University of Zurich[UZH]

Physical Properties of Soils in Swiss Agroforestry Systems

GEO 511 Master's Thesis

Author
Nina Viviane Karin Henny
22-710-057

Supervised by
Camille Rubeaud (camille.rubeaud@agroscope.admin.ch)
Dr. Johannes Köstel (johannes.koestel@agroscope.admin.ch)

Faculty representative
Prof. Dr. Michael W.I. Schmidt

27.09.2024
Department of Geography, University of Zurich

Abstract

Agroforestry is a promising nature-based solution to counteract climate change. In addition, agroforestry has the potential to increase the soil's chemical, biological and physical quality. The latter is affected by the tree roots and the increase of organic matter input in soil, which stabilize the soil structure and increase the porosity of the soil. This thesis aims to assess the soil physical properties in silvoarable alley cropping systems in Switzerland. As part of this thesis, 33 alley cropping agroforestry systems were sampled to assess bulk density, gravimetric water content, and measure penetration resistance. All samples and measurements were performed in the tree row, the arable plot in the alleys between the tree rows and in an adjacent arable control plot without trees, respectively. The analyses were performed using response ratios between the plots (tree – alley, alley – control and agroforestry – control) to assess differences between the plots. Correlations with internal system variables (density, diversity, age and average tree volume of each agroforestry system) were determined. The results showed that there were no significant differences between the plots for neither bulk density, the gravimetric water content nor the penetration resistance. For the bulk density and the gravimetric water content, differences were visible between the soil depths: the topsoil bulk density was lower than in the subsoil for the bulk density and vice-versa for the gravimetric water content. No significant correlation was found between the internal variables and the bulk density. For the gravimetric water content, there were positive effects for tree diversity, and negative effects for tree density and age. The more tree species were present in the agroforestry, the lower was the penetration resistance in the alley and agroforestry plots than in the control plots at depths between 31 and 50 cm. In addition, other significant results were found for the tree-alley and the agroforestry-control ratios of the penetration resistance at different depths and variables. The positive influences of the diversity variable are likely due to the different root traits of the various tree species. The age of the trees and therefore the growth of the root system could have an influence on the soil properties. Most of the agroforestry systems within this study are younger than ten years. Therefore, a repetition of the measurements in the future seems reasonable, as differences between the plots could become visible. Additionally, management practices and further soil properties of each site should be considered, to refine the outcome and confirm the results of this study.

Acknowledgments

I would like to express my gratitude to my supervisors Camille Rubeaud and John Köstel who made this thesis possible, organised the field campaign and provided me with valuable inputs and answers to my questions. I also want to thank Prof. Dr. Michael W.I. Schmidt for being the faculty representative of this thesis and answering open questions. I would like to thank Valerio Volpe for explaining the sampling tools and techniques, but also the penetration resistance measurements and analyses. Many thanks to Terence Cigler and all the persons helping during the field campaign. I am thankful to Marlies Sommer and Daniel Suter who helped me during the laboratory work, provided me the corresponding material and gave useful inputs on the measurements. I want to thank the members of the BQBN group at Agroscope, and I am also grateful to Lauren Clark for proofreading my thesis. Lastly, I want to thank my friends, family and boyfriend who supported me throughout this master thesis.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Overview on Agroforestry

The temperatures in Europe have risen faster within the last ten years than in other parts of the world. While agriculture is dependent on the climate, it is also responsible for about 10% of all European greenhouse gas emissions (Hernández-Morcillo et al. 2018). Worldwide, the share of agriculture on greenhouse gas emissions is even higher with 30-40%. Agriculture is therefore a major contributor to global warming as intensive agriculture can involve highly mechanised, fuel-based work, deforestation (Abbass et al. 2022), and the production and use of fertilizers (Walling & Vaneeckhaute 2020). However, the rising temperatures resulting from increasing greenhouse gas emissions are impacting crop yield (Abbass et al. 2022) and threaten food security (Cardinael et al. 2021). To face climate change, adaption and mitigation measures are needed. Agroforestry is seen as an encouraging nature-based solution to address both challenges, adaption and mitigation (Hernández-Morcillo et al. 2018). Mitigation strategies aim for a reduction of "the flow of heat-trapping GHG gases into the Earth's atmosphere, either by reducing the GHG sources or enhancing carbon sinks" (Ghale et al. 2022: p. 8). Agroforestry systems mitigate climate change by carbon sequestration of atmospheric CO_2 in the tree biomass and the soil (Ghale et al. 2022), and by decreasing deforestation (Cardinael et al. 2021).

Agroforestry is defined by the Food and Agriculture Organization of the United Nations (FAO 2024) as "a collective term for land management systems where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately integrated with agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence." Besides being a tool to counteract climate change, agroforestry offers various benefits (Hernández-Morcillo et al. 2018), which can be due to agroforestry's multifunctionality (Dmuchowski et al. 2024). These benefits extend from diversification of the farming practices, including different products and sources of income for the farmers (Cardinael et al. 2020; Quandt et al. 2023), to ecosystem services and environmental benefits, such as air and water quality improvements, biodiversity enhancements, increased carbon sequestration and soil fertility, and reduced erosion (Dmuchowski et al. 2024).

Agroforestry is found worldwide (Kumar et al. 2014) in tropical and temperate areas (Dollinger & Jose 2018). Around one billion hectares of land are found to be agroforestry systems (Cardinael et al. 2020). There are many different types of agroforestry systems. In temperate regions, agroforestry is used in applications such as riparian buffer strips, windbreaks, woodlots (Dmuchowski et al. 2024), as well as silvopastoral and silvoarable agroforestry. Silvopastoral agroforestry systems are systems combining trees with livestock (Castle et al. 2022) and pastures (Fahad et al. 2022), whereas silvoarable agroforestry combines shrubs or trees with crops, leading to so-called hedgerows (shrubs) or alley cropping systems (trees) (Dmuchowski et al. 2024). In alley cropping systems, trees are planted in rows and crops are grown between those rows (Honfy et al. 2023). The advantage of the alley cropping systems is that farmers can cultivate crops with machinery (Minarsch et al. 2022). This is visualized in Figure 1 depicting rapeseed planted in between rows of walnut trees in western Switzerland.

Figure 1: Example of an alley cropping system with rapeseed crops and walnut trees in Bussy-Chardonnay, canton Vaud (picture by T. Cigler).

Trees can be grown for different purposes. Some are used for food production, such as fruit and nut trees (Honfy et al. 2023), and others are used to produce quality timber (Honfy et al. 2023; Vaupel et al. 2022) or as a producer of biomass for energy wood (Vaupel et al. 2022). Some tree species can even fulfil two functions: cherry or walnut trees can be used for food production and, once felled, they can be used as quality wood (Kay et al. 2020).

Between the tree rows, a variety of different crops can be grown including winter wheat, winter barley, maize, sunflower (Sereke et al. 2015), triticale (Honfy et al. 2023), summer barley, summer oat (Vaupel et al. 2022), rapeseed, chickpea (Cardinael et al. 2017), beans, sorghum (Petrillo & Herzog 2016) and vegetables (Sereke et al. 2015), such as potatoes, garlic (Cardinael et al. 2017), lettuce, pumpkins, courgettes (Petrillo & Herzog 2016) and berries (Kay et al. 2020). There is also the possibility to cultivate flower strips (Minarsch et al. 2022), grow temporary meadows (Jäger 2017) or green manure or leave the inter-rows as rotational fallow (Petrillo & Herzog 2016).

1.2. Silvoarable Agroforestry in Switzerland

In Switzerland, silvoarable agroforestry has been a known practice for several centuries when fruit trees were additionally planted on plots of arable land (Jäger 2017). This method is called *streuobst* and was introduced in the 17th century (Herzog 1998). It was an important source of food for the population and at the same time part of the commercialization of food production in Europe (Nerlich et al. 2013). One hectare was planted with around 20 to 100 trees in an irregular pattern. The trees had different ages and were from different species, such as apple, pear and plum (Herzog 1998). Instead of cropland, there was also the variant where livestock was grazing under the trees (Nerlich et al. 2013).

Between around 1750 until the 1940s, the fruit orchards were reaching their peak phase (Jäger 2017), due to the modernization of tree care with the use of advanced pruning techniques and fertilisers (Keller 2022). In 1951, there were 14 million fruit trees in Switzerland (Sereke et al.

2015). As a result, the fruit harvest was high at that time and exceeded direct consumption demand, which lead to large volumes of alcohol being distilled. Resistance to alcohol production arose, and therefore, instead of fruit for liquor production, fruit was meant to be grown for fresh consumption under the cover of health benefits for the people (Keller 2022).

