	SI2	1	dense	3	13	15.8	0.0	0	15.8	47.4	
1033000	0	100		55	0	SI3	2	dense	3	23	17.5	0.0	0	17.5	96.3	
1033000	1	100	F	4							27.4	0	27.4	11	11	162.8
1033000	1	100	A	7	5	SI3	2	very loose	0	20	25.2	4	0	25.2	16.8	
1033000	1	100	B	73	37.5	SI3	2	loose	0	20	25.2	2	0	25.2	115	
1033000	1	100	C	20	62.5	Su2	1	loose	0	10	26.8	0	0	26.8	20.1	160.8
1033000	2	100	F	4							27.4	0	27.4	11	11	
1033000	2	100	A	4	5	Ls3	5	loose	0	50	29.2	0	0	29.2	11.1	
1033000	2	100	B1	16	37.5	Ls3	5	loose	0	50	29.2	4	0	29.2	29.2	
1033000	2	100	B2	80	37.5	Lu	7	medium	1	71	21.9	2	0	21.9	109.5	
1033000	3	100	A	10	17.5	SI3	2	loose	0	20	25.2	4	0	25.2	20.8	162.5

Plot	Measurement	Rooting depth [cm]	Horizon	Thickness [cm]	Skeleton content [%]	AKSK 2003	Code soil *	Soil density	Code density *	Code final *	AWC [mm/dm]	Corr [%]	Supplement by Corr [mm/dm]	AWC + supplement [mm/dm]	AWC per horizon [mm/dm]	AWC total [mm/dm]
1033000	3	100	B	90	37.5	SI3	2	loose	0	20	25.2	2	0	25.2	141.8	
1033000	3	100	C	50	62.5	SI3	2	loose	0	20	25.2	2	0	25.2	47.3	
1034000	0	100	Ah	5	0	SI3	2	loose	0	20	25.2	1.0	0	25.2	12.6	171.4
1034000	0	100		10	10	SI3	2	loose	0	20	25.2	1.0	0	25.2	22.7	
1034000	0	100		25	30	SI3	2	loose	0	20	25.2	1.0	0	25.2	44.1	
1034000	0	100		10	35	SI3	2	loose	0	20	25.2	1.0	0	25.2	16.4	
1034000	0	100		50	40	SI3	2	loose	0	20	25.2	1.0	0	25.2	75.6	
1034000	1	100	A	5	5	SI4	2	loose	0	20	25.2	8	4.5	30	14.3	258.8
1034000	1	100	B	45	5	UIs	5	loose	0	50	29.2	2	0	29.2	124.8	
1034000	1	100	C	50	5	SI3	2	loose	0	20	25.2	2	0	25.2	119.7	
1034000	2	100	H	5	5						35.7	0	0	35.7	17.9	237.4
1034000	2	100	A	4	5	Ls3	5	loose	0	50	29.2	8	6	30	11.4	
1034000	2	100	B1	11	5	Ls3	5	loose	0	50	29.2	2	0	29.2	30.5	
1034000	2	100	B2	25	5	SI3	2	loose	0	20	25.2	2	0	25.2	59.9	
1034000	2	100	B3	40	5	SI3	2	medium	1	21	20.4	0	0	20.4	77.5	
1034000	2	100	C	20	5	Su2	1	medium	1	11	21.2	0	0	21.2	40.3	
1034000	3	100	A	5	5	Ls3	5	very loose	0	50	29.2	8	6	30	14.3	207.1
1034000	3	100	B1	5	5	Ls3	5	loose	0	50	29.2	2	0	29.2	13.9	
1034000	3	100	B2	10	5	SI3	2	loose	0	20	25.2	4	0	25.2	23.9	
1034000	3	100	B3	80	5	SI3	2	medium	1	21	20.4	2	0	20.4	155	
1041000	0	120	Ah	25	20	SI3	2	loose	0	20	25.2	6.0	1.5	26.7	53.4	178.1
1041000	0	120		45	30	SI3	2	loose	0	20	25.2	2.5	0	25.2	79.4	
1041000	0	120		50	40	SI3	2	loose	0	20	25.2	1.0	0	25.2	75.6	
1041000	1	150	A	15	5	Su2	1	loose	0	10	26.8	4	0	26.8	38.2	153.8
1041000	1	150	B	45	37.5	Su2	1	loose	0	10	26.8	1	0	26.8	75.4	
1041000	1	150	C	40	62.5	Su2	1	loose	0	10	26.8	1	0	26.8	40.2	
1041000	2	60	A	5	1	SI3	2	loose	0	20	25.2	4	0	25.2	12.5	139.4
1041000	2	60	B	55	5	Lt2	9	medium	1	91	24.3	1	0	24.3	127	
1041000	3	150	A	27	1	Ls3	5	loose	0	50	29.2	10	10	30	80.2	227.1
1041000	3	150	B	33	17.5	Ls3	5	medium	1	51	24.4	1	0	24.4	66.4	
1041000	3	150	na	40	17.5	Ls3	5	medium	1	51	24.4	1	0	24.4	80.5	
1042000	0	120	Ah	25	20	Ls3	5	loose	0	50	29.2	6.0	2	31.2	62.4	187.1
1042000	0	120		45	30	SI3	2	loose	0	20	25.2	2.5	0	25.2	79.4	
1042000	0	120		50	40	SI3	2	loose	0	20	25.2	1.0	0	25.2	75.6	
1042000	1	150	Ah	50	5	SI4	2	loose	0	20	25.2	10	7.5	30	57	195.7
1042000	1	150	B	30	17.5	Ls3	5	medium	1	51	24.4	4	4	28.4	70.3	
1042000	1	150	na	50	37.5	SI4	2	medium	1	21	20.4	3	1.5	21.9	68.4	208.7
1042000	2	150	Ah	20	5	Ls3	5	loose	0	50	29.2	15	20	30	57	
1042000	2	150	B	30	17.5	Lt2	9	medium	1	91	24.3	4	3	27.3	67.6	
1042000	2	150	na	50	17.5	SI4	2	loose	1	21	20.4	2	0	20.4	84.2	
1042000	3	150	A	15	1	SI4	2	loose	0	20	25.2	8	4.5	30	44.6	91.8
1042000	3	150	B	30	37.5	SI3	2	loose	0	20	25.2	4	0	25.2	47.3	
1046000	0	200		30	5	SI3	2		0	20	25.2	2.0	0	25.2	71.8	202.1
1046000	0	200		70	15	SI3	2		1	21	20.4	3.0	1.5	21.9	130.3	
1046000	0	200		50	25	SI3	2		2	22	20.9	4.0	4.5	25.4	95.3	244.2
1046000	1	150	F	6							27.4	0		27.4	16.4	
1046000	1	150	H	6							35.7	0		35.7	21.4	
1046000	1	150	A	6	5	Lt2	9	loose	0	90	28.4	13	12	30	17.1	
1046000	1	150	B	94	17.5	Ls3	5	medium	1	51	24.4	0	0	24.4	189.2	

Plot	Measurement	Rooting depth [cm]	Horizon	Thickness [cm]	Skeleton content [%]	AKSK 2003	Code soil *	Soil density	Code density *	Code final*	AWC [mm/dm]	Corr [%]	Supplement by Corr [mm/dm]	AWC + supplement [mm/dm]	AWC per horizon [mm/dm]	AWC total [mm/dm]
1046000	2	150	F	7							27.4	0	27.4	19.2	265.8	
1046000	2	150	A	10			9	loose	0	90	28.4	8	30	29.7		
1046000	2	150	B	60			5	loose	0	50	29.2	0	29.2	166.4		
1046000	2	150	B2	30			2	medium	1	21	20.4	0	20.4	50.5		
1046000	3	150	A	10			9	loose	0	90	28.4	4	28.4	27	191.2	
1046000	3	150	B	90			5	loose	0	50	29.2	0	29.2	164.3		
2035000	0	200	A	10			3	loose	0	30	24.7	6.0	24.7	23.5	188.6	
2035000	0	200		41			3	loose	0	30	24.7	3.0	24.7	86.1		
2035000	0	200		20			3	loose	0	30	24.7	0.0	24.7	79.0		
2035000	1	150	A	30			5	loose	0	50	29.2	4	29.2	83.2	185.2	
2035000	1	150	B	50			2	medium	1	21	20.4	0	20.4	81.6		
2035000	1	150	B2	20			2	medium	1	21	20.4	0	20.4	20.4		
2035000	2	150	F	4							27.4	0	27.4	11	148	
2035000	2	150	A	35			2	loose	0	20	25.2	4	25.2	72.8		
2035000	2	150	B	35			2	medium	1	21	20.4	2	20.4	44.6		
2035000	2	150	B2	30			2	dense	3	23	17.5	0	17.5	19.7		
2035000	3	150	A	20			2	loose	0	20	25.2	8	30	49.5	136	
2035000	3	150	B	55			2	medium	1	21	20.4	2	20.4	70.1		
2035000	3	150	B2	25			2	dense	3	23	17.5	0	17.5	16.4		
2047000	0	200	A	10			3		0	30	24.7	3.0	24.7	23.5	176.2	
2047000	0	200		70			2		1	21	20.4	1.0	20.4	121.4		
2047000	0	200		70			2		2	22	20.9	0.0	20.9	109.7		
2047000	1	150	F	4							27.4	0	27.4	11	272.9	
2047000	1	150	A1	15			5	loose	0	50	29.2	8	30	44.6		
2047000	1	150	A2	31			5	loose	0	50	29.2	8	30	92.1		
2047000	1	150	B	34			1	loose	0	10	26.8	2	26.8	86.6		
2047000	1	150	B2	20			2	medium	1	21	20.4	0	20.4	38.8		
2047000	2	150	F	3							27.4	0	27.4	8.2	180.8	
2047000	2	150	A	10			1	medium	1	11	21.2	4	22.2	21.1		
2047000	2	150	B	90			2	medium	1	21	20.4	0	20.4	151.5		
2047000	3	150	F	4							27.4	0	27.4	11	186.5	
2047000	3	150	A	40			5	loose	0	50	29.2	8	30	99		
2047000	3	150	B	60			2	medium	1	21	20.4	0	20.4	76.5		
21293001	0	150		15			4	loose	0	40	31.8	10.0	30.0	45.0	279.8	
21293001	0	150		35			4	loose	0	40	31.8	6.0	33.8	118.3		
21293001	0	150		20			4	loose	0	40	31.8	1.0	31.8	57.2		
21293001	0	150		60			3	loose	0	30	24.7	0.0	24.7	118.6		
21293001	1	150	F	5							27.4	0	27.4	13.7	93.4	
21293001	1	150	H	5							35.7	0	35.7	17.9		
21293001	1	150	B	55			5	loose	0	50	29.2	8	30	61.9		
21293001	2	150	B	50			5	loose	0	50	29.2	8	30	56.3	56.3	
21293001	3	150	F	6							27.4	0	27.4	16.4	106.1	
21293001	3	150	H	5							35.7	0	35.7	17.9		
21293001	3	150	A	15			5	loose	0	50	29.2	13	30	16.9		
21293001	3	150	B1	35			2	loose	0	20	25.2	0	25.2	33.1		
21293001	3	150	B2	20			5	loose	0	50	29.2	0	29.2	21.9		
21293002	0	150		15			4	loose	0	40	31.8	10.0	30.0	45.0	279.8	
21293002	0	150		35			4	loose	0	40	31.8	6.0	33.8	118.3		
21293002	0	150		20			4	loose	0	40	31.8	1.0	31.8	57.2		

Plot	Measurement	Rooting depth [cm]	Horizon	Thickness [cm]	Skeleton content [%]	AKSK 2003	Code soil *	Soil density	Code density *	Code final *	AWC [mm/dm]	Corr [%]	Supplement by Corr [mm/dm]	AWC + supplement [mm/dm]	AWC per horizon [mm/dm]	AWC total [mm/dm]
21293002	0	150		60	20	na	3	loose	0	30	24.7	0.0	0	24.7	118.6	
21293002	1	150	A	40	75	Lx2	9	loose	0	90	28.4	4	0	28.4	28.4	72.2
21293002	1	150	B	60	75	Ls3	5	loose	0	50	29.2	0	0	29.2	43.8	
21294000	0	150	Ah	20	0	na	4	loose	0	40	31.8	10.0	10	30.0	60.0	260.3
21294000	0	150		20	5	na	4	loose	0	40	31.8	6.0	2	33.8	64.2	
21294000	0	150		60	10	na	2	loose	0	20	25.2	1.0	0	25.2	136.1	
Transition plots																
1014000	0	200	A	20	10	Sl3	2	loose	0	20	25.2	3.0	0	25.2	45.4	216.7
1014000	0	200		80	15	Sl3	2	loose	0	20	25.2	0.0	0	25.2	171.4	
1014000	0	200		80	25	Sl3	2	loose	0	20	25.2	0.0	0	25.2	151.2	
1014000	1	150	F	-7							27.4	0	0	27.4	-19.2	215.1
1014000	1	150	A	5	1	Ls3	5	medium	1	51	24.4	4	4	28.4	14.1	
1014000	1	150	B	95	5	Ls3	5	medium	1	51	24.4	0	0	24.4	220.2	
1014000	2	150	A	7	1	Ls3	5	medium	1	51	24.4	8	12	36.4	25.2	240.8
1014000	2	150	B	93	5	Ls3	5	medium	1	51	24.4	2	0	24.4	215.6	
1014000	3	150	A	4	5	Ls3	5	medium	1	51	24.4	8	12	36.4	13.8	236.4
1014000	3	150	B	96	5	Ls3	5	medium	1	51	24.4	0	0	24.4	222.5	
2034000	0	100	A	30	5	Ls4	3	loose	0	30	24.7	1.0	0	24.7	70.4	218.6
2034000	0	100		40	10	Ls4	3	loose	0	30	24.7	0.0	0	24.7	88.9	
2034000	0	100		30	20	Ls4	3	loose	0	30	24.7	0.0	0	24.7	59.3	
2034000	2	150	A	35	37.5	Sl4	2	loose	0	20	25.2	4	0	25.2	55.1	104.9
2034000	2	150	B	65	62.5	Sl4	2	medium	1	21	20.4	2	0	20.4	49.7	
2034000	3	150	A	18	37.5	Sl4	2	loose	0	20	25.2	8	4.5	30	33.8	110.1
2034000	3	150	B	62	50	Sl4	2	medium	1	21	20.4	2	0	20.4	63.2	
2034000	3	150	B2	20	62.5	Sl4	2	dense	3	23	17.5	0	0	17.5	13.1	
21290	0	150	Ah	25	10	na	2		0	20	25.2	6.0	1.5	26.7	60.1	182.5
21290	0	150		75	20	na	2		1	21	20.4	1.0	0	20.4	122.4	
21290	0	150		50	30	na	2		2	22	20.9	0.0	0	20.9	73.2	
21290	1	150	A	4	5	Sl4	2	loose	0	20	25.2	8	4.5	30	11.4	241.2
21290	1	150	B	96	5	Sl4	2	loose	0	20	25.2	2	0	25.2	229.8	
21290	2	150	A	5	17.5	Sl4	2	loose	0	20	25.2	8	4.5	30	12.4	172.3
21290	2	150	B	95	17.5	Sl4	2	medium	1	21	20.4	2	0	20.4	159.9	
21290	3	150	A	3	5	Sl4	2	loose	0	20	25.2	8	4.5	30	8.6	196.5
21290	3	150	B	97	5	Sl4	2	medium	1	21	20.4	2	0	20.4	188	

The columns marked with a * are based on codes which were provided by Teepe et al. (2003). Also visible on the diagram in Figure 7. Due to the limited layout of the PDF, some information was lost. For a detailed version, including the intermediate mathematical steps, you can contact me at tobias.kuehnhauss@gmail.com.

Lookup Tables used for calculating AWC

Table 9: Lookup table for changing from AKSK 2003 to Teepe's Soil numbering

AKSK 2003	soil number by Teepe et al. (2003)
Ls2	4
Ls3	5
Ls4	3
Lt2	9
Lt3	9
Lts	9
Lu	7
Sl2	1
Sl3	2
Sl4	2
Slu	4
Ss	1
St2	1
St3	2
Su2	1
Su3	2
Su4	2
Tl	10
Ts2	10
Ts3	9
Ts4	9
Tt	10
Tu2	10
Tu3	8
Tu4	7
Uls	5
Us	5
Ut2	6
6	Ut3
Ut4	7
Uu	6

AKSK 2003 refers to the Arbeitskreis Standortkartierung (2003). Forstliche Standortaufnahme. IHW-Verlag und Verlagsbuchhandlung, Eching bei München.

Table 10: Lookup table for changing from density category to a value

Density Category	Value
very loose	0
loose	0
medium	1
dense	3

In Table 8 column **Code final** is a combination (Table 11 (Code final) = Table 9 & Table 10). The & is a logical operator; see for example the flow diagram in Figure 7.