From 1951 until 1991, the proportion of *streuobst* was reduced by 70% (Herzog 1998). In other words, only 2.9 million trees were left (Sereke et al. 2015), which led to habitat loss for rare plants and animals, as well as a loss of traditional fruit tree species (Keller 2022). Additionally, the practical knowledge on agroforestry got lost (Jäger 2017).

Today, the share of agroforestry in agriculture is increasing again (Jäger 2017). In 2012, around 1’051’000 hectares were categorized as agricultural land in Switzerland. Out of these, 97’000 hectares of land were estimated to be used as agroforestry systems, which resulted in a share of 9.3% on total agriculture. Compared to other European countries, the share in Switzerland is rather high: only Portugal (51.2%), Greece (50.5%) and Spain (16.4%) show higher proportions of agroforestry within their total agricultural practices (Den Herder et al. 2015). Efforts in Switzerland are made to further increase this proportion. An example of this is the project *Agro4esterie*, which aims to create agroforestry systems on 280 hectares in cooperation with 140 farms located in the cantons Bern, Geneva, Jura, Neuchâtel and Vaud between 2020-2025. There are other goals of the project including enhancing the knowledge of technical and economic aspects of agroforestry systems, the promotion of biodiversity, increasing soil organic matter and erosion protection (Schoop & Carrad 2022).

There are several different types of modern agroforestry systems in Switzerland. Silvopastoral systems, which combine livestock with trees, are gaining ground, but most of the newly implemented systems are silvoarable agroforestry systems (Kay et al. 2020). Nevertheless, silvoarable agroforestry systems can be divided into different categories in Switzerland today, all of them being based on an underlying crop. The differences are found in the tree types: high-trunk fruit trees, low-trunk fruit trees, trees for use of fruit and wood and high-value timber (Kay et al. 2020).

1.3. Influence of Trees on Physical Properties of Soils

With climate change, farmers need to deal with risks concerning their soils, including, for example, the loss of nutrients, organic matter and biodiversity, dryness, wind erosion, and compaction (Rolo et al. 2023). As already mentioned, agroforestry systems can serve as an approach to deal with the changing climate. The plants, or in other words, vegetation layers interact with each other on a complementary basis when soil resources are involved. Agroforestry systems seem to enhance the soil’s chemical, biological and physical quality (Rolo et al. 2023).

Rolo et al. (2023) mention a change in the soil structure when comparing monoculture to agroforestry. Soil structure has an impact on “the availability and mobility of water, air and nutrients and influences the growth of plant roots” (Rolo et al. 2023: p. 1010) and can among other things impact soil fertility. Soil structure can be influenced by physical stress, which leads to soil compaction (Zimmermann & Schwab 2023). This is for example caused by the usage of heavy machinery for tillage (Minarsch et al. 2022). Compaction affects the soil aggregates and pores, which reduce the water infiltration capacity and soil aeration (Zimmermann & Schwab 2023). Trees and agroforestry systems can have a favorable impact on soil aggregation through the accumulation of organic matter by leaf biomass of the trees. The soil structure is interweaved by the tree roots, which has a stabilizing effect on soil structure, and is leading to an increase in macro- and microporosity (Rolo et al. 2023).

Climate, precipitation, evaporation and land use have impacts on the soil moisture, and the latter affects the soil water cycle in particular (Zhang et al. 2018). Even though crops and trees, with their differing root systems, may compete for moisture, agroforestry systems can improve the access to water, because trees have deeper roots than the crops (Cardinael et al. 2020), and increase the productivity of an agroforestry system (Honfy et al. 2023). The water can rise from deeper to shallower soil layers by the so-called *hydraulic lift*, which is induced by tree roots. This process could reduce the soil moisture competition between the trees and crops (Rolo et al. 2023) and increase the sharing of water, but it is not yet clear, if the effect of the *hydraulic lift* is significant (Cardinael et al. 2020). By increasing the organic matter content in a soil, the water-holding capacity was shown to be increased in some studies, which impacts crop yields (Minasny & McBratney 2018), and can be caused by the trees in agroforestry systems. Consequently, the porosity and the infiltration rates of the soils is increased in agroforestry systems in comparison with treeless soils (Rolo et al. 2023).

The soil property bulk density affects the infiltration, aeration or the growth of vegetation (Throop et al. 2012), and is employed to figure out if soils suffer from compaction or penetration stress (Panagos et al. 2024; Thomas et al. 2020). The bulk density might be altered if the management practices are changed (Upson et al. 2013), for example by adding crop residues or through tillage (Panagos et al. 2024), or agroforestry (Ling et al. 2019). Trees decrease the bulk density on the one hand through the input of organic material (Fahad et al. 2022), on the other hand, roots take part in improving the bulk density, depending on the quantity and concentration of the root distribution (Ling et al. 2019). Additionally, the number of pores is increased (Fahad et al. 2022). This shows the connection of bulk density and the above-mentioned soil structure. Among other parameters, the lower bulk density in the agroforestry system improves the soil hydrological properties and the vegetation performance (Cardinael et al. 2020)

The force, which roots need to apply to penetrate the soil, can be estimated by the penetration resistance (Thomas et al. 2020). The penetration resistance is depending on various parameters, such as “soil texture and bulk density (…), moisture content (…), porosity and permeability (…), particle size distribution (…), structure, mineral and organic matter content of soil (…), pH, cation-exchange-capacity, clay particle thickness, and presence of iron oxides and free aluminium hydroxide” (Kunakh et al. 2022: p. 113), as well as the overlying vegetation and human activities (Zhukov et al. 2021), such as tillage. However, the bulk density and the soil water content have the highest momentary impact on the penetration resistance (Souza et al. 2021), which can differ in a soil on a spatial and temporal scale, as it is dependent on the dynamic factors of bulk density and soil water content (Vaz et al. 2011). Penetration resistance controls the root growth of plants and the access to moisture (Souza et al. 2021). The roots of trees can compact the soil by transferring the weight of the tree into the soil while also forming a net of soil pores after their degradation (Kunakh et al. 2022). Soil compaction is defined as “the rearrangement of soil particles that causes reduction of the pore volume” (Alesso et al. 2018: p. 822). The greater the soil compaction, the greater is the resistance for the plants’ roots to grow through the soil (Kunakh et al. 2022) and the higher is the penetration resistance (Bartzen et al. 2019). If certain penetration resistance thresholds are exceeded, the yield is limited (Souza et al. 2021).

1.4. Research Questions and Hypotheses

This Master's thesis is part of Camille Rubeaud's PhD project entitled "Assessing the potential of agroforestry systems to improve soil health and ecosystem services" at Agroscope and ETH Zürich. The Master's thesis is embedded in a respective study focusing on soil health in Swiss agroforestry systems, in which, in addition to the physical parameters discussed in this thesis, further chemical and biological parameters are analyzed to obtain a broad assessment of soil health in silvoarable agroforestry systems.

In Switzerland, no study has provided an overview yet on the physical properties of the soils in alley cropping systems, which is why this thesis aims to address this research gap. It assesses the soil physical properties of 33 alley cropping systems in Switzerland and their neighboring treeless arable fields as control by measuring the bulk density, the gravimetric water content and the penetration resistance. Further, this work considers several internal (density, diversity, age and average tree volume of the agroforestry system) and external variables (mean temperature, annual precipitation and altitude of agroforestry system) to be able to answer the following research questions:

i. Is there a difference between soil physical properties in silvoarable agroforestry plots and soils in arable plots without trees in Switzerland in regard to:
   a. the bulk density,
   b. the gravimetric water content at sampling time, and
   c. the penetration resistance?
ii. Does the tree density, tree diversity, age of trees and/or average tree volume of the alley cropping systems have an impact on the soil's physical properties?

The hypotheses were stated as follows:

I. The bulk density is lower in the silvoarable agroforestry systems compared to the arable plots without trees.
II. The gravimetric water content at sampling time is higher in the agroforestry system plots than in the arable plots without trees.
III. Penetration resistance is lower in the tree plot than in the alley and control plots.
IV. Increasing tree density, diversity, age and tree volume impact physical soil properties positively.

2. Material and Methods

Since this Master's thesis was part of a PhD project, the sampling locations, the sampling protocol and the analysis methods were already defined in advance. Some adjustments were made during the field and laboratory work.

2.1. Site Description

Within this project, 33 different sampling sites were chosen. All of them are farms that practice silvoarable alley intercropping and had a corresponding treeless control field. Most of them were situated in the western and northern part of Switzerland (Figure 2).