Table 11: Respective Lookup Table for Code final and AWC

Code final	AWC [mm/dm]	Code final	AWC [mm/dm]
0	0	11	0.5
12	1.5	13	0
14	2	15	2
16	2	17	1
18	1.5	19	1.5
21	1	22	3
23	0	24	4
25	4	26	4
27	2	28	3
29	3	31	1.5
32	4.5	33	0
34	6	35	6
36	6	37	3
38	4.5	39	4.5
41	2	42	6
43	0	44	8
45	8	46	8
47	4	48	6
49	6	51	2.5
52	7.5	53	0
54	10	55	10
56	10	57	5
58	7.5	59	7.5
61	3	62	9
63	0	64	12
65	12	66	12
67	6	68	9
69	9	71	3.5
72	10.5	73	0
74	14	75	14
76	14	77	7
78	10.5	79	10.5
81	4	82	12

Table 12: The average carbon content (Corg) for each soil density

Soil Density	Corg %
0	5
1	2
2	1
3	0

If the carbon content exceeded the average value, the corresponding supplement was added using a supplement code (supplement = amount exceeded & Code soil). See the flow diagram in Figure 7.

A.2 Additional figures for DCV

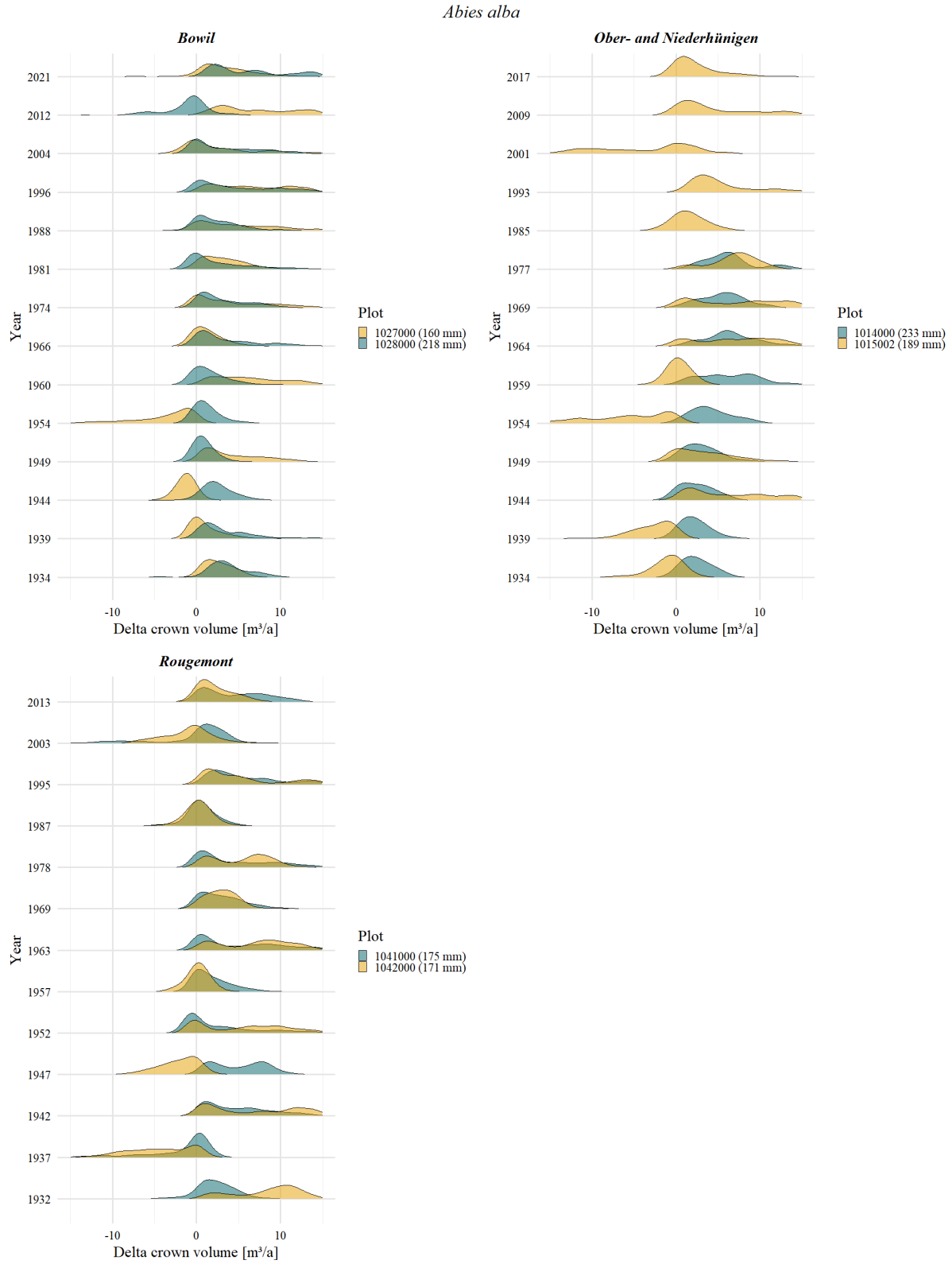


Figure 19: The Distribution shapes of the delta crown volume for *Abies alba* on different plot groups (own figure).

Fagus sylvatica

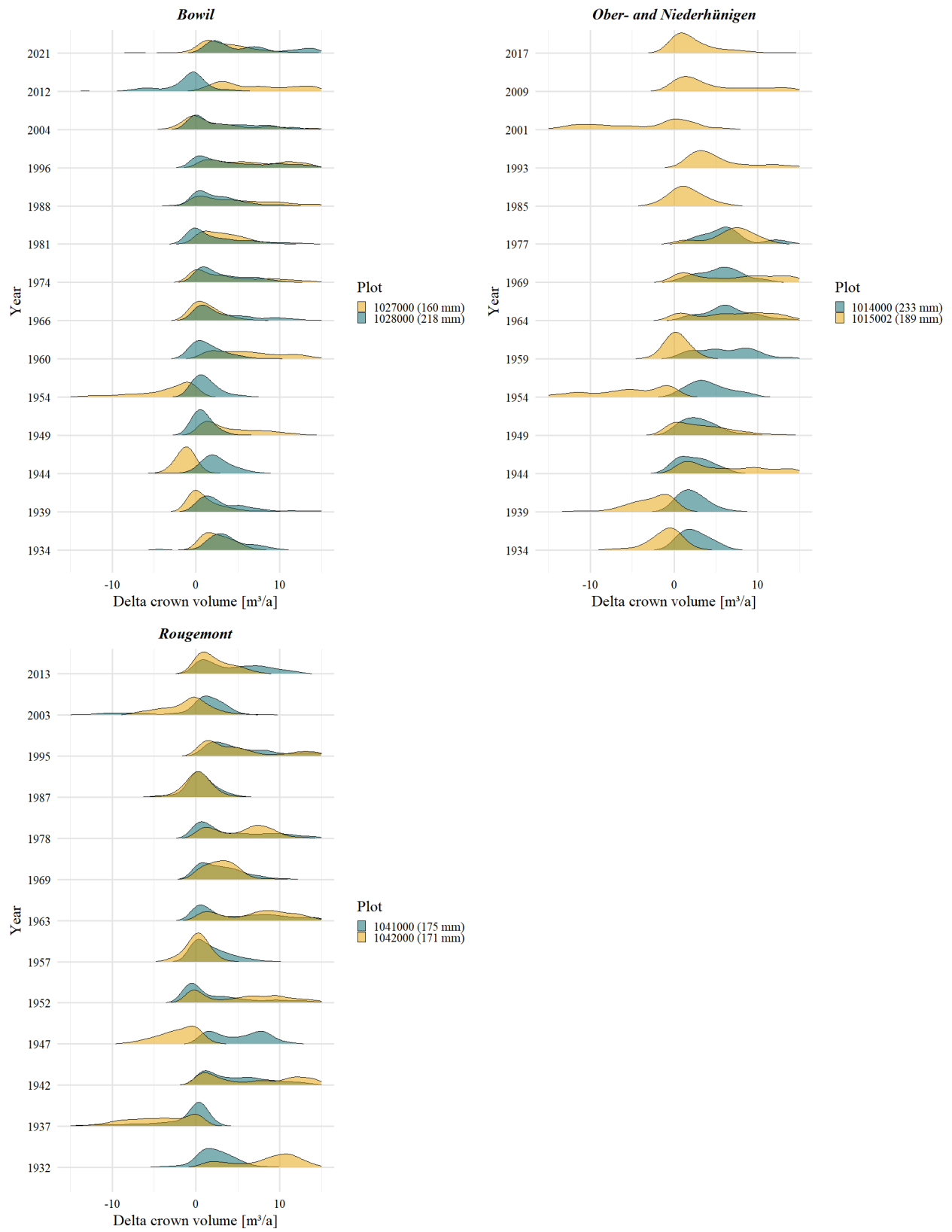


Figure 20: The Distribution shapes of the delta crown volume for *Fagus sylvatica* on different plot groups (own figure).

A.3 Figures for model validation

For the model validation the DHARMA package was used. The BAI model for *Picea abies* showed no detection of significant problems (Figure 21).. But the model for *Abies alba* did (Figure 22).. Therefore, the model for *Picea abies* is considered more reliable.

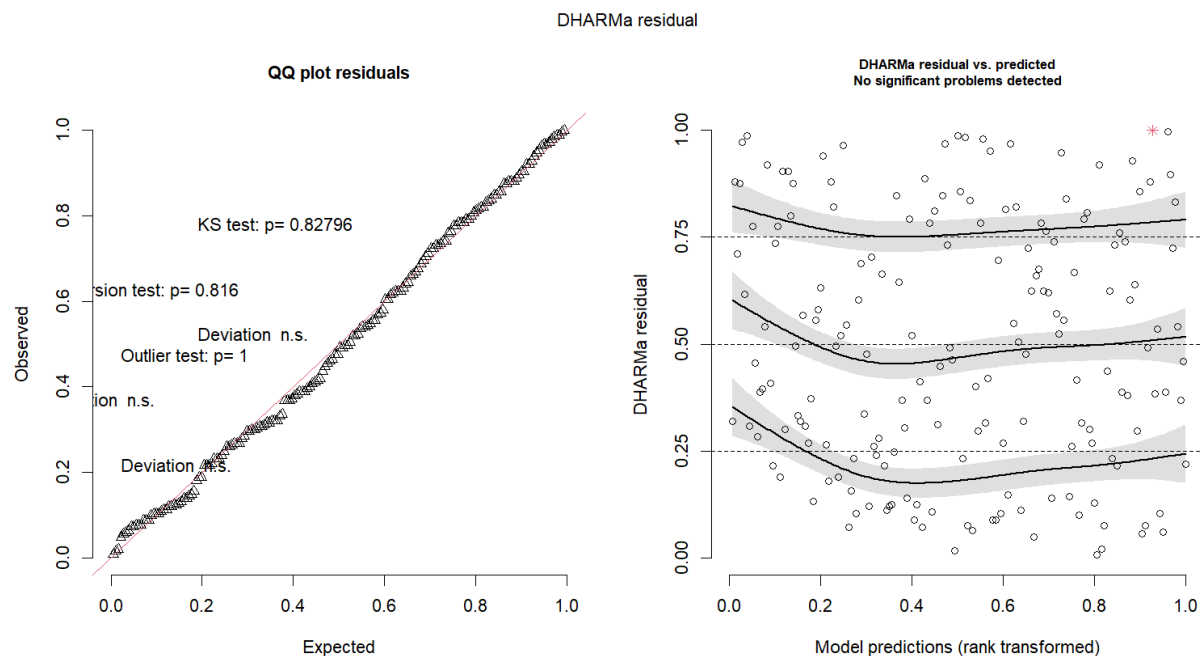


Figure 21: The DHARMA plot for the plot-level model for *Picea abies* (own figure).

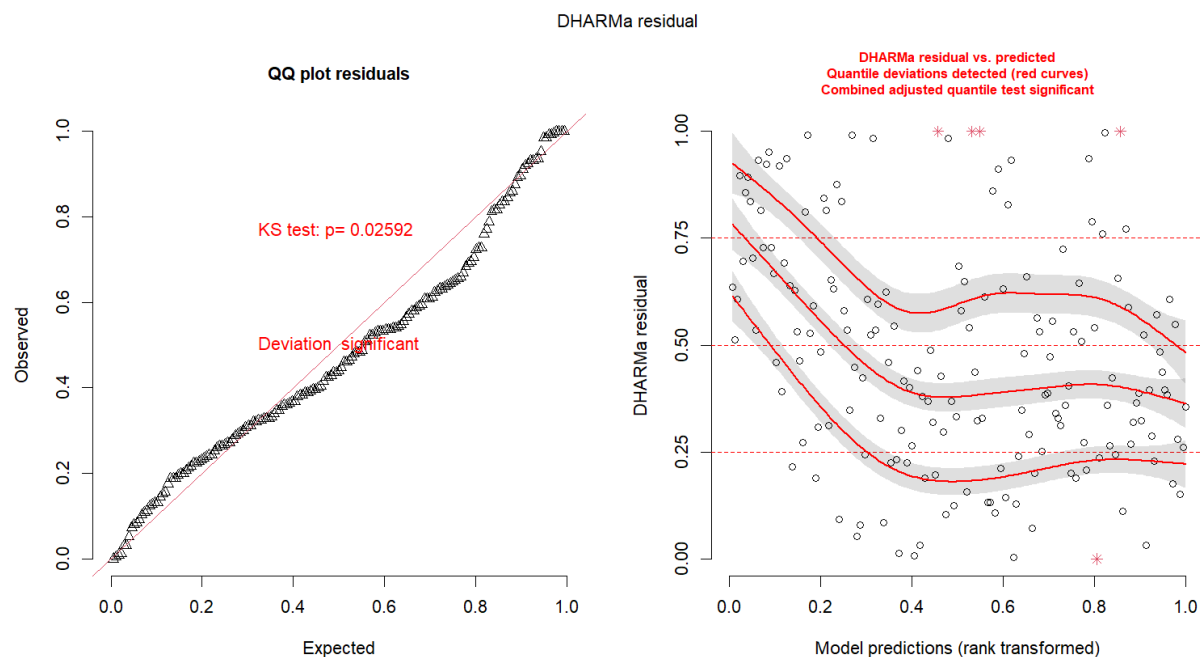


Figure 22: The DHARMA plot for the plot-level model for *Abies alba* (own figure).

The different models for the DCV had the same DHARMA plot, the model for *Abies alba* is represented for all of them (Figure 23). As the DCV dataset contained no uniform distribution, but right-skewed, the values show this curve within the QQ plot instead of a straight line.

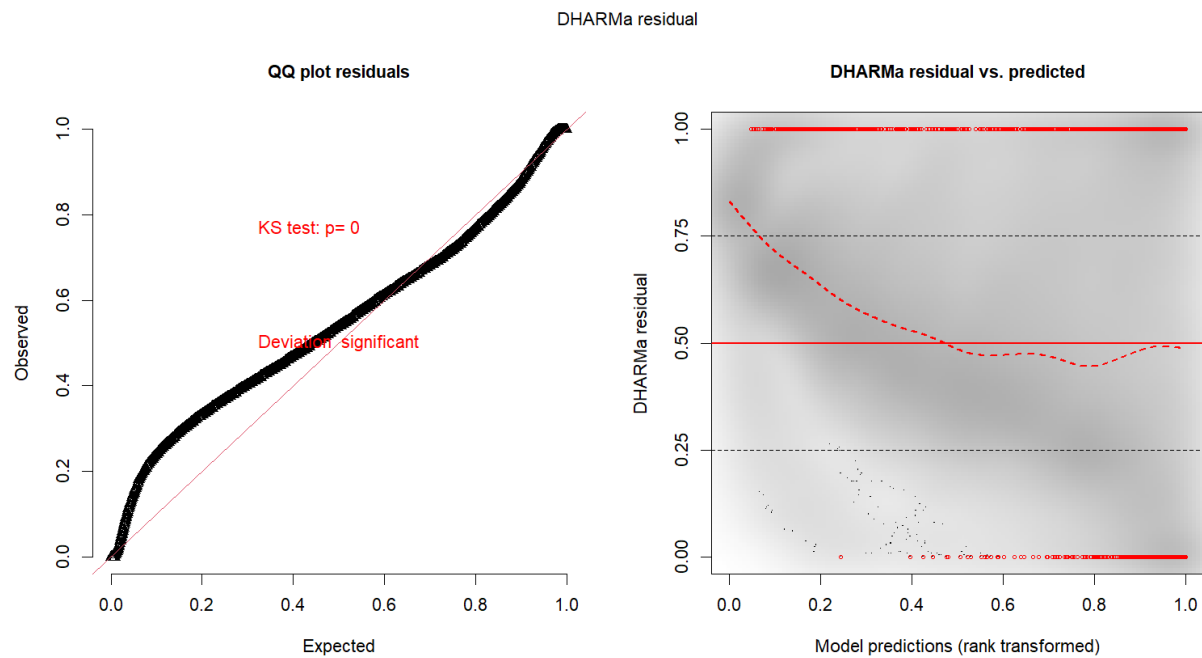


Figure 23: The DHARMA plot for the tree-level model for *Abies alba* (own figure).