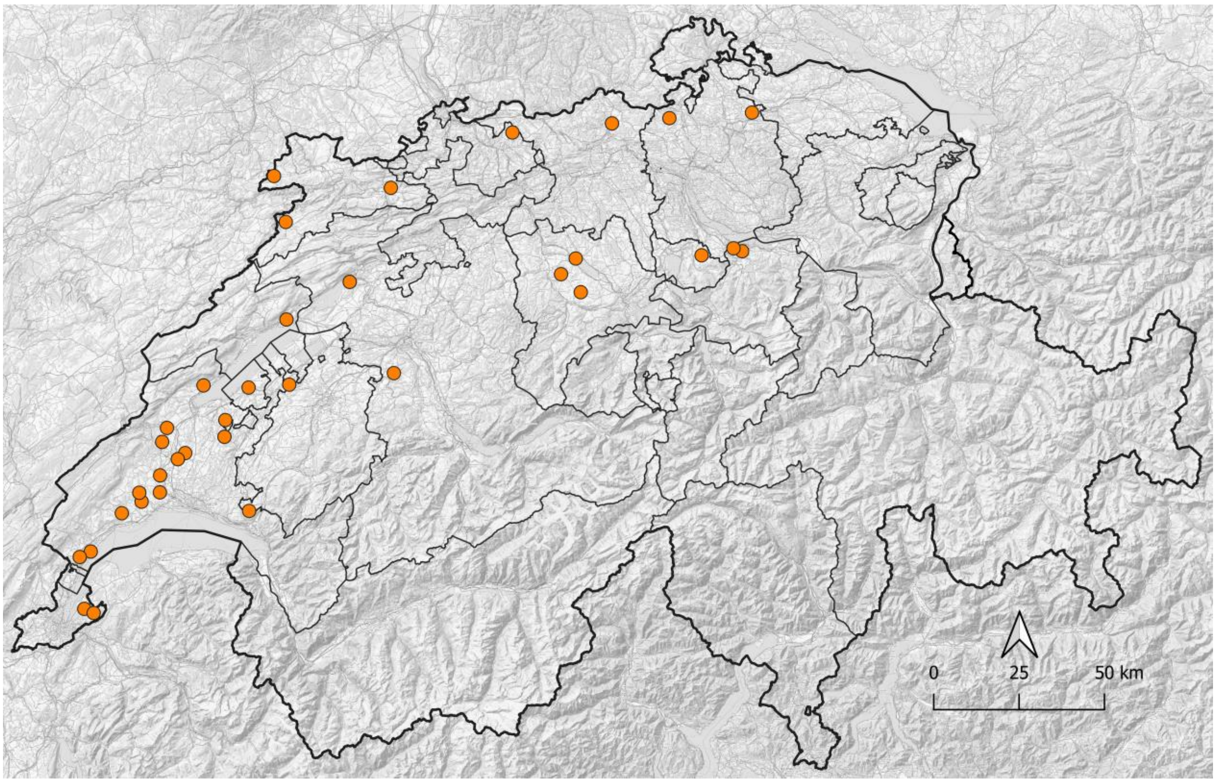

Figure 2: Overview of the 33 sampling sites within Switzerland. Each orange dot marks a sampling site (base map: OpenStreetMap contributors (2024); national and cantonal boundaries: Bundesamt für Landestopografie swisstopo (2024)).

The sites showed differences regarding the density of the planted trees, the number of tree species planted, the age of the agroforestry system and the average tree volumes. There were also differences in soil types, but an attempt was made to sample soils that were as similar as possible. In most cases, the soil types were brown soil or lime-brown soil. As the sampling locations were distributed throughout Switzerland, there were sites in the Jura, the Molasse basin of the Swiss plateau and within the foothills of the Alps. The geological background was not further assessed in this thesis, nor was the tillage type and the crop rotation.

2.2. Field Campaign and Sampling

The field campaign took place in February and March 2024. The sampling included undisturbed soil cores and the measurement of the penetration resistance, as well as various parameters, such as the distance between the trees, the width of the tree and the arable alley strip, and the characterization of the trees. In addition, the altitude of the sampling sites was measured with a GPS-device. The age of each plot was determined in advance by Camille Rubeaud in discussions with the farmers.

The same sampling design was used for all sites. There were three plots on each site: the tree strip plot, the arable alley plot and the treeless control plot (Figure 3). The control plot without trees should be as similar as possible to the arable alley plot by ensuring that it was farmed by the same farmer with the same crop rotation, the same soil tillage, and with the same soil type. In some cases, one of the mentioned criteria was not met, but the best possible control area was sampled.

Figure 3: Visualization of the tree strip plot, arable alley plot and tree-less control plot (yellow, turquoise and purple, respectively), based on a picture of the agroforestry system in Oulens-sous-Échallens, VD.

To take the samples from both the agroforestry plot (tree and alley) and the control plot from a representative location within the whole site, there was an inspection before the ideal perimeter for sampling was selected. Soil maps or information provided by the farmer were used in addition. For the tree and alley plots, each plot had a length of 20 m with the measurements starting at the trunk of a tree. The width of those plots depended on the width of the alley plot and was variable (Figure 4, A). The plots always consisted of five transects to ensure a

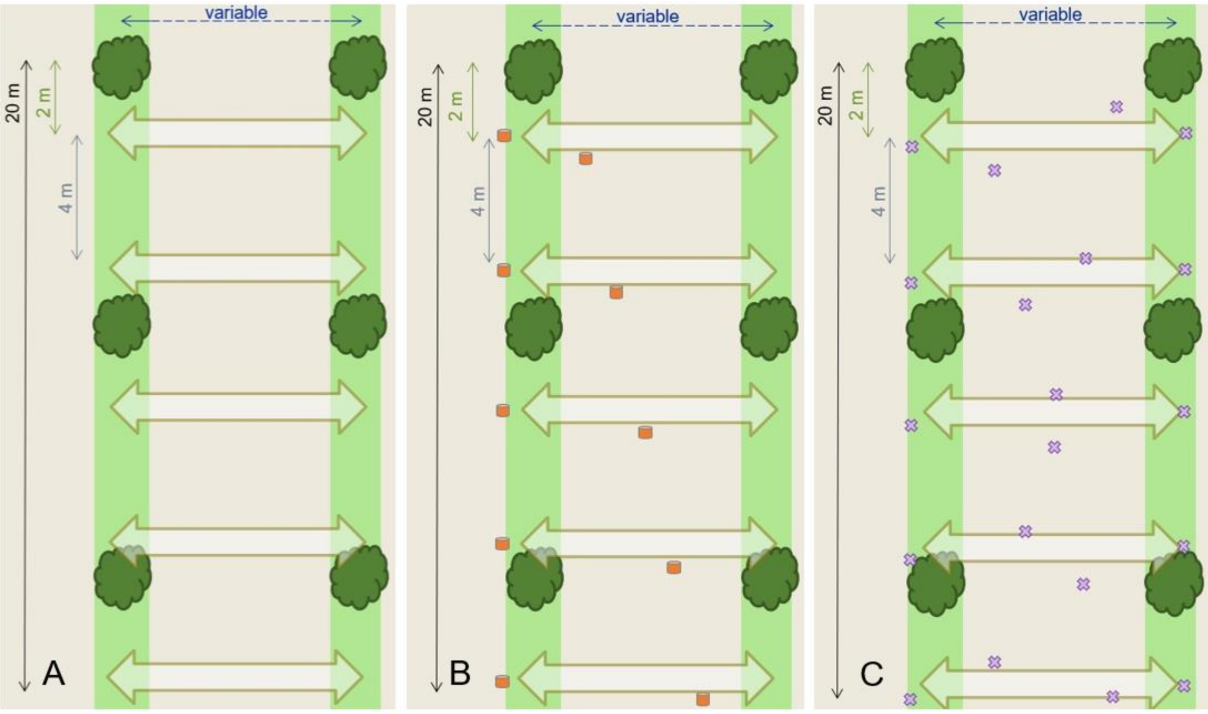

Figure 4: Overview on the schematic sampling plot, where each green arrow visualizes a transect (A). Schematic sampling plan of undisturbed soil cores for bulk density and gravimetric water content measurements (B) and penetration resistance measurements scheme (C). The visualizations are adapted from C. Rubeaud.

homogeneous sampling within the plot. The distance between two transects was 4 m, while the first one started 2 m after the beginning of the plot.

The control plot had a square shape with a side length of 16 or 20 m. Some exceptions were, however, made. Either the shape was adapted to a rhombus, or the square was reduced to a side length of 12 m if the on-site conditions made it necessary. The reasons for the exceptions were usually because the area for the control area was too small or to maintain a buffer from the tree strips, roads, forest areas or from other arable land. The samples in the control plots were taken the same way than the samples in the alley plots.