Appendix B

Calculations and statistical evaluations

B.1 Available water holding capacity

```
1 ##make a boxplot including a beautiful graph of the 3 AWC measurements + the historical
  measurement
2
3 rm(list=ls())
4
5 setwd("C:/Users/tobia/Documents/soil_vitality_plenter")
6
7
8 library(readr)
9 library(ggplot2)
10 library(ggfortify)
11 library(tidyverse)
12 library(boot)
13 library(readr)
14 library(sf)
15 library(tibble)
16 library(purrr)
17 library(plotly)
18 library(glmTMB)
19 library(DHARMA)
20 library(extrafont)
21
22
23 data<- read_csv("data/AWC_data.csv",
24                 col_types = cols(ID = col_character(), AWC = col_number(), measurement
25                                 = col_integer()))
26
27 View(dd)
28
29
30 # Remove NA values from the main data
31 dd <- na.omit(data)
32
33 hist_measurement <- data.frame(
34   ID = c(1014000, 1015001, 1015002, 1021000, 1027000, 1028000, 1030000, 1031000, 1033000,
35         1034000,
36         1041000, 1042000, 1046000, 2034000, 2035000, 2047000, 21290000, 21293001,
37         21293002, 21294000),
38   AWC = c(216.72, 192.88, 192.88, 193.20, 200.34, 175.02, 196.54, 189.12, 181.61, 171.36,
39         178.14, 187.14, 202.13, 218.60, 188.58, 176.20, 182.50, 279.82, 279.82, 260.30),
40   measurement = rep(0, 20))
41
42 data <- filter(data, measurement>=1)
43
44 zero_measurement <- hist_measurement
45 # Create the boxplot and overlay the 0-measurement points
46 ggplot(data, aes(x = as.factor(ID), y = AWC)) +
47   geom_boxplot() + # Boxplot for measurements 1-3
48   geom_point(data = hist_measurement, aes(x = as.factor(ID), y = AWC), color = "black",
49         size = 3, shape = 4) + # Overlay 0-measurement
50   labs(title = "Boxplot of AWC for Each ID (Measurements 1-3) with 0-Measurement Overlay",
51         x = "Plot", y = "AWC [mm/dm]") +
52   theme(axis.text.x = element_text(angle = 90, hjust = 1))
53
54 # Create the boxplot with 0-measurement overlay, styled similarly to p1
55 p1_boxplot <- ggplot(data, aes(x = as.factor(ID), y = AWC)) +
56   geom_boxplot(outlier.shape = NA, fill = "grey80", color = "grey30") + # Boxplot style
57   geom_point(data = hist_measurement, aes(x = as.factor(ID), y = AWC),
58         color = "black", size = 2, shape = 4) + # Overlay 0-measurement in red
59   labs(
60     subtitle = "AWC Distribution in each Plot",
61     x = "Plot",
62     y = expression("AWC [mm]")
63   ) +
64   theme_minimal(base_size = 20) +
65   theme(
66     text = element_text(family = "Times New Roman"),
67     plot.subtitle = element_text(hjust = 0.5, face = "bold"),
```

```

67   axis.text = element_text(color = "grey6"),
68   axis.text.x = element_text(angle = 90, vjust = 0.5, hjust = 1), # Rotate x-axis labels
69   panel.grid.major = element_line(color = "gray90")
70 )
71
72
73 p1_boxplot
74
75
76
77
78 # Compute the mean AWC for each ID (excluding 0-measurement)
79 mean_awc <- data %>%
80   group_by(ID) %>%
81   summarize(mean_AWC = mean(AWC, na.rm = TRUE)) %>%
82   arrange(mean_AWC) # Sort by mean AWC
83
84 # Convert ID to a factor with the desired order
85 data$ID <- factor(data$ID, levels = mean_awc$ID) ##here do or undo for order within the
86   figure
87 zero_measurement$ID <- factor(zero_measurement$ID, levels = mean_awc$ID) # Keep same order
88
89 # Create the boxplot with reordered IDs
90 p2_boxplot <- ggplot(data, aes(x = ID, y = AWC)) +
91   geom_boxplot(aes(fill = "New Measurements (3)"), outlier.shape = NA, color = "grey30") +
92   geom_point(data = zero_measurement, aes(x = ID, y = AWC, shape = "Historical
93     Measurement", color = "Historical Measurement", stroke = 0.73),
94     size = 2) +
95   labs(
96     subtitle = "AWC Distribution by Plot",
97     x = "Plot",
98     y = expression("Available Water Capacity [mm]"),
99     shape = "",
100    color = "",
101    fill = ""
102  ) +
103  scale_shape_manual(values = c("Historical Measurement" = 4)) +
104  scale_color_manual(values = c("Historical Measurement" = "black")) +
105  scale_fill_manual(values = c("New Measurements (3)" = "grey80")) +
106  guides(
107    shape = guide_legend(override.aes = list(stroke = 0.73)), # Override shape legend with
108      stroke
109    color = guide_legend(override.aes = list(stroke = 0.73)) ) +
110  theme_minimal(base_size = 20) +
111  theme(
112    text = element_text(family = "Times New Roman"),
113    plot.subtitle = element_text(hjust = 0.5, face = "bold"),
114    axis.text = element_text(color = "grey6"),
115    axis.text.x = element_text(angle = 90, vjust = 0.5, hjust = 1), # Rotate x-axis labels
116    panel.grid.major = element_line(color = "gray90"),
117    legend.position = "top"
118  )
119
120 p2_boxplot

```

B.2 Climatic factors

Calculation of basic climatic factors

```

1  ## some basic statistics,
2  ## Calculate mean temperature between days 91(april 1st) and 304 (October 31) for each year
3
4  daymet<- readRDS("data/daymet.rds")
5  daymet <- filter(daymet, year > 1992)
6
7
8  # Calculate mean temperature between days 91(april 1st) and 304 (October 31) for each year
9  # then calculate the overall mean across years
10
11
12 temp_stats <- daymet %>%
13   filter(day >= 91 & day <= 304) %>% # Filter days from April to October
14   group_by(year, plot_group) %>% # Group by year AND plot
15   summarize(mean_tmean_plot = mean(tmean, na.rm = TRUE), .groups = "drop") %>% # Mean per
16     plot per year
17   group_by(year) %>% # Now group by year
18   summarize(mean_tmean_year = mean(mean_tmean_plot, na.rm = TRUE), .groups = "drop") %>% #
19     Mean per year across plots

```



```

18   summarize(
19     overall_mean_tmean = mean(mean_tmean_year, na.rm = TRUE), # Overall mean across years
20     sd_tmean = sd(mean_tmean_year, na.rm = TRUE) # Standard deviation across years
21   )
22
23   print(temp_stats)
24
25
26   # then calculate the overall mean for min temp
27   min_temp <- daymet %>%
28     filter(day >= 91 & day <= 304) %>% # Filter days from April to October
29     group_by(plot_group, year) %>% # Group by year
30     summarize(mean_tmin_year = mean(tmin, na.rm = TRUE), .groups = "drop") %>% # Calculate
31     yearly mean
32     summarize(overall_mean_tmean = mean(mean_tmin_year, na.rm = TRUE), .groups = "drop") #
33     Calculate overall mean
34
35   print(min_temp)
36
37   # max temp
38   max_temp <- daymet %>%
39     filter(day >= 91 & day <= 304) %>% # Filter days from April to October
40     group_by(year) %>% # Group by year
41     summarize(mean_tmax_year = mean(tmax, na.rm = TRUE)) %>% # Calculate yearly mean
42     summarize(overall_mean_tmean = mean(mean_tmax_year, na.rm = TRUE)) # Calculate overall
43     mean
44
45   print(max_temp)
46
47   #standard deviation across years
48   temp_stats <- daymet %>%
49     filter(day >= 91 & day <= 304) %>% # Filter days from April to October
50     group_by(year) %>% # Group by year
51     summarize(mean_tmean_year = mean(tmean, na.rm = TRUE)) %>% # Calculate yearly mean
52     summarize(
53       overall_mean_tmean = mean(mean_tmean_year, na.rm = TRUE), # Mean across years
54       sd_tmean = sd(mean_tmean_year, na.rm = TRUE) # Standard deviation across years
55     )
56
57   print(temp_stats)
58
59   # precipitation
60   sum_prpc <- daymet %>%
61     filter(day >= 91 & day <= 304) %>% # Filter days from April to October
62     group_by(year, plot_group) %>% # Group by year
63     summarize(sum_prpc = sum(prcp, na.rm = TRUE), .groups = "drop") %>% # Calculate yearly sum
64     group_by(year) %>%
65     summarize(mean_prpc_year = mean(sum_prpc, na.rm = TRUE), .groups = "drop") %>% # Calculate
66     overall mean
67     summarize(
68       overall_mean_prpc = mean(mean_prpc_year, na.rm = TRUE), # Overall mean precipitation
69       across years
70       sd_prpc = sd(mean_prpc_year, na.rm = TRUE) # Standard deviation across years
71     )
72
73   print(sum_prpc)
74
75   #precipitation min & max
76   max_min_prpc <- daymet %>%
77     filter(day >= 91 & day <= 304) %>% # Filter days from April to October
78     group_by(year, plot_group) %>% # Group by year
79     summarize(sum_prpc = sum(prcp, na.rm = TRUE), .groups = "drop") %>% # Calculate yearly sum
80     summarize(min = min(sum_prpc, na.rm = TRUE), max = max(sum_prpc, na.rm = TRUE), .groups =
81       "drop") # Calculate overall mean
82
83   print(max_min_prpc)
84
85   ###mean and sd of * of inventories
86
87   # Define the list of numbers
88   values <- c(14, 19, 19, 18, 18, 18, 14, 17, 12, 12,
89     14, 14, 15, 17, 17, 14, 17, 12, 12, 11)
90
91   # Compute mean and standard deviation
92   mean_value <- mean(values)
93   sd_value <- sd(values)

```

```

91 mean_value
92 sd_value
93
94
95 #summary of April till , representing the growing period
96
97 days<- daymet %>%
98   filter(day >=91 & day <= 304)
99   print (days)
100
101 summary(days)

```

Mean precipitation per growing season

```

1
2 ##getting rid of the outliers 21294 Le Chenit(not measured) and 21293001 & 21293002
3 ## Sigriswil(huge stone content)
4
5
6
7 tree<- readRDS("data/tree_v4.rds")
8 daymet<- readRDS("data/daymet.rds")
9 stand<- readRDS("data/stand_v5.rds")
10 #stand<- tree
11
12 # Load necessary library
13 library(dplyr)
14
15 # Step 1: Ensure data is sorted correctly by plot_group and year
16 stand <- stand %>%
17   arrange(plot_group, year) # Sorting ensures that years are in chronological order for
18   each plot_group
19
20 # Step 2: Find the correct previous year (earliest year before the current one, not just
21 the immediate previous row)
22 stand <- stand %>%
23   group_by(plot_group) %>% # Group data by plot_group so calculations are performed within
24   each group
25   mutate(prev_year = lag(year, default = NA)) %>% # Initially assign the previous year
26   using lag()
27   rowwise() %>% # Ensure calculations are done row-by-row
28   mutate(prev_year = max(stand$year[
29     stand$plot_group == plot_group & # Match the same plot_group
30     stand$year < year # Select the largest year that is strictly less than the current
31     year
32   ], na.rm = TRUE)) %>% # Use max() to get the closest previous year available
33   ungroup() # Remove row-wise grouping to restore standard dataframe structure
34
35 # Step 3: Calculate the average growing season precipitation between the previous and
36 current year
37 stand <- stand %>%
38   rowwise() %>% # Ensure calculations are performed for each row
39   mutate(avg_prpc = mean(
40     daymet_growing_season$total_prpc[ # Extract precipitation values from
41     daymet_growing_season
42     daymet_growing_season$plot_group == plot_group & # Match plot_group to ensure the
43     right subset
44     daymet_growing_season$year >= prev_year & # Include only years from the previous
45     measurement year onward
46     daymet_growing_season$year < year # Exclude the current year
47   ],
48     na.rm = TRUE # Exclude missing values (NA) when calculating the mean
49   )) %>%
50   ungroup() # Remove row-wise grouping
51
52 # Step 4: View the final dataset
53 print(stand)
54
55 #saveRDS(stand, "data/stand_v6.rds")
56 #saveRDS(xx, "data/tree_v5.rds")

```

Calculation of the maximum number of consecutive dry days per year

```

1 ##stand add from daymet dataset the mean_dry_days/a
2
3 library(DHARMA)
4

```

```

5  ### # of consecutive DRY DAYS/a --> mean
6  #stand<- readRDS("data/tree_v3.rds")
7  stand <- readRDS("data/stand_v6.rds")
8
9  daymet <- readRDS("data/daymet.rds")
10
11 ## 1. Calculate maximum consecutive dry days per year
12
13 # Function to calculate the maximum consecutive dry days for daymet
14 calculate_CDD <- function(precipitation) {
15   max_cdd <- 0
16   current_cdd <- 0
17
18   for (rr in precipitation) {
19     if (rr < 1) {
20       current_cdd <- current_cdd + 1
21       max_cdd <- max(max_cdd, current_cdd)
22     } else {
23       current_cdd <- 0
24     }
25   }
26
27   return(max_cdd)
28 }
29
30
31 #stand <- tree
32 # Apply the function per plot_group and year in daymet
33 cdd_results <- daymet %>%
34   group_by(plot_group, year) %>%
35   summarise(max_cdd = calculate_CDD(prcp), .groups = 'drop')
36
37 # View the results
38 print(cdd_results)
39
40 # 2. Merge 'stand' data with 'daymet_dry_days' and calculate the average for each plot
41 # calculation of maximum number of consecutive dry days /per year averaged over the
42 # monitoring period.
43
44 stand <- stand %>%
45   arrange(plot_group, species) %>%
46   group_by(plot_group) %>%
47   mutate(previous_year = lag(year)) %>%
48   filter(!is.na(previous_year)) %>%
49   rowwise() %>%
50   mutate(
51     avg_max_dry_days = mean(cdd_results$max_cdd[
52       cdd_results$plot_group == plot_group &
53       cdd_results$year >= previous_year &
54       cdd_results$year <= year],
55     na.rm = TRUE)
56   ) %>%
57   ungroup()
58
59
60 # the updated 'stand' dataset with the average maximum consecutive dry days for
61 # each time period
62 print(stand_with_dry_days)
63
64 # Berechne den Mittelwert der max_consecutive_dry_days pro Jahr (ohne plot_group)
65 daymet_year_mean <- cdd_results %>%
66   group_by(year) %>%
67   summarise(mean_dry_days = mean(max_cdd, na.rm = TRUE))
68
69 # Zeitreihe /mean der max. cons. dry days
70
71 ggplot(daymet_year_mean, aes(x = year, y = mean_dry_days)) +
72   geom_line(color = "steelblue") + # Linienplot
73   labs(title = " Mean # of max. consecutive dry days/year of all plots",
74     x = "Year",
75     y = "# of consecutive dry days") +
76   theme_minimal() +
77   scale_x_continuous(limits = c(1930, 2020), breaks = seq(1930, 2020, by = 15)) + #
78     x-Achse von 1930 bis 2020
79   scale_y_continuous(limits = c(0, 50)) + # y-Achse von 0 bis 50
80   geom_smooth(method = "lm", formula = y ~ poly(x, 9), color = "black", se = FALSE) #
81     Polynomielllinie 2. Grades
82
83 # Create a plot containing every plot_group

```

```

82
83 cdd_results$plot_group <- as.factor(cdd_results$plot_group) #plot_group into a factor
84
85 ggplot(cdd_results, aes(x = year, y = max_cdd, color = plot_group)) +
86   geom_line() +
87   labs(title = "Trend for # of consecutive dry days (prec < 1mm) per year for each plot",
88        x = "Year",
89        y = "Days") +
90   # Customize line colors
91   theme_minimal() +
92   scale_x_continuous(limits = c(1930, 2020), breaks = seq(1930, 2020, by = 15)) +
93   scale_y_continuous(limits = c(10, 40)) +
94   scale_color_manual(values = c20)

```

Calculation of the total number of days with $t_{max} > 28^{\circ}C$

```

1 ##Heatwaves: Total number of days with Tmax>28
2
3 # Load necessary libraries
4
5 library(DHARMA)
6 library(patchwork)
7 ### days with Temp >= 28/Heatwaves
8
9
10 stand <- readRDS("data/stand_v4.rds")
11 daymet <- readRDS("data/daymet.rds")
12
13 # 1. Calculate the number of heatwave days (tmax >= 30) per year # berprft !
14 daymet_heatwave_days <- daymet %>%
15   group_by(plot_group, year) %>%
16   summarise(heatwave_days = sum(tmax >= 28)) %>%
17   ungroup()
18
19 # 2. Merge 'stand' data with 'daymet_heatwave_days' and calculate the mean for each plot
20 # berprft !
21 stand <- stand %>%
22   arrange(plot_group, species) %>%
23   group_by(plot_group) %>%
24   mutate(previous_year = lag(year)) %>%
25   filter(!is.na(previous_year)) %>%
26   rowwise() %>%
27   mutate(
28     tmax28 = mean(daymet_heatwave_days$heatwave_days[
29       daymet_heatwave_days$plot_group == plot_group &
30       daymet_heatwave_days$year >= previous_year &
31       daymet_heatwave_days$year <= year],
32     na.rm = TRUE)
33   ) %>%
34   ungroup()
35
36 #stand1 containing heatwave days and drydays
37 #stand1<- stand_with_heatwave_days
38
39
40
41 ##save to new file v2... containing AWC, elevation and Climate data!
42
43 #saveRDS(stand, "data/stand_v3.rds")
44
45 #save tree data aswell
46 #saveRDS(stand, "data/tree_v2.rds")
47
48 # Berechne den Mittelwert der max_consecutive_dry_days pro Jahr (ohne plot_group)
49 daymet_year_mean_heat <- daymet_heatwave_days %>%
50   group_by(year) %>%
51   summarise(mean_heatwave_days = mean(heatwave_days, na.rm = TRUE))
52
53 # Zeitreihe /mean der max. cons. dry days
54 plot2<- ggplot(daymet_year_mean_heat, aes(x = year, y = mean_heatwave_days)) +
55   geom_line(color = "steelblue") + # Linienplot
56   labs(title = "Mean of all plots # of days with Tmax > 28 C per year",
57        x = "Year",
58        y = "# of days Tmax > 28 C ") +
59   theme_minimal() +
60   scale_x_continuous(limits = c(1930, 2020), breaks = seq(1930, 2020, by = 15)) + #
61     x-Achse von 1930 bis 2020

```

```

61 scale_y_continuous(limits = c(0, 10)) + # y-Achse von 0 bis 50
62 geom_smooth(method = "lm", formula = y ~ poly(x, 7.5), color = "black", se = FALSE) #
   Polynomielllinie 2. Grades
63
64
65 plot2
66 # Reshape the data to long format
67 daymet_combined <- daymet_year_mean %>%
68   select(year, mean_dry_days) %>%
69   rename(mean_values = mean_dry_days) %>%
70   mutate(variable = "Dry days") %>%
71   bind_rows(
72     daymet_year_mean_heat %>%
73       select(year, mean_heatwave_days) %>%
74       rename(mean_values = mean_heatwave_days) %>%
75       mutate(variable = "Heatwave days")
76   )
77
78 # Create the plot
79 ##komischerweise weniger heatwave tage als bei erster Durchf hrung, siehe Image
80
81 ggplot(daymet_combined, aes(x = year, y = mean_values, color = variable)) +
82   geom_line() +
83   labs(title = "Trend for # of consecutive dry days (prec < 1mm) and # of heatwave days(
      Tmax > 28 C ) per year",
84     x = "Year",
85     y = "Days") +
86   scale_color_manual(values = c("darkgoldenrod3", "tomato3")) + # Customize line colors
87   theme_minimal() +
88   scale_x_continuous(limits = c(1930, 2020), breaks = seq(1930, 2020, by = 15)) +
89   scale_y_continuous(limits = c(0, 50)) +
90   geom_smooth(data = subset(daymet_combined, variable == "Dry Days"),
91     method = "lm", formula = y ~ poly(x, 9),
92     color = "gray51", se = FALSE) +
93   geom_smooth(data = subset(daymet_combined, variable == "Dry Days"),
94     method = "lm",
95     color = "black", se = FALSE, linetype = "dashed", size =0.25)

```

B.3 Vitality

Addition of basic parameters

```

1 ##add the AWC and the elevation to stand file
2 setwd("C:/Users/tobia/Documents/soil_vitality_plenter")
3
4 rm(list=ls())
5
6 library(readr)
7 library(ggplot2)
8 library(ggfortify)
9 library(tidyverse)
10 library(boot)
11 library(readr)
12 library(sf)
13 library(tibble)
14 library(extrafont)
15 library(purrr)
16 library(plotly)
17 library(glmTMB)
18
19
20 plot<- readRDS("data/plot.rds")
21
22
23 stand <- readRDS("data/stand_v6.rds")
24 tree <- readRDS("data/tree_v6.rds")
25
26
27 tree$plot<-as.numeric(tree$plot)
28
29
30 # Create a lookup table for AWC and plot values
31 awc_table <- data.frame(
32   AWC = c(232.02, 174.22, 188.19, 251.81, 159.34, 217.53, 170.20, 186.08, 166.92,
33     218.66, 174.62, 170.85, 225.81, 144.52, 164.47, 204.08, 198.13, 133.91,
34     124.11, 260.30),
35   plot = c(1014000, 1015001, 1015002, 1021000, 1027000, 1028000, 1030000, 1031000,
36     1033000, 1034000, 1041000, 1042000, 1046000, 2034000, 2035000, 2047000,

```

```

37         21290000, 21293001, 21293002, 21294000)
38     )
39
40     stand <- stand %>%
41       left_join(awc_table, by = "plot")
42
43     tree <- tree %>%
44       left_join(awc_table, by = "plot")
45
46
47     #add rounded AWC values
48     #create a lookup table for AWC and plot values
49     awc_rounded <- data.frame(
50       AWC_rounded = c(232, 174, 188, 252, 159, 217, 170, 186, 167,
51                       219, 175, 171, 226, 145, 164, 204, 198, 134,
52                       124, 260),
53       plot = c(1014000, 1015001, 1015002, 1021000, 1027000, 1028000, 1030000, 1031000,
54                1033000, 1034000, 1041000, 1042000, 1046000, 2034000, 2035000, 2047000,
55                21290000, 21293001, 21293002, 21294000)
56     )
57
58
59     stand <- stand %>%
60       left_join(awc_rounded, by = "plot")
61
62     tree <- tree %>%
63       left_join(awc_rounded, by = "plot")
64
65
66     # Check the updated data
67     head(stand)
68
69
70
71     ## add elevation to stand
72
73
74     #get elevation from plot data
75
76     count(plot,elevation, plot)
77
78     el_table <- data.frame(
79       elevation = c(1040, 947, 931, 1040, 861, 970, 910, 920, 1810, 1810, 1294,
80                    1185, 930, 975, 983, 1070, 960, 1370, 1400, 1340),
81       plot = c(1014000, 1015001, 1015002, 1021000, 1027000, 1028000, 1030001, 1031000,
82                1033000, 1034000, 1041000, 1042000, 1046000, 2034000, 2035000, 2047000,
83                21290000, 21293001, 21293002, 21294000)
84     )
85
86
87     stand <- stand %>%
88       left_join(el_table, by = "plot")
89
90     tree <- tree %>%
91       left_join(el_table, by = "plot")
92
93     # Check the updated data
94     head(stand)
95
96     saveRDS(stand, "data/stand_awc.rds")
97
98     ##same for tree
99     tree <- tree %>%
100       left_join (el_table, by = "plot")
101
102     saveRDS(tree, "data/tree_awc.rds")
103
104
105
106
107     ##AWC_old
108
109
110     # Create a lookup table for AWC and plot values
111     awc_old_table <- data.frame(
112       AWC_old = c(216.72, 192.88, 192.88, 193.20, 200.34, 175.02, 196.54, 189.12,
113                  181.61, 171.36, 178.14, 187.14, 202.13, 218.60, 188.58, 176.20,
114                  182.50, 279.82, 279.82, 260.30),
115       plot = c(1014000, 1015001, 1015002, 1021000, 1027000, 1028000, 1030000, 1031000,

```

```

116         1033000, 1034000, 1041000, 1042000, 1046000, 2034000, 2035000, 2047000,
117         21290000, 21293001, 21293002, 21294000)
118     )
119
120     stand <- stand %>%
121       left_join(awc_old_table, by = "plot")
122
123     # Check the updated data
124     head(stand)
125
126     #add time value--> time= year-1905
127
128
129     stand$time <- stand$year-1904
130
131
132     #add stem_number
133
134     #stand$stem_number <- plot$stem_number
135     #with id plot
136
137     stand <- left_join(stand, plot[, c("plot", "stem_number")], by = "plot")
138
139
140
141
142     # add proportion of picea abies
143
144     picea_table <- data.frame(
145       prop_picea = c(50.23, 29.17, 41.2, 52.87, 30.88, 21.34, 42.25, 35.2, 63.8, 57.68,
146                     49.67, 41.89, 54.95, 14.15, 22.1, 15.93, 84.418, 97.91, 95.83, 84.57),
147       plot = c(1014000, 1015001, 1015002, 1021000, 1027000, 1028000, 1030000, 1031000,
148               1033000, 1034000, 1041000, 1042000, 1046000, 2034000, 2035000, 2047000,
149               21290000, 21293001, 21293002, 21294000)
150     )
151
152     stand <- stand %>%
153       left_join(picea_table, by = "plot")
154
155     tree <- tree %>%
156       left_join(picea_table, by = "plot")
157
158
159     ##add proportion of abies alba
160     abies_table <- data.frame(
161       prop_abies = c(49.761575, 65.65795, 53.19671, 36.178888, 63.12235, 65.21393, 23.533601,
162                     59.49461, 0, 0, 46.529253, 54.73439, 40.498970, 59.60842, 53.85661,
163                     65.29992,
164                     10.119000, 0,0, 7.11),
165       plot = c(1014000, 1015001, 1015002, 1021000, 1027000, 1028000, 1030000, 1031000,
166               1033000, 1034000, 1041000, 1042000, 1046000, 2034000, 2035000, 2047000,
167               21290000, 21293001, 21293002, 21294000)
168     )
169
170
171     stand <- stand %>%
172       left_join(abies_table, by = "plot")
173
174     tree <- tree %>%
175       left_join(abies_table, by = "plot")
176
177     ##Save
178     saveRDS(stand, "data/stand_v7.rds")
179
180     saveRDS(tree, "data/tree_v7.rds")

```

Basal area increment (BAI)

The Basal area of different species for each plot

```

1 ##new plot
2
3 plot <- readRDS("data/plot.rds")
4 tree <- readRDS("data/tree.rds")
5 stand<- readRDS("data/stand_original.rds")
6 stand_v1<- readRDS("data/stand.rds")

```

```

7
8 ##all 1030001 and 1030002 and 1030003 together
9
10 stand <- stand %>%
11   mutate(plot = ifelse(plot_group == 1030, 1030000, plot))
12
13 ##add 1014
14 data_1014<-stand_v1 %>% filter(plot==1014000 & year > 1968)
15
16 stand<- bind_rows(stand, data_1014)
17
18 stand <- stand[!is.na(stand$species), ] # deleting NAs = deleting species 9999 = deleting
19   stand values
20
21 ##all species except picea, abies & fagus = NA
22
23 stand <- stand %>%
24   mutate(species = ifelse(species %in% c("Picea abies", "Abies alba", "Fagus sylvatica"),
25     species, NA))
26
27 stand_2013 <- filter(stand, year >= 2013 | plot_group ==1014 & year >=1965 )
28 summary(stand_2013$plot_group)
29
30 newest_recordings <- filter(stand_2013, year > 2014 | plot_group == 1041 |plot_group==1042
31   |plot_group==21294| plot_group == 1014)
32
33 newest_recordings$plot <- as.factor(newest_recordings$plot)
34 summary(newest_recordings)
35
36 ##make a nice bar graph to show quantity of species
37 newest_recordings <- mutate(newest_recordings, plot_group = as.factor(plot_group))
38
39 stand_2013<-mutate(stand_2013, plot=as.factor(plot))
40
41 ggplot(stand_2013, aes(x = plot, y = basal_area_retained, fill = species)) +
42   geom_bar(stat = "identity")
43
44 #change the order
45 newest_recordings <- newest_recordings %>%
46   mutate(species = factor(species, levels = c("NA", "Fagus sylvatica", "Abies alba","Picea
47     abies")))
48
49 # Replace NA values in species column with "NA" as a string
50 newest_recordings <- newest_recordings %>%
51   mutate(species = ifelse(is.na(species), "NA", species))
52
53 # Create the bar plot with manually set legend labels
54 bp <- ggplot(newest_recordings, aes(x = plot, y = basal_area_retained, fill = species)) +
55   geom_bar(stat = "identity") +
56   scale_fill_manual(
57     values = c("4" = "#007058",
58       "3" = "#77B6EA",
59       "2" = "#E69F00",
60       "NA" = "grey55"), # Assigning a color to "NA"
61     labels = c("4" = "Picea abies",
62       "3" = "Abies alba",
63       "2" = "Fagus sylvatica",
64       "NA" = "Other") # Ensuring "NA" appears in the legend
65   ) +
66   guides(fill = guide_legend(title = "Species")) +
67   labs(
68     subtitle = "Species proportion in the plenter forests for the recent inventory",
69     x = "Plots",
70     y = expression("Basal area retained [m^2*"/ha]"))
71   ) +
72   theme_minimal(base_size = 20) +
73   theme(
74     text = element_text(family = "Times New Roman"),
75     plot.subtitle = element_text(hjust = 0.5),
76     axis.text = element_text(color = "grey6"),
77     axis.text.x = element_text(angle = 45, hjust = 1),
78     panel.grid.major = element_line(color = "gray90"),
79     legend.title = element_text(size = 14)
80   )
81
82 # Print the plot
83 bp

```


Plot of BAI_{adj} for different plot groups

```

1 ## new graph of two plots
2 ## stand level
3 ## one containing low AWC other containing high AWC values
4 ## temporal change
5
6 ##getting rid of the outliers 21294 Le Chenit(not measured) and 21293001 &21293002
7 ## Sigriswil(huge stone content)
8
9 plot<- readRDS("data/plot.rds")
10 stand <- readRDS("data/stand_v6.rds")
11 df <- stand %>% filter(!(plot_group %in% c("21294", "21293")))
12 df<- df %>% filter(!(year<1930))
13
14
15 ##subsetting each species
16 abies_alba <- subset(df, species == "Abies alba")
17 # Select rows where the species is "Fagus sylvatica"
18 fagus_sylvatica <- subset(df, species == "Fagus sylvatica")
19 # Select rows where the species is "Picea abies"
20 picea_abies <- subset(df, species == "Picea abies")
21
22 ##delete NAs
23 stand_sub <- filter(df, basal_area_increment >0)
24 picea_sub <- filter(picea_abies, basal_area_increment > 0)
25 fagus_sub <- filter(fagus_sylvatica, basal_area_increment >0)
26 abies_sub <- filter(abies_alba, basal_area_increment >0)
27
28 ##add adjusted BAI
29 picea_sub$BAI_adj <- picea_sub$basal_area_increment / picea_sub$prop_picea * 100
30
31 abies_sub$BAI_adj <- abies_sub$basal_area_increment / abies_sub$prop_abies * 100
32
33
34 summary(picea_sub)
35
36
37 fagus_sub$BAI_adj<-fagus_sub$basal_area_increment
38
39
40 selected_plots <- c(1031000,21290000)
41
42 picea_filtered <- picea_sub %>%
43   filter(plot %in% selected_plots)
44
45 ggplot(picea_filtered, aes(x = year, y = basal_area_increment, color = as.factor(plot))) +
46   geom_line() +
47   geom_point(alpha = 0.7) +
48   labs(title = "Temporal Change in BAI_adj for Selected Plots",
49     x = "Year",
50     y = "BAI_adj",
51     color = "Plot") +
52   theme_minimal()
53
54
55 #picea_sub<-abies_sub
56
57 #-----
58 #the real deal
59
60 library(ggplot2)
61 library(ggtext)
62 library(patchwork)
63 library(dplyr)
64
65 # Define color palettes for each group
66 colors_plot1 <- c("1015002" = "#E69F00", "1014000" = "#006268ff")
67 colors_plot2 <- c("1033000" = "#E69F00", "1034000" = "#006268ff")
68 colors_plot3 <- c("1042000" = "#E69F00", "1041000" = "#006268ff")
69 colors_plot4 <- c("1027000" = "#E69F00", "1028000" = "#006268ff")
70
71
72 # Filter data for each plot group
73 picea_plot1 <- picea_sub %>% filter(plot %in% c(1015002, 1014000))
74 picea_plot2 <- picea_sub %>% filter(plot %in% c(1033000, 1034000))
75 picea_plot3 <- picea_sub %>% filter(plot %in% c(1042000, 1041000))
76 picea_plot4 <- picea_sub %>% filter(plot %in% c(1027000, 1028000))
77
78 p1