2.2.1. Bulk Density and Gravimetric Water Content

The bulk density and the gravimetric water content were both measured in undisturbed soil cores sampled using steal cylinders. Each cylinder had a diameter of 53 mm and a volume of 100 cm^3 (Royal Eijkelkamp 2019). Per site, 30 samples were taken, corresponding to ten per plot (Figure 4, B). The undisturbed soil cores were taken at two depths: once in the topsoil (0-20 cm) and once in the subsoil (20-40 cm). Care was taken to sample the middle of each layer, which resulted in sampling depths of 7.5-12.5 cm and 27.5-32.5 cm (Figure 5). During sampling, no sample was taken within close proximity to a tree to avoid large roots within the samples. In addition, the samples were taken in the axis between the trees. The sampling was performed as quickly as possible, when the groundwater was high to avoid an overrepresentation of the moisture. If the soil contained too many stones or a sample contained rock fragments sticking out of the cylinder, the replicate was rejected, and a new attempt was made. After the cylinder was removed from the soil, the excess material on both sides of the cylinder was cut off exactly at the edges, leading to a sample volume of exactly 100 cm^3. The sample was then placed in a plastic sample bad and sealed airtight.

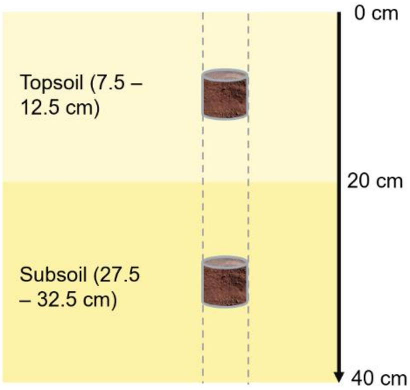

Figure 5: Undisturbed soil core sampling depths.

In total, 981 undisturbed soil samples for the bulk density and the gravimetric water content were taken. Nine samples could not be taken in the subsoil of site 6 due to too many stones in the soil. For this site, only the values from the topsoil of the tree and alley plot were considered. For the control plot at this site, both the topsoil and subsoil were considered.

2.2.2. Penetration Resistance

The penetration resistance was measured in the field with the Penetrologger from Eiijkelkamp with a measuring cone with a base area of 1 cm^2 and a depth resolution of 1 cm (Royal Eijkelkamp 2022, Figure 6). The measurement unit of the penetration resistance is MPa (Bartzen et al. 2019). Ten measurements were performed per plot, leading to 30 measurements per site (Figure 4, C). In the tree plot, measurements were carried out five times per tree strip. In the alley and control plots, measurements were taken crosswise five times per diagonal. The measurements were carried out vertically and with a constant velocity to obtain comparable results. Where possible, measurements were performed to a depth of 80 cm. This corresponds to the maximum depth which can be measured with the probing rod (Royal Eijkelkamp 2022). If it was impossible after five tries at slightly shifted positions, a maximal penetration depth of 60 cm was attempted. If this could neither be reached, the maximal possible depth of the site was accepted. This was the case in soils with lots of stones, roots or with an insufficient soil depth.

Figure 6: Measurement with the Penetrologger in the field (picture by T. Cigler).

2.3. Sample Preparation in the Laboratory

2.3.1. Bulk Density

The undisturbed soil core samples for the bulk density were stored in the cooling room (at 4°C) to prevent the formation of mold. The bulk density was assessed at the same time, once all samples were collected. The samples were processed in a specific order: only one replicate per site, plot and depth was dried at the same time to avoid the loss of entire sites in the event that an error by the person measuring or a failure of the oven would have occurred. In addition, with this approach randomization and a reduction of the laboratory bias was ensured. The moist samples were removed from the sample bags and placed in aluminium trays (Figure 7). The containers were weighed before the samples were filled to obtain the tara weight for each tray individually. The scale had a precision of 0.01 g (Mettler Toledo) and was connected to a computer, which allowed automatic transmission of the measured values to avoid possible typing errors. The samples were crushed when necessary to speed up the drying process if the samples were very clayey or otherwise compacted. The prepared, moist samples were weighed to determine the moisture content. In this thesis, it is assessed as gravimetric water content, which “is the mass of water per mass of dry soil” (Bilskie 2001: p. 1) and is expressed in grams of water per gram of soil (Lu et al. 2024), or g g^{-1} (Bilskie 2001). After the samples were weighed for the first time, they were dried in an oven at 105°C for at least 48 hours. Some of the used ovens ran constantly, while others switched off automatically after 48 hours. For the latter, the ovens were turned on for an additional hour if the samples could not be removed exactly after the 48 hours, to eliminate

Figure 7: Examples of moist bulk density samples.

any moisture that may have re-entered the samples. The samples were then weighed as quickly as possible to minimize moisture entering and to treat all samples equally. With this, the bulk density was assessed, which is the “oven-dry mass of soil per unit volume” (Poeplau et al. 2016: p. 61), expressed as g cm^{-3} (Cardinael et al. 2017).

2.3.2. Stone Content

The stone content of the cylinder samples varied greatly depending on the location and plot, which became apparent as soon as the samples were prepared for drying. As stone content influenced bulk density, a stone correction was done for all the samples.

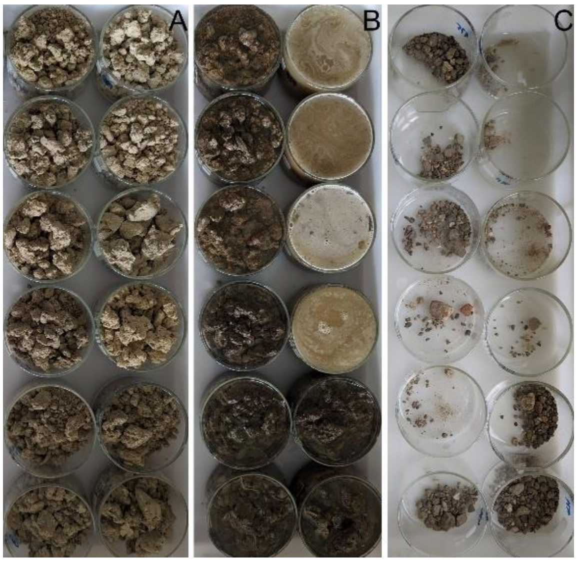

Figure 8: Process of stone content determination: dried samples from bulk density measurements (A), samples filled up with water (B, left) and water filled samples, mixed (B, right), and washed-out stone samples (C).

The former dried samples were placed in water and left a few hours to allow the soil to separate more easily from the stone fragments (Figure 8, A and B). The samples were then washed out over a 2 mm sieve to retain only the particles larger than 2 mm (Figure 8, C). The coarse fragments were dried until the steady-state weight was reached and were then weighed. The samples of one site were pooled, as it was assumed that the stones of one site had the same density, resulting in 33 stone samples. Then the stone volume determination was measured using water displacement for all the samples of one site. The samples were weighed again as a whole for the density calculation. Immediately afterwards, the rock fragments were placed in a bag made of a plastic fabric with a mesh size of 1 mm, which is permeable by water. The bag filled with the rock fragments was then placed in a container filled with water, which was placed on a scale. The bag was immersed in the water up to a previously marked line to ensure the same treatment for each sample. It was important that the bag did not touch the sides or the bottom of the container. Due to the Archimedes’ principle, the volume of the stone sample corresponded exactly to the weight loss in water as compacted to air, which was shown on the scale (Figure 9). The used Kern scale had an accuracy of 2 g up to a weight of 5 kg. The measurement was performed until the same weight was displayed twice.

Figure 9: Organization of stone volume determination measurement.

2.4. Data Processing and Analysis

2.4.1. Bulk Density: Stone Correction Calculation

As stated in 2.3.2, the bulk density was corrected regarding the stone content to get the bulk density of the fine soil. The $BD_{fine\ soil}$ was calculated with the following formula, which is also used in Don et al (2007):

$$BD_{fine\ soil} = \frac{mass_{sample} - mass_{stones}}{volume_{sample} \frac{mass_{stones}}{\rho_{stones}}}$$

The calculation of the $BD_{fine\ soil}$ was performed in Excel (Microsoft Corporation 2024) for each replicate with the associated masses of the dried sample, the coarse fraction and the stone density for each site. When the term bulk density is used in the following work, it refers to the bulk density of the fine soil. One replicate (site 33, subsoil, alley plot) was excluded from the analysis because the bulk density was unusually low (0.46 g cm^{-3}). This was probably due to a high stone content or a measurement error, as this was the only sample with a bulk density below 0.66 g cm^{-3}.

2.4.2 Penetration Resistance Data

After the penetration resistance measurements were conducted in the field, the data was extracted with the Penetroviewer (Version 6.08 (Royal Eijkelkamp 2019)) program and converted into a .txt-file for each of the 33 sites. Afterwards, those files were converted into .csv-files, which were loaded into R (R Core Team 2024). Based on an existing R script (F. Walder, personal communication, 19.04.2024), different calculations and plots were made. In the beginning, for each site, plot and depth (in steps of 1 cm) the median value of the ten measurements was calculated. Based on this, the median value of each site and plot was calculated for subsets of 10 cm. These median values were used for the further analysis as stated in 2.4.4.

2.4.3. Derivation of Agroforestry System Parameters

Some parameters had to be calculated after the field work. The tree density was calculated to get a better comparison value between the different sites and to get a value which could be used for the statistical analysis and comparison with literature. Therefore, the tree density value (trees per hectare), was determined for each site using the following calculation, based on the adapted formula of Scholz (n.d.):

$$Tree\ Density\ \left[\frac{1}{hectare}\right] = \frac{10'000}{Tree\ Distance\ [m] \times (Width\ Arable\ Strip\ [m] + Width\ Tree\ Strip\ [m])}$$

For the tree diversity parameter, the number of observed individual tree species on each site was summed up, to get a comparable value. The specific tree species were not recorded, only the number of species per site.

The tree volume was calculated based on the formula of Roberti et al. (2023):

$$V_T = (\frac{BHD}{2})^2\ \times H\ \times\ \pi$$

The variables are V_T: tree volume in m^3; BHD: breast high diameter of the tree's trunk [m]; H: height of the tree [m]. To get the average tree volume of each site, the average BHD and height for all the measured trees within each tree plot was used as an input for the formula above.

The gravimetric water content (θg) was calculated after the bulk density dry and wet masses (m_{dry} and m_{wet}, without stone correction) were obtained according to the formula of Bilskie (2001):

$$\theta g = \frac{m_{wet} - m_{dry}}{m_{dry}}$$

For the precipitation and temperature parameter, the data of MeteoSchweiz (2024a) was used. For each site, a corresponding weather station was chosen, which considers the location of the site as well as the site's altitude or geographic position. It is possible that two different weather stations (one for precipitation, one for temperature) were used for one site if the stations differed in terms of parameter availability. The annual summed up values (precipitation) or average daily means (temperature) of a year were used for the analysis. The sampling day was decisive for the calculation to maintain the same observation period for each site and to exclude subsequent precipitation. The altitude for each site was measured on-site with a GPS-device and was used to see whether it influenced any of the analyzed soil properties.

2.4.4. Statistical Analysis

The data was processed and analyzed using the software programs Excel (Microsoft Corporation 2024) and R (R Core Team 2024). To be able to compare differences between two plots from each site, $\log_{10}$ response ratios were calculated for the tree-alley and alley-control plots of bulk density, gravimetric water content and penetration resistance with the following formula:

$$log_{10}\ Response\ Ratio = log_{10}(\frac{MV\ Plot_1}{MV\ Plot_2})$$

The variable MV symbolizes the median value of the five replicates for each plot. The bulk density and gravimetric water content response ratios were calculated for the topsoil and subsoil, and the penetration resistance response ratios were calculated for subsets of 10 cm depth. For the agroforestry-control ratio, the proportions of the tree and alley plots were calculated according to the width of the respective strip to get the weighted width (T_{ww} and A_{ww}, respectively):

$$T_{ww} = \frac{Width\ Tree\ Strip\ [m]}{Width\ Tree\ Strip\ [m] + Width\ Alley\ Strip\ [m]}$$

$$A_{ww} = \frac{Width\ Alley\ Strip\ [m]}{Width\ Tree\ Strip\ [m] + Width\ Alley\ Strip\ [m]}$$

By inserting these values, the adjusted formula can be calculated as follows for the topsoil, subsoil as well as the 10 cm depth subsets for the agroforestry-control response ratio:

$$log_{10}\ Response\ Ratio\ AFS/C = log_{10}(\frac{(MV\ Tree\ Plot\ \times\ T_{ww}) + (MV\ Alley\ Plot\ \times\ A_{ww})}{MV\ Control\ Plot})$$

Depending on the research question, different analyses were carried out with the response ratios, the internal variables and the external variables (Table 1). ANOVAs were performed to understand differences between groups (e.g. response ratios and depth of bulk density). Linear regressions and Spearman's correlation were calculated to determine correlations between a response ratio and an internal variable (i.e. tree-alley response ratio and age). After these analyses, the extreme values of the internal variables were removed to see whether these extreme values had an influence on the outcomes of the linear regressions. The decision was taken to remove sites with the highest values of each variable as were only a few sites with high values (Table 2). Multiple regressions were also used to analyze possible connections between the obtained data (bulk density, gravimetric water content and penetration resistance) and the possible influence of the different internal and external variables.

Table 1: Overview of analyzed response ratios, internal variables and external variables with the applied statistical analyses.

<table>
<tr><td colspan="2"></td><td colspan="3">Applied Statistical Analyses</td></tr>
<tr><td rowspan="3">Log$_{10}$ response ratios</td><td>Tree – alley (T/A)</td><td rowspan="3">ANOVA</td><td rowspan="7">Linear Regression and Spearman's Correlation</td><td rowspan="10">Multiple Regression Analysis</td></tr>
<tr><td>Alley – control (A/C)</td></tr>
<tr><td>Agroforestry – control (AFS/C)</td></tr>
<tr><td rowspan="4">Internal variables</td><td>Agroforestry system density [trees/ha]</td><td rowspan="4"></td></tr>
<tr><td>Agroforestry system diversity [number of different tree species]</td></tr>
<tr><td>Age of agroforestry system [years]</td></tr>
<tr><td>Average tree volume of agroforestry system [m^3]</td></tr>
<tr><td rowspan="3">External variables</td><td>Altitude of agroforestry system [m a.s.l.]</td><td colspan="2" rowspan="3"></td></tr>
<tr><td>Average temperature of agroforestry system within one year [°C]</td></tr>
<tr><td>Precipitation amount of agroforestry system within one year [mm/year]</td></tr>
</table>

Table 2: Extreme value limits of internal variables.

Internal variable	Extreme value limits
Agroforestry system density	< 200 trees/ha
Agroforestry system diversity	≤ 6 different tree species
Age of agroforestry system	< 20 years
Average tree volume of agroforestry system	< 0.4 m^3

Overall, the level of significance for this thesis was defined at a p-value of 0.1. The residuals of the analyses were checked for normal distribution with the Shapiro-Wilk test. In case of linear regression residuals being significant with the Shapiro-Wilk test, Spearman correlations were calculated. In case of ANOVA and multiple regression, the Kruskal-Wallis test was applied if the data was not normally distributed to check the statistical significance between the medians of different groups. The data was also checked for homoscedasticity (equal variances) with the Levene's test before an ANOVA. If the result was significant, the Welch-ANOVA was applied. After an ANOVA, a post hoc test (TukeyHSD) was conducted to check for significant differences between the groups and variables.

The $\log_{10}$ response ratio values used for the analysis are listed in the Appendix (S2, S3 & S4). Exemplary codes for each of the statistical tests used can also be found in the Appendix (S6).

3. Results

3.1. Site Characteristics

The 33 sampling sites differed greatly from each other in many regards, among others due to the geographical location, the climatic conditions and the farming practices. In this chapter, an overview is given on the site characteristics. A table with all the variable values can be found in the Appendix (S1) as well as maps showing the distribution of the variables within the sampled agroforestry systems in Switzerland (S5).

<u>External Variables</u>

The geographical location was decisive for the altitude which varied between 408 m a.s.l. (site 19, Prangins VD) and 771 m a.s.l. (site 25, Bonvillars VD) with an average altitude (based on all sites) of 557.6 m a.s.l. The highest precipitation amount was found at site 33 (Menzingen ZG) with 1’989.1 mm/year, and the lowest was at site 25 (Bonvillars VD) with 804 mm/year. The average amount of precipitation throughout all sample sites was 1’176.2 mm/year. The highest averaged daily temperature within the year before the sampling campaign was reached at site 20 (Eysin VD) with 12.72°C. The lowest with 8.39°C was at site 5 (Arnex-sur-Orbe VD). The average temperature over all sites was 11°C.

<u>Internal Variables</u>

The highest tree density was found at site 31 (Rickenbach ZH) with 500 trees per hectare, and the lowest was at site 26 (Würenlingen AG) with 9.62 trees/ha. The average density over all agroforestry systems were 74 trees/ha. Within all the sampled agroforestry systems, there were between one and eleven different tree species found. Dominantly, there was only one or two tree species planted (on twelve and ten sites, respectively). Three species were counted on five sites, and two sites each had agroforestry systems with four or six tree species. One farm planted nine different species, and another one planted eleven species, which was the highest number of different species. The average number of tree species planted within an agroforestry system was 2.7.