```

```

79
80 # Create individual plots
81 p3 <- ggplot(picea_plot1, aes(x = year, y = BAI_adj, color = as.factor(plot), shape =
82   as.factor(plot))) +
83   geom_line() +
84   geom_point(alpha = 0.7, size=2) +
85   scale_color_manual(values = colors_plot1,
86     labels = c("1015002" = "1015002 (188.19mm)", "1014000" = "1014000
87     (232.04mm)")) +
88   scale_shape_manual(values = c("1015002" = 18, "1014000" = 17),
89     labels = c("1015002" = "1015002 (188.19mm)", "1014000" = "1014000
90     (232.04mm)")) + # Ensure labels match
91   labs(
92     title = "Ober- and Niederh nigen",
93     x = "Year",
94     y = expression(BAI[adj] ~ "[" ~ m^2 ~ "/ha a]"),
95     color = "Plot",
96     shape = "Plot"
97   ) +
98   scale_x_continuous(limits = c(1930, 2020), breaks = seq(1930, 2020, by = 15)) +
99   scale_y_continuous(limits = c(1, 11), breaks = seq(0,10, by = 2.5)) +
100   guides(shape = guide_legend(override.aes = list(size = 3))) +
101   theme_minimal(base_size = 16) +
102   theme(
103     text = element_text(family = "Times New Roman"),
104     plot.title = element_text(hjust = 0.5, face = "bold"),
105     axis.text = element_text(color = "grey6"),
106     panel.grid.major = element_line(color = "gray90")
107   )
108
109 # St. Moritz
110 p2 <- ggplot(picea_plot2, aes(x = year, y = BAI_adj, color = as.factor(plot), shape =
111   as.factor(plot))) +
112   geom_line() +
113   geom_point(alpha = 0.7, size = 2) +
114   scale_color_manual(values = colors_plot2,
115     labels = c("1033000" = "1033000 (166.92mm)", "1034000" = "1034000
116     (218.66mm)")) +
117   scale_shape_manual(values = c("1033000" = 18, "1034000" = 17),
118     labels = c("1033000" = "1033000 (166.92mm)", "1034000" = "1034000
119     (218.66mm)")) +
120   labs(
121     title = "St. Moritz",
122     x = "Year",
123     y = expression(BAI[adj] ~ "[" ~ m^2 ~ "/ha a]"),
124     color = "Plot",
125     shape = "Plot"
126   ) +
127   scale_x_continuous(limits = c(1930, 2020), breaks = seq(1930, 2020, by = 15)) +
128   scale_y_continuous(limits = c(1, 11), breaks = seq(0, 10, by = 2.5)) +
129   guides(
130     color = guide_legend(override.aes = list(shape = c(18, 17), size = 3)),
131     shape = "none"
132   ) +
133   theme_minimal(base_size = 16) +
134   theme(
135     text = element_text(family = "Times New Roman"),
136     plot.title = element_text(hjust = 0.5, face = "bold"),
137     axis.text = element_text(color = "grey6"),
138     panel.grid.major = element_line(color = "gray90")
139   )
140
141 # Rougemont
142 p4 <- ggplot(picea_plot3, aes(x = year, y = BAI_adj, color = as.factor(plot), shape =
143   as.factor(plot))) +
144   geom_line() +
145   geom_point(alpha = 0.7, size = 2) +
146   scale_color_manual(values = colors_plot3,
147     labels = c("1042000" = "1042000 (170.85mm)", "1041000" = "1041000
148     (174.62mm)")) +
149   scale_shape_manual(values = c("1042000" = 18, "1041000" = 17),
150     labels = c("1042000" = "1042000 (170.85mm)", "1041000" = "1041000
151     (174.62mm)")) +
152   labs(
153     title = "Rougemont",
154     x = "Year",
155     y = expression(BAI[adj] ~ "[" ~ m^2 ~ "/ha a]"),
156     color = "Plot",

```

```

149   shape = "Plot"
150 ) +
151 scale_x_continuous(limits = c(1930, 2020), breaks = seq(1930, 2020, by = 15)) +
152 scale_y_continuous(limits = c(1, 11), breaks = seq(0, 10, by = 2.5)) +
153 guides(
154   color = guide_legend(override.aes = list(shape = c(17, 18), size = 3)),
155   shape = "none"
156 ) +
157 theme_minimal(base_size = 16) +
158 theme(
159   text = element_text(family = "Times New Roman"),
160   plot.title = element_text(hjust = 0.5, face = "bold"),
161   axis.text = element_text(color = "grey6"),
162   panel.grid.major = element_line(color = "gray90")
163 )
164
165 # Bowil
166 p1 <- ggplot(picea_plot4, aes(x = year, y = BAI_adj, color = as.factor(plot), shape =
167   as.factor(plot))) +
168   geom_line() +
169   geom_point(alpha = 0.7, size = 2) +
170   scale_color_manual(values = colors_plot4,
171     labels = c("1027000" = "1027000 (159.34mm)", "1028000" = "1028000
172     (217.53mm)")) +
173   scale_shape_manual(values = c("1027000" = 18, "1028000" = 17),
174     labels = c("1027000" = "1027000 (159.34mm)", "1028000" = "1028000
175     (217.53mm)")) +
176   labs(
177     title = "Bowil",
178     x = "Year",
179     y = expression(BAI[adj] ~ "[" ~ m^2 ~ "/ha a]"),
180     color = "Plot",
181     shape = "Plot"
182   ) +
183   scale_x_continuous(limits = c(1930, 2020), breaks = seq(1930, 2020, by = 15)) +
184   scale_y_continuous(limits = c(1, 11), breaks = seq(0, 10, by = 2.5)) +
185   guides(
186     color = guide_legend(override.aes = list(shape = c(18, 17), size = 3)),
187     shape = "none"
188   ) +
189   theme_minimal(base_size = 16) +
190   theme(
191     text = element_text(family = "Times New Roman"),
192     plot.title = element_text(hjust = 0.5, face = "bold"),
193     axis.text = element_text(color = "grey6"),
194     panel.grid.major = element_line(color = "gray90")
195   )
196
197 # Combine the plots in a 2x2 layout
198 p00 <- wrap_plots(p1, p2, p3, p4, ncol = 2) +
199   plot_annotation(
200     title = expression(paste("Temporal change in BAI"[adj],
201       " across different plot groups for ", italic("Picea abies"))),
202     theme = theme(
203       text = element_text(family = "Times New Roman"),
204       plot.title = element_text(hjust = 0.5, face = "bold", size = 22)
205     )
206   )
207
208 p00 # Display the combined plot

```

Statistical analysis using glmmTMB

```

1 ## Results and point estimates
2
3 ##getting rid of the outliers 21294 Le Chenit(not measured) and 21293001 & 21293002
4 ## Sigriswil(huge stone content)
5
6 stand <- readRDS("data/stand_v6.rds")
7 df <- stand %>% filter(!(plot_group %in% c("21294", "21293")))
8 df <- df %>% filter(!(year < 1930))
9
10 summary(df)
11 ##subsetting each species
12 abies_alba <- subset(df, species == "Abies alba")
13 # Select rows where the species is "Fagus sylvatica"
14 fagus_sylvatica <- subset(df, species == "Fagus sylvatica")
15 # Select rows where the species is "Picea abies"

```

```

16 picea_abies <- subset(df, species == "Picea abies")
17
18 ##delete NAs
19 stand_sub <- filter(df, basal_area_increment > 0)
20 picea_sub <- filter(picea_abies, basal_area_increment > 0)
21 fagus_sub <- filter(fagus_sylvatica, basal_area_increment > 0)
22 abies_sub <- filter(abies_alba, basal_area_increment > 0)
23
24 ##add adjusted BAI
25 picea_sub$BAI_adj <- picea_sub$basal_area_increment / picea_sub$prop_picea * 100
26
27 abies_sub$BAI_adj <- abies_sub$basal_area_increment / abies_sub$prop_abies * 100
28
29 picea_sub_o20 <- picea_sub %>% filter(!(prop_picea < 20))
30 picea_sub_o20 <- picea_sub_o20[complete.cases(picea_sub_o20[, c("AWC", "BAI_adj", "time",
31 "avg_prdp", "tmax28", "avg_max_dry_days", "prop_picea", "elevation", "QMD")]), ]
32 abies_sub <- abies_sub[complete.cases(abies_sub[, c("AWC", "BAI_adj", "time", "avg_prdp",
33 "tmax28", "avg_max_dry_days", "prop_picea", "elevation", "QMD")]), ]
34
35 #histogramm for BAI_adj
36
37 picea_sub$avg_max_dry_days %>% hist()
38
39 plot(picea_sub$BAI_adj ~ picea_sub$prop_picea)
40
41 lm(picea_sub$BAI_adj ~ picea_sub$prop_picea)
42 abline(lm(picea_sub$BAI_adj ~ picea_sub$prop_picea))
43
44 plot(abies_sub$BAI_adj ~ abies_sub$prop_abies)
45
46 lm(picea_sub$BAI_adj ~ picea_sub$prop_picea)
47 abline(lm(abies_sub$BAI_adj ~ abies_sub$prop_picea))
48 #macht Sinn das abies gerade Linie(nicht von Fichte abh ngig, da Tiefwurzler)
49 #macht Sinn das picea schr g, heisst je mehr monokultur desto schlechter, da Flachwurzler,
50 gleich mehr intraspecies konkurrenz
51 #only data with more than 20 % prop_picea because of sample size effect
52
53 ##CHECK AGAIN, Picea
54
55 n0 <- glmmTMB(BAI_adj ~ AWC + time +
56 avg_prdp +
57 tmax28 +
58 avg_max_dry_days +
59 prop_picea +
60 elevation +
61 QMD + (1 | plot), data = picea_sub_o20,
62 family = gaussian("identity"))
63
64 n3 <- glmmTMB(BAI_adj ~ time +
65 AWC * avg_prdp +
66 tmax28 +
67 AWC * avg_max_dry_days +
68 prop_picea +
69 elevation +
70 QMD + (1 | plot), data = picea_sub_o20,
71 family = gaussian("identity"))
72
73 #-AWC
74 n3_2 <- glmmTMB(BAI_adj ~ time +
75 avg_prdp +
76 tmax28 +
77 avg_max_dry_days +
78 prop_picea +
79 elevation +
80 QMD + (1 | plot), data = picea_sub_o20,
81 family = gaussian("identity"))
82
83 #-avg_prdp
84 n3_3 <- glmmTMB(BAI_adj ~ time +
85 AWC * avg_max_dry_days +
86 tmax28 +
87 prop_picea +
88 elevation +
89 QMD + (1 | plot), data = picea_sub_o20,
90 family = gaussian("identity"))
91
92 #-avg_max_dry_days
93 n3_4 <- glmmTMB(BAI_adj ~ time +

```

```

92         AWC * avg_prcp +
93         tmax28 +
94         prop_picea +
95         elevation +
96         QMD + (1 | plot), data = picea_sub_o20,
97         family = gaussian("identity"))
98
99 anova(n3, n3_2)
100 anova(n3, n3_3)
101 anova(n3, n3_4)
102
103 ##Abies alba
104
105
106 n4 <- glmmTMB(BAI_adj ~ time +
107               AWC * avg_prcp +
108               tmax28 +
109               AWC * avg_max_dry_days +
110               prop_abies +
111               elevation +
112               QMD + (1 | plot), data = abies_sub,
113               family = gaussian("identity"))
114
115 #-AWC
116 n4_2 <- glmmTMB(BAI_adj ~ time +
117                 avg_prcp +
118                 tmax28 +
119                 avg_max_dry_days +
120                 prop_abies +
121                 elevation +
122                 QMD + (1 | plot), data = abies_sub,
123                 family = gaussian("identity"))
124
125 #-avg_prcp
126 n4_3 <- glmmTMB(BAI_adj ~ time +
127                 AWC * avg_max_dry_days +
128                 tmax28 +
129                 prop_abies +
130                 elevation +
131                 QMD + (1 | plot), data = abies_sub,
132                 family = gaussian("identity"))
133
134 #-avg_max_dry_days
135 n4_4 <- glmmTMB(BAI_adj ~ time +
136                 AWC * avg_prcp +
137                 tmax28 +
138                 prop_abies +
139                 elevation +
140                 QMD + (1 | plot), data = abies_sub,
141                 family = gaussian("identity"))
142
143 anova(n4, n4_2)
144 anova(n4, n4_3)
145 anova(n4, n4_4)
146
147 plot(simulateResiduals(n3))
148 plot(simulateResiduals(n4))
149
150 summary(picea_sub_o20)
151
152 ##point estimates
153
154 new_data <- expand.grid(
155   AWC = c(150, 200, 250),
156   time = c(71),
157   avg_prcp = mean(df$avg_prcp, na.rm = TRUE),
158   avg_max_dry_days = mean(df$avg_max_dry_days, na.rm = TRUE),
159   tmax28 = mean(df$tmax28, na.rm = TRUE),
160   prop_picea = c(50),
161   elevation = mean(df$elevation, na.rm = TRUE),
162   QMD = c(30))
163 )
164
165
166 new_data <- expand.grid(
167   AWC = c(150, 200, 250),
168   time = c(36, 71, 106),
169   avg_prcp = mean(df$avg_prcp, na.rm = TRUE),
170   avg_max_dry_days = mean(df$avg_max_dry_days, na.rm = TRUE),

```

```

171   tmax28 = mean(df$tmax28, na.rm = TRUE),
172   prop_abies = c(50),
173   elevation = mean(df$elevation, na.rm = TRUE),
174   QMD = c(25,40))
175 )
176
177
178
179 new_data_v1 <- expand.grid(
180   AWC = c(150, 250),
181   time = c(71),
182   avg_prdp = c(600,1200),
183   avg_max_dry_days = c(15,35),
184   tmax28 = mean(df$tmax28, na.rm = TRUE),
185   prop_picea = c(50),
186   elevation = mean(df$elevation, na.rm = TRUE),
187   QMD = mean(df$QMD, na.rm = TRUE)
188 )
189
190
191 new_data$predicted_BAI <- predict(n4, new_data, re.form = NA)
192 new_data$predicted_BAI <- predict(n3, new_data, re.form = NA)
193
194 new_data_v1$predicted_BAI <- predict(n3, new_data_v1, re.form = NA)
195
196 print(new_data)
197 print(new_data_v1)
198
199
200 ##precipitation
201 new_data_02 <- expand.grid(
202   AWC = c(100, 200, 300),
203   time = c(71),
204   avg_prdp = c(700,1100),
205   avg_max_dry_days = mean(df$avg_max_dry_days, na.rm = TRUE),
206   tmax28 = mean(df$tmax28, na.rm = TRUE),
207   prop_picea = c(50),
208   elevation = mean(df$elevation, na.rm = TRUE),
209   QMD = c(30))
210
211
212 #max # dry days
213 new_data_03<- expand.grid(
214   AWC = c(100, 200, 300),
215   time = c(71),
216   avg_prdp = mean(df$avg_prdp, na.rm = TRUE),
217   avg_max_dry_days = c(13,27),
218   tmax28 = mean(df$tmax28, na.rm = TRUE),
219   prop_picea = c(50),
220   elevation = mean(df$elevation, na.rm = TRUE),
221   QMD = c(30))
222
223
224 new_data_02$predicted_BAI <- predict(n4, new_data_02, re.form = NA)
225 new_data_03$predicted_BAI <- predict(n4, new_data, re.form = NA)
226
227 print(new_data_02)
228 print(new_data_03)
229
230
231
232
233 new_data_v2 <- expand.grid(
234   AWC = c(150, 250),
235   time = c(71),
236   avg_prdp = c(600,1200),
237   avg_max_dry_days = c(15,35),
238   tmax28 = mean(df$tmax28, na.rm = TRUE),
239   prop_abies = c(50),
240   elevation = mean(df$elevation, na.rm = TRUE),
241   QMD = mean(df$QMD, na.rm = TRUE)
242 )
243 new_data_v2$predicted_BAI <- predict(n4, new_data_v2, re.form = NA)
244 print(new_data_v2)

```

Change of tree crown volume (DCV)

Tree crown volume calculation

```

1 ##tree crown volume calculation
2
3 tree <- readRDS("data/tree.rds")
4 tree_crown_volume <- readRDS("data/tree_crown_volume.rds")
5
6 view(tree)
7
8 calculate_crown_volume <- function(species, l, dia) {
9   # Define species-specific parameters
10  species_params <- list(
11    "Picea abies" = list(l0_factor = 0.66, b = 1, a_exp = 1, rcb_factor = 0.5),
12    "Abies alba" = list(l0_factor = 0.5, b = 0.5, a_exp = 0.5, rcb_factor = 0.5),
13    "Pinus silvestris" = list(l0_factor = 0.68, b = 0.5, a_exp = 1, rcb_factor = 0.63),
14    "Larix decidua" = list(l0_factor = 0.66, b = 0.5, a_exp = 1, rcb_factor = 0.5),
15    "Fagus sylvatica" = list(l0_factor = 0.40, b = 0.33, a_exp = 0.33, rcb_factor = 0.33),
16    "Acer pseudoplatanus" = list(l0_factor = 0.35, b = 0.52, a_exp = 0.33, rcb_factor = 1)
17  )
18
19  # Get parameters for the species
20  params <- species_params[[species]]
21  if (is.null(params)) {
22    stop(paste("species", species, "is not supported."))
23  }
24
25  # Calculate rmax, l0, a, rcb, d, c
26  rmax <- dia / 2
27  l0 <- l * params$l0_factor
28  b <- params$b
29  a <- rmax / (10^b)
30  rcb <- rmax * params$rcb_factor
31  d <- (rcb - rmax) / (1 - l0)
32  c <- rmax - d * l0
33
34  # Define the integrand functions
35  f1 <- function(x) pi * (a * x^params$b)^2
36  f2 <- function(x) pi * (c + d * x)^2
37
38  # Integrate to find the volume
39  v1 <- integrate(f1, lower = 0, upper = l0)$value
40  v2 <- integrate(f2, lower = l0, upper = 1)$value
41
42  # Total volume
43  v1 + v2
44 }
45
46 tree$crown_volume <- NA # Initialize a new column for the crown volumes
47
48 # Loop through each row
49 for (i in 1:nrow(tree)) {
50   species <- as.character(tree$species[i]) # Extract species as a character string
51
52   if (species == "Picea abies" ||
53       species == "Abies alba" ||
54       species == "Pinus silvestris" ||
55       species == "Larix decidua" ||
56       species == "Fagus sylvatica" ||
57       species == "Acer pseudoplatanus") {
58
59     # Calculate crown volume only for these species
60     tree$crown_volume[i] <- calculate_crown_volume(
61       species = species,
62       l = tree$live_crown_length_calc[i],
63       dia = tree$crown_diameter_calc[i]
64     )
65   } else {
66     # Set to NA if species is not recognized
67     tree$crown_volume[i] <- NA
68   }
69 }
70
71 ##SAMPLE trees for calculating with hand to check if it worked properly!
72
73 sampled_trees <- tree_crown_volume %>%
74   slice_sample(n=20)
75
76 #tree_crown_volume <- tree
77
78 saveRDS(tree, "data/tree_crown_volume_2.rds")