The age of the trees reached from four to 31 years; thus, the agroforestry systems were created between 1993 and 2021. The youngest agroforestry systems were sites 1 and 19 (Courroux JU and Prangins VD). The oldest systems were found in Feusisberg SZ and Fey VD (sites 6 and 9). The average age of the agroforestry systems was 10.2 years. The age of the agroforestry system had a significant impact on the average tree volume of the agroforestry system (p-value < 0.01, Spearman’s $\rho = 0.88$). The indicated effect was positive: the older the trees, the greater the tree volume was. The average tree volume per site varied between 0.0005405 m^3 (site 22, Oberbalm BE) and 2.40 m^3 (site 6, Feusisberg SZ) with an average over all the agroforestry systems of 0.14 m^3.

3.2. Bulk Density

The results for the whole dataset of bulk density showed that there were no significant differences between the plots (tree, alley and control) at individual soil depths (p-value > 0.74; Figure 10, A). There were, however, significant differences between the bulk density values at the topsoil and subsoil (p-value < 0.01; Figure 10, A) for all the plots. The median values of the topsoil were significantly lower than those of the subsoil. The bulk density ranged between

0.67 g cm^{-3} and 1.65 g cm^{-3} in the topsoil and between 0.70 g cm^{-3} and 1.80 g cm^{-3} in the subsoil.

For the bulk density response ratios, there were no significant differences between the three calculated ratios and the two soil depths found (p-value = 0.53 and 0.54, respectively; Figure 10, B). This applied also to the individual linear regressions with the response ratios and internal variables, as there was no significant correlation found. The same was also observed for the multiple regressions, as none of them showed a significant result for the bulk density response ratios and the different variables. Therefore, for this study, the presence of trees had no effect on the bulk density.

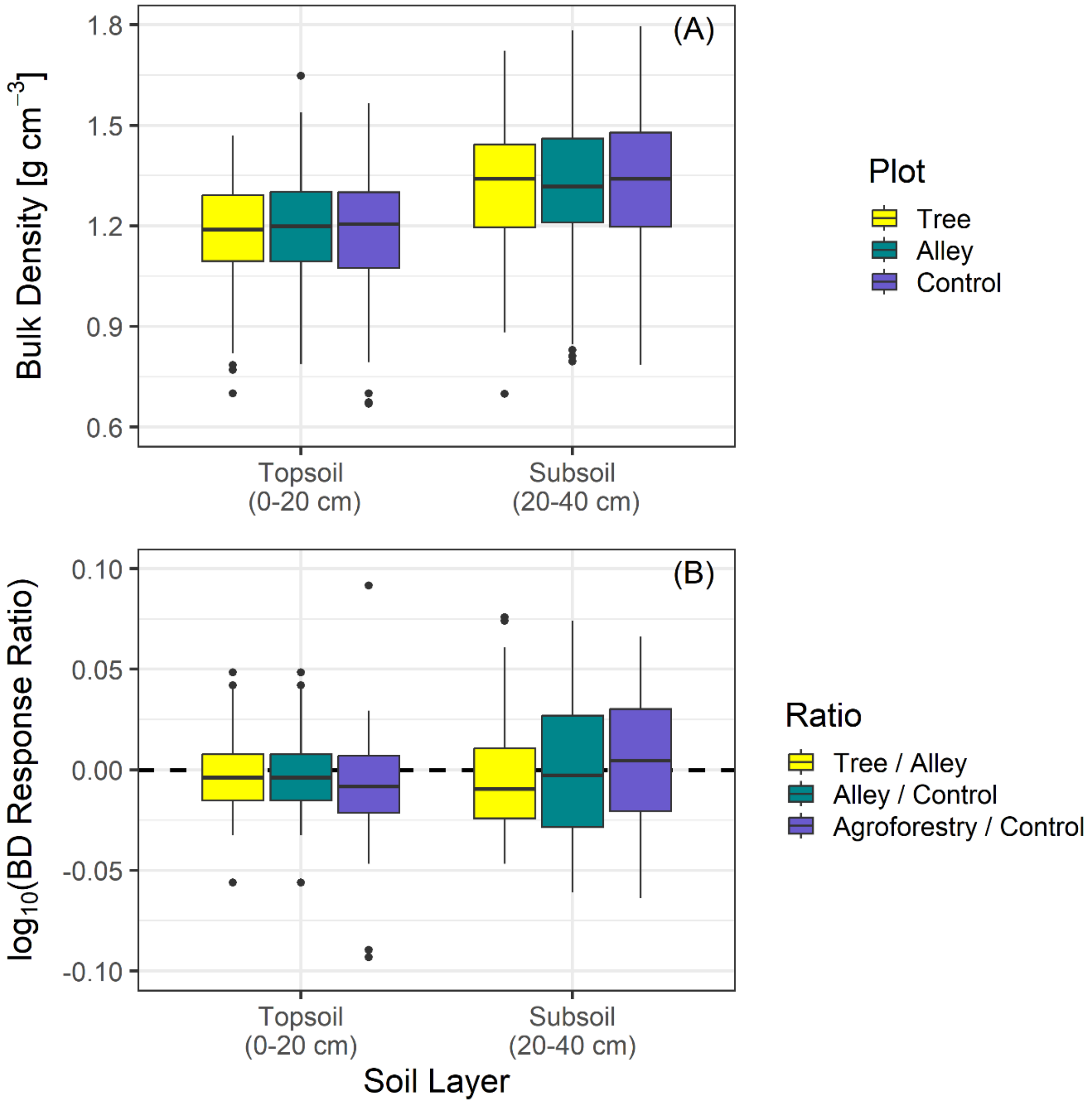

Figure 10: Bulk density (BD) values per soil depth (topsoil and subsoil) and plot (yellow = tree plot, turquoise = alley plot, purple = control plot) (A). log$_{10}$ response ratio of the bulk density for each soil depth and plot (yellow = tree / alley, turquoise = alley / control, purple = agroforestry / control). The dashed line indicates a log$_{10}$ response ratio of 0 (no difference between the two plots) (B).

3.3. Gravimetric Water Content

For the whole dataset, there were no significant differences regarding the gravimetric water content between the plots (tree, alley and control) within the same soil depth (TukeyHSD p-values > 0.53). However, between the topsoil and the subsoil, the topsoil values were significantly higher than the subsoil values (TukeyHSD p-value < 0.01; Figure 11, A). The topsoil gravimetric water content values ranged from 0.08 to 0.72 g g^{-1}, and the subsoil values ranged from 0.06 to 0.50 g g^{-1}.

No significant differences were found between the two soil depths or the calculated ratios regarding the gravimetric water content log_{10} response ratios (p-values = 0.77 and 0.66, respectively; Figure 11, B). The calculated multiple regressions did not show any significant results regarding the gravimetric water content response ratios in the topsoil or subsoil nor in the different internal or external variables.

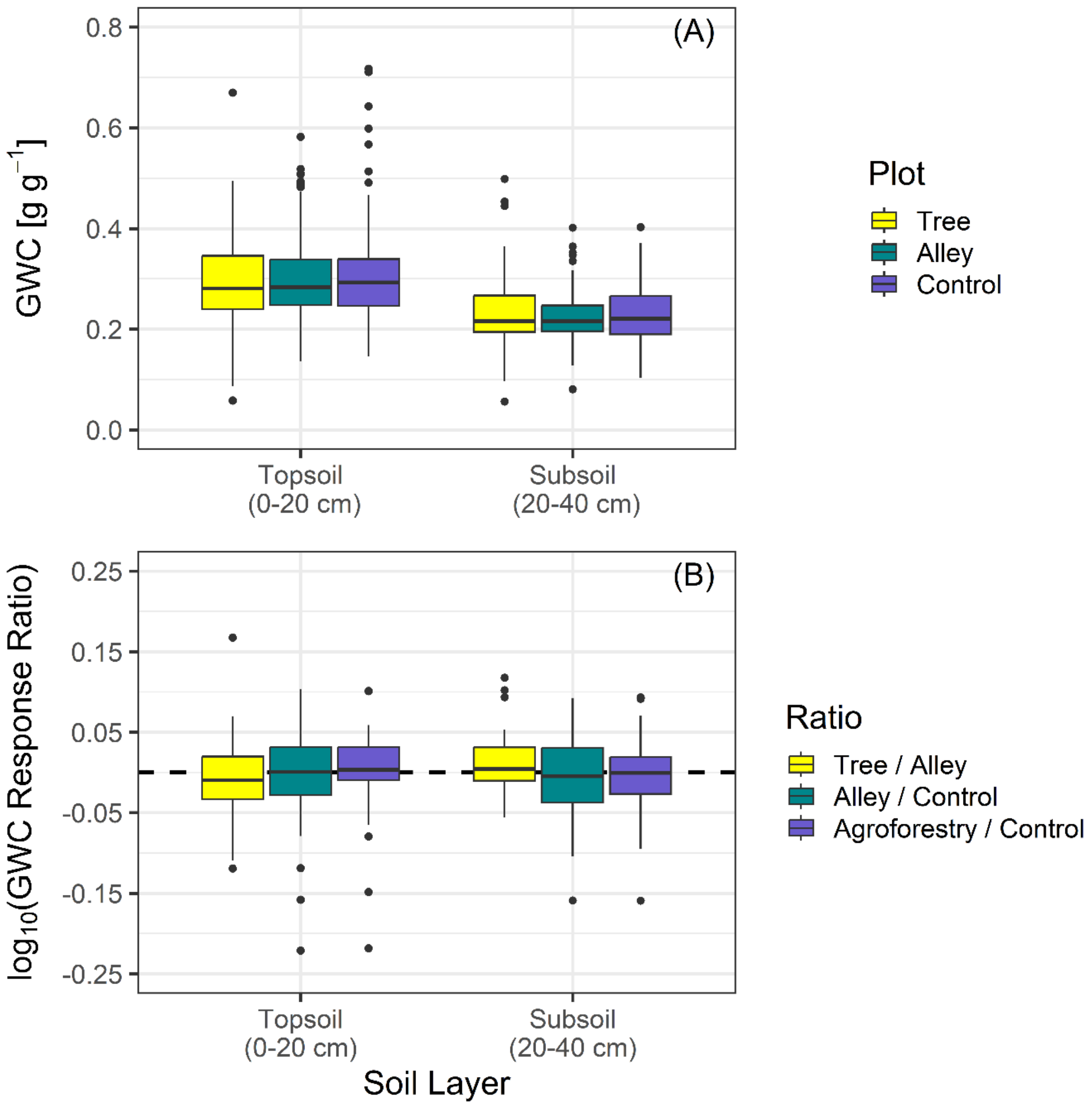

Figure 11: Gravimetric water content (GWC) values per soil depth (topsoil and subsoil) and plot (yellow = tree plot, turquoise = alley plot, purple = control plot) (A). log_{10} response ratio of the gravimetric water content for each soil depth and plot (yellow = tree / alley, turquoise = alley / control, purple = agroforestry / control). The dashed line indicates a log_{10} response ratio of 0 (no difference between the two plots) (B).

Based on linear regression, tree density had no significant effect on the gravimetric water content response ratios. When the extreme values were excluded (tree density greater than 200 trees/ha), a significant effect of the tree density was found in the subsoil tree-alley ratio (Figure 12, B). The effect was negative: with increasing tree density, the gravimetric water content tree-alley response ratio decreased. For gravimetric water content with a tree density < 60 trees/ha, the gravimetric water content tended to be higher in the tree plot than in the alley plot. With a tree density > 60 trees/ha, the gravimetric water content tended to be lower in the tree plot compared to the alley plot (Figure 12, B).

Regarding the tree diversity and the gravimetric water content response ratios, no significant result occurred when the linear regressions were calculated. When the extreme values were excluded (agroforestry systems with six or more different tree species), three significant results occurred. One was found in the topsoil (tree-alley ratio; Figure 12, A), and two were found in the subsoil (alley-control and agroforestry-control ratio; Figure 12, D and E, respectively). In the tree-alley ratio, the effect was negative: with increasing tree species number, the gravimetric water content response ratio decreased. The tree-alley gravimetric water content response ratio was above 0, meaning that the gravimetric water content was higher in the tree plot than in the alley plot, when only one tree species was present in an agroforestry system. With two or more species, the gravimetric water content was higher in the alley plot. (Figure 12, A). In the alley-control and agroforestry-control ratios, the effect of tree diversity was positive: the more tree species, the higher the gravimetric water content response ratio. When there was only one tree species in an agroforestry system, the gravimetric water content in the subsoil was higher in the control plot than in the alley plot. The same applied to the agroforestry-control ratio, where the gravimetric water content in the subsoil was higher in the control plot than in the combined agroforestry system plot when one tree species was planted in the agroforestry system. With more tree species, the gravimetric water content in the subsoil was higher in the alley plot and agroforestry system plot than in the control plot (Figure 12, D and E).

The age of the agroforestry systems had a significant effect on the gravimetric water content tree-alley response ratio in the subsoil (Figure 12, C). The effect was negative: the older the agroforestry system, the lower was the gravimetric water content response ratio. For the agroforestry systems younger than 18 years, the gravimetric water content tended to be higher in the tree plot than in the alley plot. With an agroforestry system aged approximately 18 years ($\log_{10}$ of the age ≈ 1.26), the gravimetric water content response ratio turned negative, indicating a higher gravimetric water content value in the alley plot than in the tree plot. When the extreme values were excluded (agroforestry systems aged higher than 20 years), no significant results were reported.

The tree volume showed no significant effect on the gravimetric water content response ratios. With the removal of the extreme values (average tree volumes greater than 0.4 m^3) no results either were significant for the linear regressions.

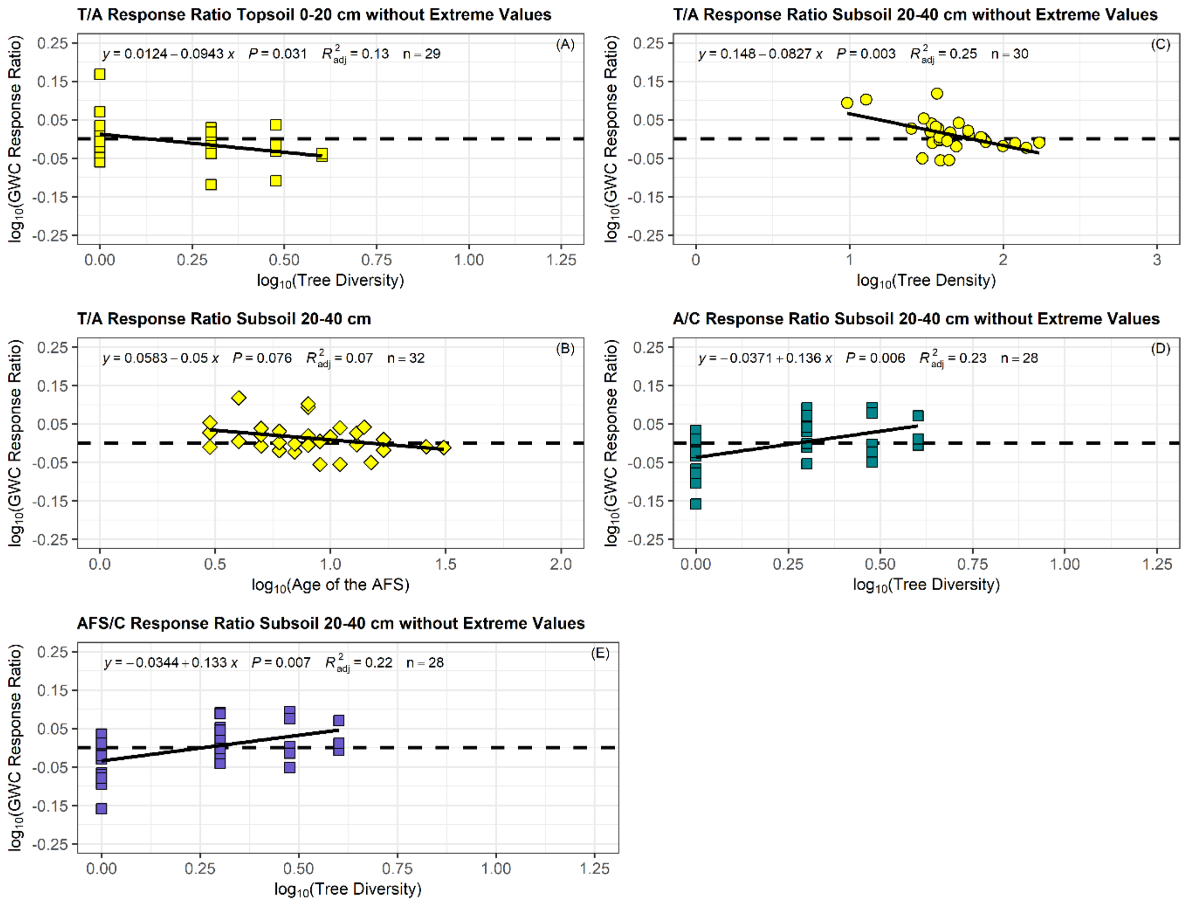

Figure 12: Significant gravimetric water content (GWC) log_{10} response ratios (yellow = tree / alley ratio (T/A), turquoise = alley / control (A/C), purple = agroforestry system / control (AFS/C)). The slope of the linear regression, the p-value, the R2-adj value and the number of observations (n) are displayed in the respective graph. The dashed line indicates a log_{10} response ratio of 0 (no difference between the two plots). The different symbols represent the variables (dot = tree density, square = tree diversity, diamond = age of agroforestry system).