```

```

79
80 view (tree_crown_volume)

```

Graphic for the three dimensional crown volume

```

1 # Load required library
2 library(plotly)
3 library(reticulate)
4
5 # Function to create 3D plot of tree crown
6 plot_3d_crown <- function(l, dia, species) {
7   # Parameters
8   rmax <- dia / 2
9
10  # Define species parameters
11  species_params <- list(
12    "Picea abies" = list(l0 = 1 * 0.66, a_factor = 1, b = 1, rcb_factor = 0.5),
13    "Abies alba" = list(l0 = 1 * 0.5, a_factor = 0.5, b = 0.5, rcb_factor = 0.5),
14    "Pinus silvestris" = list(l0 = 1 * 0.68, a_factor = 1, b = 0.5, rcb_factor = 0.63),
15    "Larix decidua" = list(l0 = 1 * 0.66, a_factor = 1, b = 0.5, rcb_factor = 0.5),
16    "Fagus sylvatica" = list(l0 = 1 * 0.4, a_factor = 0.33, b = 0.33, rcb_factor = 0.33),
17    "Acer pseudoplatanus" = list(l0 = 1 * 0.35, a_factor = 0.33, b = 0.52, rcb_factor = 0)
18  )
19
20  if (!species %in% names(species_params)) {
21    stop("Species not defined in the parameters list.")
22  }
23
24  # Retrieve parameters for the species
25  params <- species_params[[species]]
26  l0 <- params$l0
27  b <- params$b
28  a <- rmax / (l0^b)
29  rcb <- rmax * params$rcb_factor
30  d <- (rcb - rmax) / (1 - l0)
31  c <- rmax - d * l0
32
33  # Create data for the two functions
34  x1 <- seq(0, l0, length.out = 100) # Range for the first function
35  x2 <- seq(l0, 1, length.out = 100) # Range for the second function
36
37  r1 <- a * x1^b # r = a * x^b
38  r2 <- c + d * x2 # r = c + d * x
39
40  # Combine x and r values
41  x <- c(x1, x2)
42  r <- c(r1, r2)
43
44  # Generate points for 3D rotation
45  theta <- seq(0, 2 * pi, length.out = 500) # Angles for rotation
46  x_grid <- rep(x, each = length(theta)) # Duplicate x values for each angle
47  r_grid <- rep(r, each = length(theta)) # Duplicate r values for each angle
48  theta_grid <- rep(theta, times = length(x)) # Repeat angles for each x
49
50  # Convert polar to Cartesian coordinates
51  y <- r_grid * cos(theta_grid)
52  z <- r_grid * sin(theta_grid)
53
54  # Create a segment indicator
55  segment <- c(rep("r = a * x^b", length(x1) * length(theta)),
56    rep("r = c + d * x", length(x2) * length(theta)))
57
58  # Create a data frame
59  plot_data <- data.frame(y = y, x = x_grid, z = z, segment = segment)
60
61  # 3D Plot using Plotly
62  plot_ly(
63    plot_data,
64    x = ~y,
65    y = ~x,
66    z = ~z,
67    type = "scatter3d",
68    mode = "markers",
69    marker = list(size = 1),
70    color = ~segment, # Map color to the segment
71    colors = c("#ccccccff", "#999999ff"), # Specify colors for each segment
72    showlegend = FALSE
73  ) %>%

```



```

74 layout(
75   scene = list(
76     xaxis = list(title = " ", showgrid = FALSE, showaxis = FALSE, showticklabels =
77       FALSE),
78     yaxis = list(showgrid = TRUE, title = " ",
79       showaxis = FALSE,
80       showticklabels = FALSE,
81       dtick = 15,
82       tickmode = "array", # Set tick values manually
83       tickvals = seq(0, max(plot_data$x), by = 15), # Reversed ticks
84       ticktext = rev(seq(0, max(plot_data$x), by = 15)) # Reversed tick
85       labels
86     ),
87     zaxis = list(title = " ", showgrid = FALSE, showaxis = FALSE, showticklabels =
88       FALSE),
89     camera = list(
90       eye = list(x = 0, y = 0.05, z = 3.4) # Fixed perspective
91     )
92   )
93 }
94 #plotly from the start.
95 p <- plot_3d_crown (l = 15, dia = 8, species = "Acer pseudoplatanus")
96
97 p
98 save_image(p, file="images/Acer_pseudoplatanus.svg", width = 300, height= 600)
99
100
101
102 use_python("C:/Users/tobia/AnacondaPython/python.exe")
103
104
105 ##deviation from Pretzsch:
106
107 #1. factor_a is equal to b, otherwise the two functions will not meet at the point where
108    10*factor_l0.
109    #holds for Pinus silvestris, latic decidua and Acer pseudoplatanus
110
111 #2. acer pseudoplatanus rmax is not equal to rcb: but rcb is equal to 0.

```

BAL calculation

```

1 tree_crown_volume <- readRDS("data/tree_AWC.rds")
2
3
4 plot<-readRDS("data/plot.rds")
5
6 #add BAL (Basal area of larger trees)
7
8 # Calculate BAL for each tree within each plot and year
9 tree_with_BAL <- tree%>%
10   group_by(plot, year) %>% # Group data by plot and year
11   arrange(plot, year, basal_area) %>% # Arrange trees by basal area within each plot and
12     year
13   mutate(
14     BAL = sapply(basal_area, function(ba) {
15       sum(basal_area[basal_area > ba])
16     })
17   )
18
19 # View the updated dataframe with BAL
20 print(tree_with_BAL)

```

DCV Calculation

```

1 ree_v8 <- readRDS("data/tree_v8.rds")
2
3 plot<-readRDS("data/plot.rds")
4
5 #add BAL (Basal area of larger trees)
6
7 # Calculate BAL for each tree within each plot and year
8 tree_with_BAL <- tree_v8%>%
9   group_by(plot, year) %>% # Group data by plot and year

```

```

10 arrange(plot, year, basal_area) %>% # Arrange trees by basal area within each plot and
    year
11 mutate(
12   BAL = sapply(basal_area, function(ba) {
13     sum(basal_area[basal_area > ba])
14   })2
15 )
16
17 # View the updated dataframe with BAL
18 summary(tree_with_BAL)
19
20
21
22
23 ##new column annual_change_crown_volume
24 tree <- tree %>%
25   arrange(plot, TreeNo, year) %>% # Ensure data is sorted by plot, TreeNo, and year
26   group_by(plot, TreeNo) %>% # Group by both plot and TreeNo
27   mutate(x
28     crown_diff = crown_volume - lag(crown_volume), # Difference in crown volume
29     year_diff = year - lag(year), # Difference in years
30     delta_crown_volume = crown_diff / year_diff # Annual average change
31   ) %>%
32   ungroup()
33
34 head(annual_change_crown_volume)
35
36
37 # Function to plot crown volume or difference over time for specific trees in a specific
    plot
38 plot_tree_v1 <- function(tree_numbers, plot_number, data) {
39   # Filter data for the selected trees and plot
40   filtered_data <- data %>%
41     filter(TreeNo %in% tree_numbers, plot == plot_number)
42
43   # Create a plot for each tree in the selection
44   ggplot(filtered_data, aes(x = year, y = crown_volume, color = factor(TreeNo), group =
    TreeNo)) +
45     geom_line(size = 1) +
46     geom_point(size = 2) +
47     labs(
48       title = paste("Crown Volume Change Over Time for Plot", plot_number),
49       x = "Year",
50       y = "Crown Volume",
51       color = "Tree Number"
52     ) +
53     theme_minimal() +
54     theme(legend.position = "bottom")
55 }

```

DCV and their distribution shapes

```

1 ##tree data
2
3
4 ##new try with deleting 29294 and 29293 and 1030 --> Le Chenit( da nicht gemessen)
5 ## Sigriswil da zuviele Steine und ##Lauperswil da spezielle Fl che
6
7
8 tree<- readRDS("data/tree_v9.rds")
9
10 #tree$time <- tree$year-1904
11
12 tree$plot <- as.character(tree$plot)
13 tree$TreeNo<- as.character(tree$TreeNo)
14 tree$AWC_rounded<- as.factor(tree$AWC_rounded)
15
16 df_tree <- tree %>% filter(!(plot_group %in% c("21294", "21293")))
17 df_tree<- df_tree %>% filter(!(year<1930))
18
19
20 ##subsetting each species
21 abies_alba <- subset(df_tree, species == "Abies alba")
22 # Select rows where the species is "Fagus sylvatica"
23 fagus_sylvatica <- subset(df_tree, species == "Fagus sylvatica")
24 # Select rows where the species is "Picea abies"
25 picea_abies <- subset(df_tree, species == "Picea abies")
26

```

```

27
28 ##filtering NAs and Infites
29 picea_abies_clean <- picea_abies %>%
30   filter(!is.na(delta_crown_volume) & !is.na(AWC) & !is.na(year) &
31     is.finite(delta_crown_volume) & is.finite(AWC) & is.finite(year))
32
33 abies_clean <- abies_alba %>%
34   filter(!is.na(delta_crown_volume) & !is.na(AWC) & !is.na(year) &
35     is.finite(delta_crown_volume) & is.finite(AWC) & is.finite(year))
36
37 fagus_clean <- fagus_sylvatica %>%
38   filter(!is.na(delta_crown_volume) & !is.na(AWC) & !is.na(year) &
39     is.finite(delta_crown_volume) & is.finite(AWC) & is.finite(year))
40
41
42
43 # Picea abies plot
44 p1 <- ggplot(picea_abies_clean, aes(x = delta_crown_volume, y = AWC_rounded, fill = year)) +
45   geom_density_ridges(scale = 1.5, rel_min_height = 0.01, alpha = 0.8) + # Colored ridges
46   scale_fill_gradient(low = "#006268ff", high = "#faefb1ff") + # Gradient color for ridges
47   scale_x_continuous(limits = c(-15, 15)) + # Crown Volume limits
48   theme_ridges() +
49   labs(
50     subtitle = "Picea abies",
51     x = "",
52     y = "Available water capacity [mm]",
53     fill = "Year"
54   ) +
55   theme_minimal(base_size = 20) + # Match theme style
56   theme(
57     text = element_text(family = "Times New Roman"),
58     plot.subtitle = element_text(hjust = 0.5, face = "bold.italic"),
59     axis.text = element_text(color = "black"),
60     panel.grid.major = element_line(color = "gray90"),
61     legend.position = "right" # Keep legend to show color gradient for year
62   )
63
64 # Abies alba plot
65 p2 <- ggplot(abies_clean, aes(x = delta_crown_volume, y = AWC_rounded, fill = year)) +
66   geom_density_ridges(scale = 1.5, rel_min_height = 0.01, alpha = 0.8) + # Colored ridges
67   scale_fill_gradient(low = "#006268ff", high = "#faefb1ff") + # Gradient color for ridges
68   scale_x_continuous(limits = c(-15, 15)) + # Crown Volume limits
69   theme_ridges() +
70   labs(
71     subtitle = "Abies alba",
72     x = expression("Delta crown volume [ m ]"),
73     y = "",
74     fill = "Year"
75   ) +
76   theme_minimal(base_size = 20) + # Match theme style
77   theme(
78     text = element_text(family = "Times New Roman"),
79     plot.subtitle = element_text(hjust = 0.5, face = "bold.italic"),
80     axis.text = element_text(color = "black"),
81     axis.text.y = element_blank(),
82     panel.grid.major = element_line(color = "gray90"),
83     legend.position = "right" # Keep legend to show color gradient for year
84   )
85
86 # Fagus sylvatica plot
87 p3 <- ggplot(fagus_clean, aes(x = delta_crown_volume, y = AWC_rounded, fill = year)) +
88   geom_density_ridges(scale = 1.5, rel_min_height = 0.01, alpha = 0.8) + # Colored ridges
89   scale_fill_gradient(low = "#006268ff", high = "#faefb1ff") + # Gradient color for ridges
90   scale_x_continuous(limits = c(-15, 15)) + # Crown Volume limits
91   theme_ridges() +
92   labs(
93     subtitle = "Fagus sylvatica",
94     x = "",
95     y = "",
96     fill = "Year"
97   ) +
98   theme_minimal(base_size = 20) + # Match theme style
99   theme(
100     text = element_text(family = "Times New Roman"),
101     plot.subtitle = element_text(hjust = 0.5, face = "bold.italic"),
102     axis.text = element_text(color = "black"),
103     axis.text.y = element_blank(), # Remove y-axis numbers
104     panel.grid.major = element_line(color = "gray90"),
105     legend.position = "right", # Remove y-axis numbers # Keep legend to show color gradient

```

```

    for year
  )
# Combine the three plots
p00 <- (p1 | p2 | p3) +
  plot_annotation(
    title = expression("Distribution shapes of delta crown volume at a given AWC for
      different tree species"),
    theme = theme(
      text = element_text(family = "Times New Roman"),
      plot.title = element_text(hjust = 0.5, face = "bold", size = 22)
    )
  )
p00 # Display the final plot

```

DCV and distribution shapes for plot groups

```

1 ##getting rid of the outliers 21294 Le Chenit(not measured) and 21293001 & 21293002
2 ## Sigriswil(huge stone content)
3
4
5 plot<- readRDS("data/plot.rds")
6 tree <- readRDS("data/tree_v9.rds")
7 df <- tree %>% filter(!(plot_group %in% c("21294", "21293")))
8 df<- df %>% filter(!(year<1930))
9
10 summary(df)
11
12
13 abies_alba <- subset(df, species == "Abies alba")
14 # Select rows where the species is "Fagus sylvatica"
15 fagus_sylvatica <- subset(df, species == "Fagus sylvatica")
16 # Select rows where the species is "Picea abies"
17 picea_abies <- subset(df, species == "Picea abies")
18
19 #delete NAs and INFs
20 abies_sub <- abies_alba[is.finite(abies_alba$delta_crown_volume), ]
21 picea_sub <- picea_abies[is.finite(picea_abies$delta_crown_volume), ]
22 fagus_sub <- fagus_sylvatica[is.finite(fagus_sylvatica$delta_crown_volume), ]
23 stand_sub<- df[is.finite(df$delta_crown_volume), ]
24
25 summary(stand_sub)
26 summary(abies_sub)
27 summary(picea_sub)
28 summary(fagus_sub)
29
30 abies_cc <- abies_sub[, c("plot", "year", "delta_crown_volume")]
31 abies_cc<- abies_cc [is.finite(abies_cc$delta_crown_volume), ]
32 abies_cc <- as.data.frame(abies_cc)
33 summary(abies_cc)
34 picea_sub<-abies_sub
35
36
37 #-----
38
39 # Define color palettes for each group
40
41 colors_plot1 <- c("1015002" = "#E69F00", "1014000" = "#006268ff")
42 colors_plot2 <- c("1033000" = "#E69F00", "1034000" = "#006268ff")
43 colors_plot3 <- c("1042000" = "#E69F00", "1041000" = "#006268ff")
44 colors_plot4 <- c("1027000" = "#E69F00", "1028000" = "#006268ff")
45
46 # Filter data for each plot group
47 picea_plot1 <- picea_sub %>% filter(plot %in% c(1015002, 1014000))
48 picea_plot2 <- picea_sub %>% filter(plot %in% c(1033000, 1034000))
49 picea_plot3 <- picea_sub %>% filter(plot %in% c(1042000, 1041000))
50 picea_plot4 <- picea_sub %>% filter(plot %in% c(1027000, 1028000))
51
52 # Create individual plots for each group
53 p3 <- ggplot(picea_plot1, aes(x = delta_crown_volume, y = factor(year), fill = plot)) +
54   geom_density_ridges(scale = 0.7, rel_min_height = 0.01, alpha = 0.5) + # Overlapping
55   ridges
56   scale_fill_manual(values = colors_plot1,
57     labels = c("1015002" = "1015002 (188.19mm)", "1014000" = "1014000
58       (232.04mm)")) + # Gradient color for ridges
59   scale_x_continuous(limits = c(-15, 15)) + # Crown Volume limits
60   scale_y_discrete() + # Remove y-axis labels but keep the title

```

```

59 labs(
60   subtitle = "Ober- and Niederh nigen",
61   x = expression("Delta crown volume [ m ]"),
62   y = "Year", # Y-axis title remains
63   fill = "Plot"
64 ) +
65 theme_minimal(base_size = 20) + # Match theme style
66 theme(
67   text = element_text(family = "Times New Roman"),
68   plot.subtitle = element_text(hjust = 0.5, face = "bold.italic"),
69   axis.text = element_text(color = "black"),
70   panel.grid.major = element_line(color = "gray90"),
71   legend.position = "right" # Keep legend to show color gradient for year
72 )
73
74 p2 <- ggplot(picea_plot2, aes(x = delta_crown_volume, y = factor (year) , fill = plot)) +
75   geom_density_ridges(scale = 0.7, rel_min_height = 0.01, alpha = 0.5) + # Overlapping
76   ridges
77   scale_fill_manual(values = colors_plot2,
78                     labels = c("1033000" = "1033000 (166.92mm)", "1034000" = "1034000
79                               (218.66mm)")) + # Gradient color for ridges
80   scale_x_continuous(limits = c(-15, 15)) + # Crown Volume limits
81   scale_y_discrete() + # Remove y-axis labels but keep the title
82   labs(
83     subtitle = "St. Moritz",
84     x = expression("Delta crown volume [ m ]"),
85     y = "Year", # Y-axis title remains
86     fill = "Plot"
87   ) +
88   theme_minimal(base_size = 20) + # Match theme style
89   theme(
90     text = element_text(family = "Times New Roman"),
91     plot.subtitle = element_text(hjust = 0.5, face = "bold.italic"),
92     axis.text = element_text(color = "black"),
93     panel.grid.major = element_line(color = "gray90"),
94     legend.position = "right" # Keep legend to show color gradient for year
95   )
96
97 p4 <- ggplot(picea_plot3, aes(x = delta_crown_volume, y = factor(year) , fill = plot)) +
98   geom_density_ridges(scale = 0.7, rel_min_height = 0.01, alpha = 0.5) + # Overlapping
99   ridges
100   scale_fill_manual(values = colors_plot3,
101                     labels = c("1042000" = "1042000 (170.85mm)", "1041000" = "1041000
102                               (174.62mm)")) + # Gradient color for ridges
103   scale_x_continuous(limits = c(-15, 15)) + # Crown Volume limits
104   scale_y_discrete() + # Remove y-axis labels but keep the title
105   labs(
106     subtitle = "Rougemont",
107     x = expression("Delta crown volume [ m ]"),
108     y = "Year", # Y-axis title remains
109     fill = "Plot"
110   ) +
111   theme_minimal(base_size = 20) + # Match theme style
112   theme(
113     text = element_text(family = "Times New Roman"),
114     plot.subtitle = element_text(hjust = 0.5, face = "bold.italic"),
115     axis.text = element_text(color = "black"),
116     panel.grid.major = element_line(color = "gray90"),
117     legend.position = "right" # Keep legend to show color gradient for year
118   )
119
120 p1 <- ggplot(picea_plot4, aes(x = delta_crown_volume, y = factor (year) , fill = plot)) +
121   geom_density_ridges(scale = 0.7, rel_min_height = 0.01, alpha = 0.5) + # Overlapping
122   ridges
123   scale_fill_manual(values = colors_plot4,
124                     labels = c("1027000" = "1027000 (159.34mm)", "1028000" = "1028000
125                               (217.53mm)")) +
126   labs() + # Gradient color for ridges
127   scale_x_continuous(limits = c(-15, 15)) + # Crown Volume limits
128   scale_y_discrete() + # Remove y-axis labels but keep the title
129   labs(
130     subtitle = "Bowil",
131     x = expression("Delta crown volume [ m ]"),
132     y = "Year", # Y-axis title remains
133     fill = "Plot"
134   ) +
135   theme_minimal(base_size = 20) + # Match theme style
136   theme(
137     text = element_text(family = "Times New Roman"),

```

```

132 plot.subtitle = element_text(hjust = 0.5, face = "bold.italic"),
133 axis.text = element_text(color = "black"),
134 panel.grid.major = element_line(color = "gray90"),
135 legend.position = "right" # Keep legend to show color gradient for year
136 )
137
138 # Combine the plots in a 2x2 layout
139
140 p00 <- wrap_plots(p1, p3, p4, ncol = 2) +
141   plot_annotation(
142     title = expression(paste("Distribution shapes of delta crown volume across different
143       plot groups for ", italic("Fagus sylvatica"))),
144     theme = theme(
145       text = element_text(family = "Times New Roman"),
146       plot.title = element_text(hjust = 0.5, face = "bold", size = 22)
147     )
148   )
149 p00 # Display the combined plot
150
151
152
153 # Abies alba plot
154 p2 <- ggplot(abies_clean, aes(x = delta_crown_volume, y = AWC_rounded, fill = year)) +
155   geom_density_ridges(scale = 1.5, rel_min_height = 0.01, alpha = 0.8) + # Colored ridges
156   scale_fill_gradient(low = "#006268ff", high = "#faefb1ff") + # Gradient color for ridges
157   scale_x_continuous(limits = c(-15, 15)) + # Crown Volume limits
158   theme_ridges() +
159   labs(
160     subtitle = "Abies alba",
161     x = expression("Delta crown volume [ m ]"),
162     y = "",
163     fill = "Year"
164   ) +
165   theme_minimal(base_size = 20) + # Match theme style
166   theme(
167     text = element_text(family = "Times New Roman"),
168     plot.subtitle = element_text(hjust = 0.5, face = "bold.italic"),
169     axis.text = element_text(color = "black"),
170     axis.text.y = element_blank(),
171     panel.grid.major = element_line(color = "gray90"),
172     legend.position = "right" # Keep legend to show color gradient for year
173   )
174
175 p4 <- ggplot(picea_plot4, aes(x = delta_crown_volume, y = factor(year), fill = plot)) +
176   geom_density_ridges(scale = 0.7, rel_min_height = 0.01, alpha = 0.5) + # Overlapping
177   ridges
178   scale_fill_manual(values = colors_plot4,
179     labels = c("1027000" = "1027000 (159.34mm)", "1028000" = "1028000
180     (217.53mm)")) +
181   labs() + # Gradient color for ridges
182   scale_x_continuous(limits = c(-25, 25)) + # Crown Volume limits
183   scale_y_discrete() + # Remove y-axis labels but keep the title
184   labs(
185     subtitle = "Bowil",
186     x = expression("Delta crown volume [ m ]"),
187     y = "Density estimate", # Y-axis title remains
188     fill = "Plot"
189   ) +
190   theme_minimal(base_size = 20) + # Match theme style
191   theme(
192     text = element_text(family = "Times New Roman"),
193     plot.subtitle = element_text(hjust = 0.5, face = "bold.italic"),
194     axis.text = element_text(color = "black"),
195     panel.grid.major = element_line(color = "gray90"),
196     legend.position = "right" # Keep legend to show color gradient for year
197   )
198 p4
199
200 sum(!is.finite(picea_sub)) # Count non-finite values (Inf, -Inf, NaN)

```

Statistical analysis using glmmTMB

```

1 #tree_point_estimates_glmm
2 ##getting rid of the outliers 21294 Le Chenit(not measured) and 21293001 & 21293002
3 ## Sigriswil(huge stone content)
4
5 tree <- readRDS("data/tree_v10.rds")

```

```

6 df <- tree %>% filter(!(plot_group %in% c("21294", "21293")))
7 df<- df %>% filter(!(year<1930))
8 df <- df[, !(names(df) %in% c("local_geo", "ref_geo"))]
9 df$local_geo <- NULL
10 df <- df[complete.cases(df[, c("AWC", "delta_crown_volume", "time", "avg_prdp", "tmax28",
    "avg_max_dry_days", "prop_picea", "elevation", "BAL")]), ]
11
12
13 abies_sub %>% filter(plot == 1028000) %>% summary()
14 abies_sub %>%
15   count(plot) %>%
16   arrange(desc(n))
17
18 abies_sub_28$delta_crown_volume %>% hist()
19 summary(df)
20 ##subsetting each species
21 abies_alba <- subset(df, species == "Abies alba")
22 # Select rows where the species is "Fagus sylvatica"
23 fagus_sylvatica <- subset(df, species == "Fagus sylvatica")
24 # Select rows where the species is "Picea abies"
25 picea_abies <- subset(df, species == "Picea abies")
26
27
28 picea_sub <- picea_abies %>%
29   filter(!is.na(delta_crown_volume) & !is.na(AWC) & !is.na(year) &
30     is.finite(delta_crown_volume) & is.finite(AWC) & is.finite(year))
31
32 abies_sub <- abies_alba %>%
33   filter(!is.na(delta_crown_volume) & !is.na(AWC) & !is.na(year) &
34     is.finite(delta_crown_volume) & is.finite(AWC) & is.finite(year))
35 abies_sub <- abies_sub %>%
36   filter(plot != 21290000)
37
38 fagus_sub <- fagus_sylvatica %>%
39   filter(!is.na(delta_crown_volume) & !is.na(AWC) & !is.na(year) &
40     is.finite(delta_crown_volume) & is.finite(AWC) & is.finite(year))
41
42
43 summary(abies_sub)
44 #abies alba
45
46
47 n1 <- glmmTMB(delta_crown_volume ~ time +
48   AWC * avg_prdp +
49   tmax28 +
50   AWC * avg_max_dry_days +
51   prop_abies +
52   elevation +
53   BAL + (1 | plot / TreeNo), data = abies_sub,
54   family = gaussian("identity"))
55 summary(n1)
56 #-AWC
57 n1_2 <- glmmTMB(delta_crown_volume ~ time +
58   avg_prdp +
59   tmax28 +
60   avg_max_dry_days +
61   prop_abies +
62   elevation +
63   BAL + (1 | plot / TreeNo), data = abies_sub,
64   family = gaussian("identity"))
65 #-avg_prdp
66 n1_3 <- glmmTMB(delta_crown_volume ~ time +
67   AWC * avg_max_dry_days +
68   tmax28 +
69   prop_abies +
70   elevation +
71   BAL + (1 | plot / TreeNo), data = abies_sub,
72   family = gaussian("identity"))
73
74 #-avg_max_dry_days
75 n1_4<- glmmTMB(delta_crown_volume ~ time +
76   AWC * avg_prdp +
77   tmax28 +
78   prop_abies +
79   elevation +
80   BAL + (1 | plot / TreeNo), data = abies_sub,
81   family = gaussian("identity"))
82
83 anova(n1, n1_2)

```

```

84 anova(n1, n1_3)
85 anova(n1, n1_4)
86
87 summary(n1)
88
89 # picea abies
90
91 n2 <- glmmTMB(delta_crown_volume ~ time +
92               AWC * avg_prcp +
93               tmax28 +
94               AWC * avg_max_dry_days +
95               prop_picea +
96               elevation +
97               BAL + (1 | plot/ TreeNo), data = picea_sub,
98               family = gaussian("identity"))
99 summary(n2)
100 #-AWC
101 n2_2 <- glmmTMB(delta_crown_volume ~ time +
102                 avg_prcp +
103                 tmax28 +
104                 avg_max_dry_days +
105                 prop_picea +
106                 elevation +
107                 BAL + (1 | plot / TreeNo), data = picea_sub,
108                 family = gaussian("identity"))
109 #-avg_prcp
110 n2_3 <- glmmTMB(delta_crown_volume ~ time +
111                 AWC * avg_max_dry_days +
112                 tmax28 +
113                 prop_picea +
114                 elevation +
115                 BAL + (1 | plot / TreeNo), data = picea_sub,
116                 family = gaussian("identity"))
117
118 #-avg_max_dry_days
119 n2_4 <- glmmTMB(delta_crown_volume ~ time +
120                 AWC * avg_prcp +
121                 tmax28 +
122                 prop_picea +
123                 elevation +
124                 BAL + (1 | plot / TreeNo), data = picea_sub,
125                 family = gaussian("identity"))
126
127 anova(n2, n2_2)
128 anova(n2, n2_3)
129 anova(n2, n2_4)
130 summary(n2)
131
132 #fagus sylvatica
133
134 n3 <- glmmTMB(delta_crown_volume ~ time +
135               AWC * avg_prcp +
136               tmax28 +
137               AWC * avg_max_dry_days +
138               elevation +
139               BAL + (1 | plot/ TreeNo), data = fagus_sub,
140               family = gaussian("identity"))
141 summary(n3)
142 summary(n3_1)
143 #-AWC
144 n3_2 <- glmmTMB(delta_crown_volume ~ time +
145                 avg_prcp +
146                 tmax28 +
147                 avg_max_dry_days +
148                 elevation +
149                 BAL + (1 | plot / TreeNo), data = fagus_sub,
150                 family = gaussian("identity"))
151
152
153 #-avg_prcp
154 n3_3 <- glmmTMB(delta_crown_volume ~ time +
155                 AWC * avg_max_dry_days +
156                 tmax28 +
157                 elevation +
158                 BAL + (1 | plot / TreeNo), data = fagus_sub,
159                 family = gaussian("identity"))
160
161 #-avg_max_dry_days
162 n3_4 <- glmmTMB(delta_crown_volume ~ time +

```



```

163         AWC * avg_prctp +
164         tmax28 +
165         elevation +
166         BAL + (1 | plot / TreeNo), data = fagus_sub,
167         family = gaussian("identity"))
168
169 anova(n3, n3_2)
170 anova(n3, n3_3)
171 anova(n3, n3_4)
172
173 #####
174
175 n3_2 <- glmmTMB(delta_crown_volume ~ AWC + time +
176               AWC * avg_prctp +
177               # tmax28 +
178               AWC * avg_max_dry_days +
179               prop_abies +
180               elevation +
181               BAL + (1 | plot), data = abies_sub,
182               family = gaussian("identity"))
183
184
185 summary(n3)
186
187
188 n4 <- glmmTMB(delta_crown_volume ~ AWC + time +
189               AWC * avg_prctp +
190               tmax28 +
191               AWC * avg_max_dry_days +
192               prop_picea +
193               elevation +
194               BAL + (1 | plot), data = picea_sub,
195               family = gaussian("identity"))
196
197
198
199
200 n5 <- glmmTMB(BAI_adj ~ AWC + time +
201               AWC + avg_prctp +
202               tmax28 +
203               AWC * avg_max_dry_days +
204               prop_abies +
205               elevation +
206               QMDS + (1 | plot), data = abies_sub,
207               family = gaussian("identity"))
208
209 x*y
210 x + y + x:y
211
212 n6 <- glmmTMB(BAI_adj ~ AWC + time +
213               AWC * avg_prctp +
214               tmax28 +
215               AWC + avg_max_dry_days +
216               prop_abies +
217               elevation +
218               QMD + (1 | plot), data = abies_sub,
219               family = gaussian("identity"))
220
221 summary(n1)
222 summary (n2)
223 summary(n3)
224 avg_prctp<-AIC(n4)-AIC(n5)
225 dry_days<-AIC(n4)-AIC(n6)
226
227
228 plot(simulateResiduals(n1))
229 plot(simulateResiduals(n2))
230 plot(simulateResiduals(n3))
231 plot(simulateResiduals(n4))
232
233 nrow(model.frame(n1))
234 nrow(model.frame(n1_3))
235
236
237
238 new_data_v2 <- expand.grid(
239   AWC = c(150, 200, 250),
240   time = c(36, 71, 106),
241   avg_prctp = c(946),

```

```

242   avg_max_dry_days = c(18.3),
243   tmax28 = c(2.95),
244   prop_abies = c(50),
245   elevation = c(1052),
246   BAL = c(51.41))
247
248 new_data_v2$predicted_DCV <- predict(n1, new_data_v2, re.form = NA)
249 print(new_data_v2)
250
251
252
253 new_data_v2_pic <- expand.grid(
254   AWC = c(150, 200, 250),
255   time = c(36, 71, 106),
256   avg_prctp = mean(df$avg_prctp, na.rm = TRUE),
257   avg_max_dry_days = mean(df$avg_max_dry_days, na.rm = TRUE),
258   tmax28 = mean(df$tmax28, na.rm = TRUE),
259   prop_picea = c(50),
260   elevation = mean(df$elevation, na.rm = TRUE),
261   BAL = mean(df$BAL, na.rm = TRUE))
262
263 new_data_v2_pic$predicted_DCV <- predict(n2, new_data_v2_pic, re.form = NA)
264 print(new_data_v2_pic)
265
266
267 new_data_v2_fag <- expand.grid(
268   AWC = c(150, 200, 250),
269   time = c(36, 71, 106),
270   avg_prctp = c(946),
271   avg_max_dry_days = c(18.3),
272   tmax28 = c(2.95),
273   elevation = c(1052),
274   BAL = c(51.41))
275
276
277 new_data_v2_fag$predicted_DCV <- predict(n3, new_data_v2_fag, re.form = NA)
278 print(new_data_v2_fag)
279
280
281
282
283 new_data_v2_pic$predicted_DCV <- predict(n2, new_data_v2_pic, re.form = NA)
284 print(new_data_v2_pic)
285
286
287 new_data_v2_fag$predicted_DCV <- predict(n3, new_data_v2_fag, re.form = NA)
288 print(new_data_v2_fag)
289
290 new_data_v3$predicted_DCV <- predict(n2, new_data_v3, re.form = NA)
291 print(new_data_v3)
292 # interesting one, the smaller a tree desto st rker w chst er wenn AWC zunimmt oder desto
293 # weniger schrumpft er:)
294 #Riese abfack:))
295
296
297 new_data_v1 <- expand.grid(
298   AWC = c(150, 200, 250),
299   time = c(36, 71, 106),
300   avg_prctp = mean(df$avg_prctp, na.rm = TRUE),
301   avg_max_dry_days = c(10,30,40),
302   tmax28 = mean(df$tmax28, na.rm = TRUE),
303   prop_picea = c(50),
304   elevation = mean(df$elevation, na.rm = TRUE),
305   BAL = mean(df$BAL, na.rm = TRUE))
306
307
308 new_data_v3 <- expand.grid(
309   AWC = c(150, 200, 250),
310   time = c(106),
311   avg_prctp = mean(df$avg_prctp, na.rm = TRUE),
312   avg_max_dry_days = c(15,30,40),
313   tmax28 = mean(df$tmax28, na.rm = TRUE),
314   prop_picea = c(50),
315   elevation = mean(df$elevation, na.rm = TRUE),
316   BAL = c(15,50,200))
317
318
319 #abies_sub
320 climate_1 <- expand.grid(
321   AWC = c(150, 250),
322   time = c(71),
323   avg_prctp = c(600,1200),

```

```

320   avg_max_dry_days = c(15,35),
321   tmax28 = c(3,9),
322   prop_abies = c(50),
323   elevation = c(1052),
324   BAL = mean(df$BAL, na.rm = TRUE)
325 )
326
327
328 climate_1$predicted_DCV <- predict(n1, climate_1, re.form = NA)
329 print(climate_1)
330
331 #picea_sub
332 climate_2 <- expand.grid(
333   AWC = c(150, 250),
334   time = c(71),
335   avg_prdp = c(600,1200),
336   avg_max_dry_days = c(15,35),
337   tmax28 = c(3,9),
338   prop_picea = c(50),
339   elevation = c(1052),
340   BAL = mean(df$BAL, na.rm = TRUE)
341 )
342
343 climate_2$predicted_DCV <- predict(n2, climate_2, re.form = NA)
344 print(climate_2)
345
346 #fagus_sub
347 climate_3 <- expand.grid(
348   AWC = c(150, 250),
349   time = c(71),
350   avg_prdp = c(600,1200),
351   avg_max_dry_days = c(15,35),
352   tmax28 = c(3,9),
353   elevation = c(1052),
354   BAL = mean(df$BAL, na.rm = TRUE)
355 )
356
357 climate_3$predicted_DCV <- predict(n3, climate_3, re.form = NA)
358 print(climate_3)
359
360
361
362
363 new_data_v2 <- expand.grid(
364   AWC = c(150,200,250),
365   time = c(76),
366   avg_prdp = c(1000),
367   avg_max_dry_days = mean(df$avg_max_dry_days, na.rm = TRUE),
368   tmax28 = mean(df$tmax28, na.rm = TRUE),
369   prop_picea = c(50),
370   elevation = c(500,1000,2000),
371   BAL = c(1,110))
372
373 new_data_v2$predicted_DCV <- predict(n2, new_data_v2, re.form = NA)
374 print(new_data_v2)
375 summary(n3)

```

Appendix C

Decipherment of the historical soil profiles

1015000 and 21293000 have only one historical measurement for both subplots. For the plots 1014000, 1021000, 1030000, 1031000, 1046000 and 2047000 no decipherment was made. The original papers were mostly readable and are available in the WSL archive.

'xy' = Assumption (...) = Transcription not possible ? = unassured transcription idea

Soil Profile Descriptions / 1015 Niederhünigen

Soil Profile

1. (Fir) Fairly uniform yellow, highly sandy loam with pebble nodules, main root distribution up to 125 cm, deepest root at 190 cm. The soil shows no "Dammerde", with a sharp transition from raw humus (up to 8 cm with "Dammerde") to mineral soil. 2. (Spruce) Uniform sandy loam with interspersed pebbles, greatest root penetration at 40 cm, deepest root at 100 cm.

Soil Composition

1. Parent Material: Marine Molasse 2. Soil Components: a) Mineral Composition: Clay, sand, quartz nodules b) Stone Inclusion: – c) Humus Content: Raw humus 3. Physical Soil Properties: a) Depth: – b) Cohesion: – c) Color: Yellow d) Moisture: – 4. Soil Condition, Surface Cover, and Flora: Blueberry shrubs are widespread but slightly less prevalent in dense "Schlune" compared to other stands. Raw humus is present but somewhat less abundant. Moss, swamp moss, brush moss, and ferns appear in intermediate areas. Wood sorrel is sparse.

Stand Description

A. Tree Species: Fir and Spruce B. Forest Management: Selection forest C. Age: –

Soil Profile Descriptions / 1021 Oberhünigen

Soil Profile

Loamy soil with raw humus dry runoff. From surface to 160 cm depth, sandy loam with Nagelfluh rock nodules. Main root distribution: 45-55 cm. Deepest root (spruce) at 160 cm.

Soil Composition

1. Parent Material: Nagelfluh to marine molasse, fairly compact, dipping NW 2. Soil Components: a) Mineral Composition: Clay, quartz sand b) Stone Inclusion: Abundant stone inclusion, Nagelfluh up to 1 dm³ c) Humus Content: Raw humus 3. Physical Soil Properties: a) Depth: Deep b) Soil Type: Loamy soil c) Structure and Texture: Angel structure, no crumb formation d) Cohesion: Loose e) Color: Yellowish f) Moisture: Fresh 4. Soil Condition, Surface Cover, and Flora: Surface covered exclusively with moss (Sphagnum) and some blueberry plants.

Stand Description

D. Tree Species: – E. Forest Management: – F. Age: 68

Soil Profile Descriptions / 1027 Bowil

Soil Profile

Two test pits were dug, both showing the same soil characteristics: From top to bottom, yellowish, acidic-rich clay to loam with abundant Nagelfluh nodules. Soil is deep, allowing for root penetration. Main root distribution: 60-80 cm. Deepest root at 200 cm.

Soil Composition

1. Parent Material: Nagelfluh to marine molasse 2. Soil Components: a) Mineral Composition: Clay, quartz sand b) Soil Type: Loam with coarse sand c) Stone Inclusion: Abundant stone inclusion d) Humus Content: Raw humus 3. Physical Soil Properties: a) Depth: Deep b) Cohesion: Fairly loose c) Color: Yellowish d) Moisture: Fresh 4. Soil Condition, Surface Cover, and Flora: Grass, blueberry, moss, ferns.

Stand Description

G. Tree Species: – H. Forest Management: – I. Age: –

Soil Profile Descriptions / 1028 Bowil

Soil Profile

Two test pits were opened. In the western test pit, a sand layer (fine sluice sand(?)) lies beneath a 50-55 cm clay layer, with clay interspersed with rock nodules of Nagelfluh. In the eastern test pit, the soil is cohesive loamy, transitioning into sandstone in the subsoil, penetrated by roots. Deepest roots: eastern fir 2m / western spruce 1.7m.

Soil Composition

1. Parent Material: Nagelfluh to marine molasse 2. Soil Components: a) Mineral Composition: High quartz content b) Soil Type: Loam to land soil(?) c) Stone Inclusion: – d) Humus Content: Raw humus 3. Physical Soil Properties: a) Depth: Deep b) Cohesion: Loose to cohesive c) Color: Yellow to gray d) Moisture: Fresh to moist 4. Soil Condition, Surface Cover, and Flora: Raw humus, dry peat from blueberries. Transition from fir to spruce. Beech rejuvenation, more blueberries, and also ferns.

Stand Description

J. Tree Species: – K. Forest Management: – L. Age: –

Soil Profile Descriptions / 1033 St Moritz

Soil Profile

Spruce Logging No. 12: Living ground cover consists of blueberries and mosses, curiously interspersed with wood sorrel. -7 cm: Raw humus, very richly rooted. All large roots are in the raw humus. 10-15 cm: A well-developed bleaching sand layer. 15-45 cm: The bleaching sand layer gradually transitions into the (...) raw soil, consisting of yellow-red sandy loam with abundant angular stones. >50 cm: The soil transitions into (...) 'mica,' which is highly weathered. The large tree roots extend beyond the bleaching sand layer into raw humus. Some medium roots penetrate down to 1m into the decayed rock. The distribution of fiber roots mainly reaches 50 cm, with most located in the raw humus.

Unknown number / likely Arve logging No. 9 Living ground cover: Dense "herbaceous layer" of blueberries, lingonberries, and few mosses. 10-15 cm: Loosely structured raw humus, richly rooted by trees and Vaccinium (blueberries). 15-25 cm: Typical fine bleaching sand without any stone inclusion. 25-75 cm: Fine yellow mucous sand without any stone inclusion. This sand is very compact, weakly permeated, with barely any air channels. >75 cm: Decayed schistose rock, at which point roots cease. Large roots extend entirely in the raw humus and on the bleaching sand. Fiber roots are mainly distributed in the raw humus. Deepest root: 70 cm.

Soil Composition

1. Parent Material: Gneiss, mica schist 2. Soil Components: a) Mineral Composition: – b) Soil Type: – c) Stone Inclusion: – d) Humus Content: Raw humus 3. Physical Soil Properties: a) Depth: – b) Cohesion: – c) Color: – d) Moisture: – 4. Soil Condition, Surface Cover, and Flora: The soil is densely and completely covered with blueberries, significantly hindering natural rejuvenation.

Stand Description

M. Tree Species: Spruce, Swiss stone pine + larch mixed N. Forest Management: Selection forest O. Age: –

Soil Profile Descriptions / 1034 St Moritz

Soil Profile

Spruce No. 21: 8-10 cm: Loosely structured raw humus, richly rooted. 10-20 cm: Bleaching sand. 20-50 cm: Yellow loam interspersed with stones and individual zones of embedded bleaching sand. Loosely packed and well-rooted by fine roots. 50-80 cm: Yellow loose loam, without bleaching sand, sparsely rooted. >80 cm: Sharp transition to gray sand and gravel, likely ('film-', 'fine-') sedimentation. The large roots rest on the bleaching sand. The fine roots are mainly distributed up to 60 cm but can extend to a maximum of 80 cm.

Swiss stone pine No. 5: 5 cm: Loose raw humus. 5-10 cm: Bleaching sand, weak and irregularly developed. 10-30 cm: 'Rough' sandy loam, color varies strongly from brown-red to light yellow-red. 30-50 cm: Yellow sandy loam with abundant small stones. >50 cm: Transitions into gray loam and gravel, rich in mica. Rooting reaches only down to the raw soil at 50 cm.

Larch No. 23: 5-7 cm: Raw humus. 5-15 cm: Bleaching sand. 15-45 cm: Raw soil with abundant small stones, gradually transitioning to gray sand and gravel at 40 cm depth. >45 cm: Gray sand and gravel. Even strong larches penetrate the bleaching sand and extend obliquely downward into the gray raw soil. At 80 cm depth, 4 cm thick roots are still present.

Soil Composition

1. Parent Material: Gneiss with mica schist 2. Soil Components: a) Mineral Composition: – b) Soil Type: – c) Stone Inclusion: – d) Humus Content: Raw humus 3. Physical Soil Properties: a) Depth: – b) Cohesion: – c) Color: – d) Moisture: – 4. Soil Condition, Surface Cover, and Flora: Blueberry, weakly interspersed with wood sorrel.

Stand Description

P. Tree Species: Spruce, Swiss stone pine + larch mixed Q. Forest Management: Selection forest

Soil Profile Descriptions / 1041 Rougement

Soil Profile

Spruce No. 70: 0-25 cm: Rock fragments embedded throughout. 25-70 cm: Fine soil and rock fragments up to boulder size embedded. Many fine roots present. 70-120 cm: Deepest root at 120 cm.

Fir No. 63: 20-40 cm: Upper layer still humic, black earth. Main roots reach down to 70 cm. Deepest root: 115 cm.

Soil Composition

1. Parent Material: Flysch, with an overlying Upper Jurassic block. 2. Soil Components: a) Mineral Composition: – b) Soil Type: Debris soil | Loam layer, rocky soil. c) Stone Inclusion: Very little, stones of all sizes up to boulders. d) Humus Content: Mull humus. e) Structure: Completely irregular. 3. Physical Soil Properties: a) Depth: Rocky soil (....) b) Cohesion: 'Very variable.' c) Color: Gray-black. d) Moisture: Fresh. 4. Soil Condition, Surface Cover, and Flora: Well-rooted where fine soil is present, otherwise highly variable. Blueberry, moss, 'Fannenkraut'.

Stand Description

R. Tree Species: Spruce and fir. S. Forest Management: Selection forest.

Soil Profile Descriptions / 1042 Rougement

Soil Profile

Spruce No. 65: 20 cm → 70 cm → 100 cm: Alpine humus. The soil is similar to area 41 but with slightly fewer surface stones. Stones and boulders embedded in the soil with fine earth. Deepest root: 100 cm.

Fir No. 48: >25 cm: Black humus, silt down to 20-30 cm. 70-80 cm: Main root distribution. 140 cm: Deepest root.

Soil Composition

1. Parent Material: Flysch with overlying Upper Jurassic block. 2. Soil Components: a) Mineral Composition: Clay and limestone. b) Soil Type: Rocky soil, debris soil. c) Stone Inclusion: Stones of all sizes, up to boulders. d) Humus Content: (...) Mull humus. 3. Physical Soil Properties: a) Depth: Highly variable. b) Cohesion: Loose. c) Color: Rather black-gray, brownish downward. d) Moisture: Fresh, no groundwater. 4. Soil Condition, Surface Cover, and Flora: Blueberry, 'Pelanites' rather strong, moss cover, ferns, natural spruce, fir rejuvenation, raspberries, (...), hazelnut, (...).

Stand Description

T. Tree Species: Spruce and fir. U. Forest Management: Selection forest. V. Age: –

Soil Profile Descriptions / 2034 Buttes

Soil Profile

0-70 cm: Loam heavily interspersed with large and small stones, light brown in color. >70 cm: Yellow below, consistently wet. Main root distribution: 70 cm. Deepest roots: 100 cm.

Soil Composition

1. Parent Material: Upper Jurassic, (...) 2. Soil Components: a) Mineral Composition: Clay, sand, and limestone. b) Structure: Steeply sloping layers towards NW. c) Soil Type: Calcareous loam. d) Stone Inclusion: The upper layer is weakly humic and brown, while the lower layer is yellow and heavily interspersed with coarse and fine stones. e) Humus Content: Mull humus. 3. Physical Soil Properties: a) Depth: Deep. b) Cohesion: Loose. c) Color: Light yellow-brown, yellow below. d) Moisture: Fresh. 4. Soil Condition, Surface Cover, and Flora: Silver fir and beech regeneration, (...) Oralis, moss, shrubs (...), few blueberries.

Stand Description

W. Tree Species: Spruce, beech, and fir. X. Forest Management: Originated from volume regeneration, was 'harvested' around 50 years ago. Y. Age: 135.

Soil Profile Descriptions / 2035 Buttes

Soil Profile

Fir No. 42 ('or 42 cm?'): >10 cm: Mild humus. 10-60 cm: Loamy, loose, heavily humus-enriched Damerde. >60 cm: Gradually transitioning into gravel, becoming loose mountain (...) material. Root main distribution: 90 cm. Deepest root: 160 cm.

Spruce root main distribution: 60 cm, deepest root: 120 cm. Beech root main distribution: 45 cm, deepest root: 65 cm.

Soil Composition

1. Parent Material: Upper Jurassic, (...) 2. Soil Components: a) Mineral Composition: Clay, sand, and limestone gravel. b) Structure: Layers dipping NW, highly fractured. c) Soil Type: Loamy soil on limestone gravel. d) Stone Inclusion: Upper layer humic, interspersed with stones; lower layer gravel with little clay. e) Humus Content: Mull humus, crumbly. 3. Physical Soil Properties: a) Depth: Deep. b) Cohesion: Loose. c) Color: Dark brown (upper layer), yellow (lower layer). d) Moisture: Fresh. 4. Soil Condition, Surface Cover, and Flora: Mull humus, weakly decomposed leaf mixture, loose and absorbent. 'Oralis,' 'Tasukraut,' (...), moss, blueberries.

Stand Description

A. Tree Species: Fir, spruce, and beech. B. Forest Management: Selection forest. C. Age: –

Soil Profile Descriptions / 21293 Sigriswil

Soil Profile

>15 cm: Humus layer. 15-50 cm: Strongly mixed with humus. 50-70 cm: Main root distribution. 130 cm: Deepest root.

Soil selection is very difficult due to countless rock blocks of highly variable external characteristics. Providing a standard soil profile description is impossible. The profile is derived from a test pit in the lower areas.

Soil Composition

1. Parent Material: Flysch with sandstones, lime (...) 2. Soil Components: a) Mineral Composition: – b) Soil Type: Calcareous soil with a high humus content. c) Stone Inclusion: Very little, small to large rock blocks. d) Humus Content: Thick raw humus layer. 3. Physical Soil Properties: a) Depth: Variable. b) Cohesion: Loose. c) Color: Dark. d) Moisture: Highly variable, from dry to moist sections. 4. Soil Condition, Surface Cover, and Flora: Besides blueberries, some moss, sycamore maple, rowan tree (...).

Stand Description

A. Tree Species: Spruce. B. Forest Management: Selection forest. C. Age: –

Soil Profile Descriptions / 21294 Le Chenit

Soil Profile

The soil is covered with boulders (...), but in between, good humus-rich soil can be found. Two test pits were dug.

>20 cm: Black humus, with raw humus. 20-40 cm: Soil clumps, (...) interspersed with soil. 65 cm: Main root distribution. 90 cm: Deepest root.

Soil Composition

1. Parent Material: Upper Jurassic, (...) 2. Soil Components: a) Mineral Composition: Clay and limestone. b) Soil Type: Calcareous soil. c) Stone Inclusion: Very little, from soil clumps to large boulders. d) Humus Content: – 3. Physical Soil Properties: a) Depth: Highly variable. b) Cohesion: Loose. c) Color: Brown to black. d) Moisture: Slightly dry. 4. Soil Condition, Surface Cover, and Flora: Thick raw humus layer, 'dry peat' and black soil, moss-covered, shrubs, maple, rowan tree (...).

Stand Description

D. Tree Species: Spruce. E. Forest Management: Selection forest. F. Age: –

Personal declaration

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

Signature:

Tobias Kichlas