3.4. Penetration Resistance

An overview of the penetration resistance is visualized in Figure 13 (A), where box plots of the medians of all sites, for each 10 cm depth increment and the three plots were combined. Regarding the absolute values, the median for all plots between 0 and 30 cm was below 2 MPa. Between 31 and 60 cm, the median penetration resistance of each plot was between 2 and 2.5 MPa. The same applied to the tree and control plots between 61 and 80 cm, whereas the median penetration resistance of the alley plot in these depths exceeded this threshold with 2.55 MPa (61-70 cm) and 2.525 MPa (71-80 cm), respectively.

The penetration resistance increased between 0-10 cm and 31-40 cm. Between 41-50 cm and until 80 cm were reached, the penetration resistance had constant values. The scattering of the median values increased with greater depth. There was no clear, visible trend signifying which plot had the highest or lowest penetration resistance (Figure 13, A).

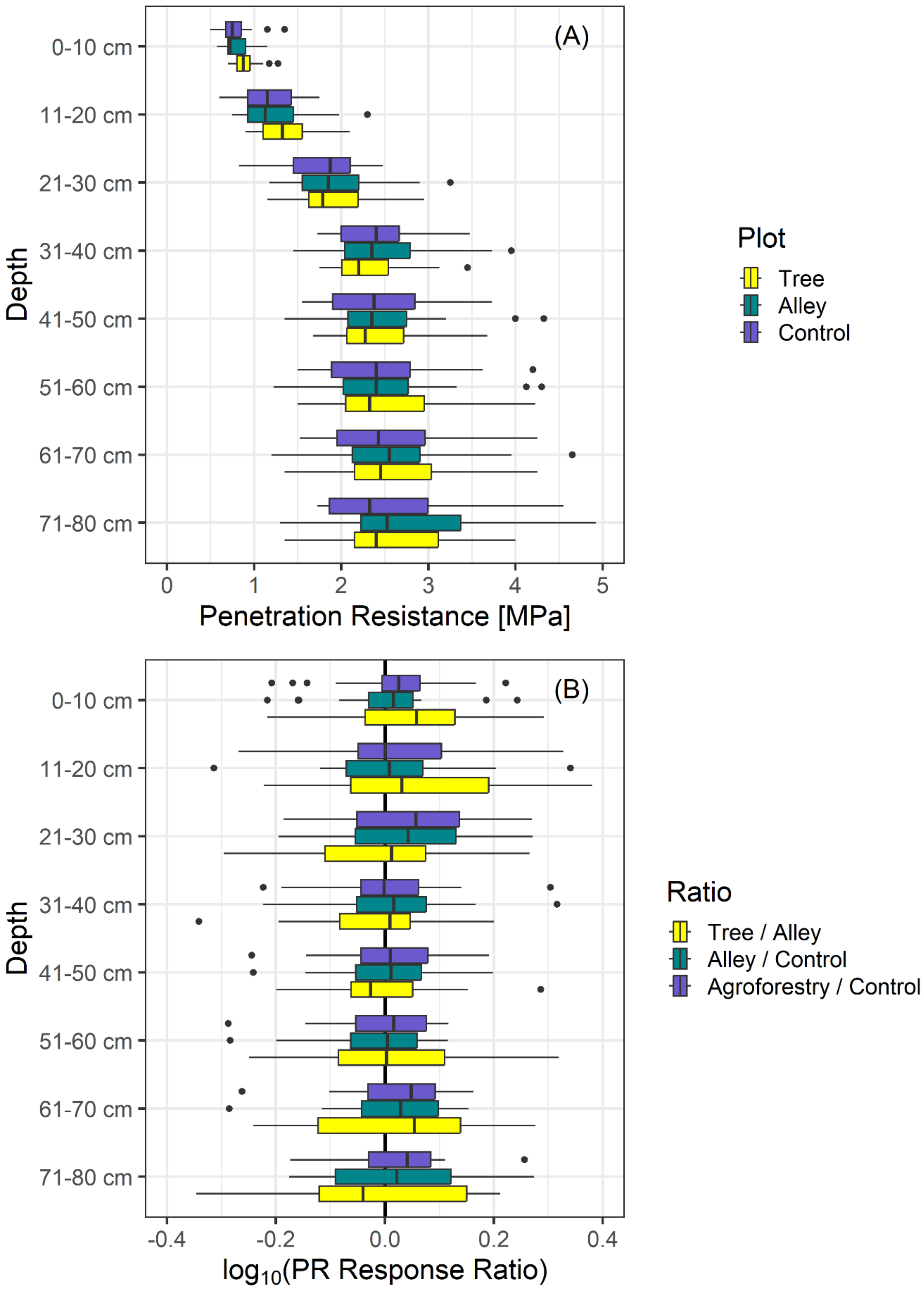

Figure 13: Penetration resistance (PR) values per soil depth subset and plot (yellow = tree plot, turquoise = alley plot, purple = control plot) (A). log10 response ratio of the penetration resistance for each soil depth layer and plot ratios (yellow = tree / alley, turquoise = alley / control, purple = agroforestry / control). The solid line indicates a log_{10} response ratio of 0 (no difference between the two plots) (B).

Regarding the penetration resistance and the response ratios, there was no significant difference found for the ANOVA between the ratios (p-value = 0.79) and the depths (p-value = 0.65) (Figure 13, B).

The penetration resistance response ratios showed no significant results for the linear regressions with the tree density, with one exception, which was found in the tree-alley ratio at a depth of 31-40 cm (Figure 14, B). Tree density had a positive effect: with increasing the tree density, the penetration resistance response ratio also increased. The response ratio was negative for agroforestry systems with a tree density lower than approximately 80 trees/ha (log_{10} value ≈ 1.9), meaning that penetration resistance tended to be higher in the alley plot than in the tree plot. With tree densities higher than 80 trees/ha, the response ratio turned positive: the penetration resistance tended to be higher in the tree plot than in the alley plot.

Tree diversity had a significant effect for the penetration resistance linear regressions in the 31-40 cm layer for two response ratios. The alley-control ratio (Figure 14, C) and the agroforestry-control ratio (Figure 14, D). Both effects were negative: with increasing tree species, the penetration resistance response ratio decreased. The penetration resistance response ratio turned negative between two and three different tree species. Thus, the penetration resistance was higher in the control plot than in the alley plot and the agroforestry plot. With the removal of the extreme values (agroforestry systems with six or more different tree species), two significant results occurred for the calculated linear regressions with the response ratios of the penetration resistance and the tree diversity. Both were found at a depth of 41-50 cm: one for the alley-control response ratio (Figure 14, E) and the other for the agroforestry-control response ratio (Figure 14, F). Both had a negative effect: with increasing number of different tree species, the penetration resistance response ratio decreased. For both cases, the response ratio tended to be positive in agroforestry systems with only one species but turned negative when more tree species were present.

The age of the agroforestry systems showed two significant results for the linear regressions regarding the penetration resistance response ratios. One was found at a depth of 21-30 cm of the tree-alley ratio (Figure 14, A), and the other was found at a depth of 51-60 cm of the agroforestry-control ratio (Figure 14, G). The indicated effects were both positive: as the tree age increased, the penetration resistance response ratio increased too. The tree-alley ratio became positive with a tree age of 10 years (log_{10} of the age = 1). The agroforestry-control ratio became positive from a tree age of approximately 8 years (log_{10} ≈ 0.90). When the extreme values were removed (agroforestry systems older than 20 years), the tree age had no significant effect on the penetration resistance response ratios.

The tree volume had a significant result for the linear regressions calculated for the penetration resistance response ratios in the agroforestry-control ratio at a depth of 51-60 cm (Figure 14, H). The effect was positive: when the tree volume increased, the penetration resistance response ratio increased too. The penetration resistance response ratio was positive from an average tree volume of approximately 0.015 m^3 (log_{10} ≈ -1.82). The other significant result regarding the tree volume and the penetration resistance response ratio was found in the tree-alley ratio at a depth of 61-70 cm (Figure 14, I). Again, a positive effect was found: as the tree volume increased, the penetration resistance response ratio increased too. Like the agroforestry-control ratio, the penetration resistance tree-alley response ratio was positive from an approximate average tree volume of 0.015 m^3 (log^{10} ≈ -1.82). Therefore, the penetration resistance tended to be higher in the tree plot than in the alley plot when the tree volume was higher than 0.015 m^3. The other calculated linear regressions did not show any significant results for the average tree volume variable.

The only significant result for the calculated multiple regressions regarding the penetration resistance response ratios was found at a depth of 21-30 cm (tree/alley ratio), with the mean annual temperature being significant. The effect was negative: with increasing temperature, the penetration resistance response ratio decreased. With increasing temperature, the penetration resistance tended to be lower in the tree plot than in the alley plot. None of the other multiple regressions regarding the penetration resistance was significant.

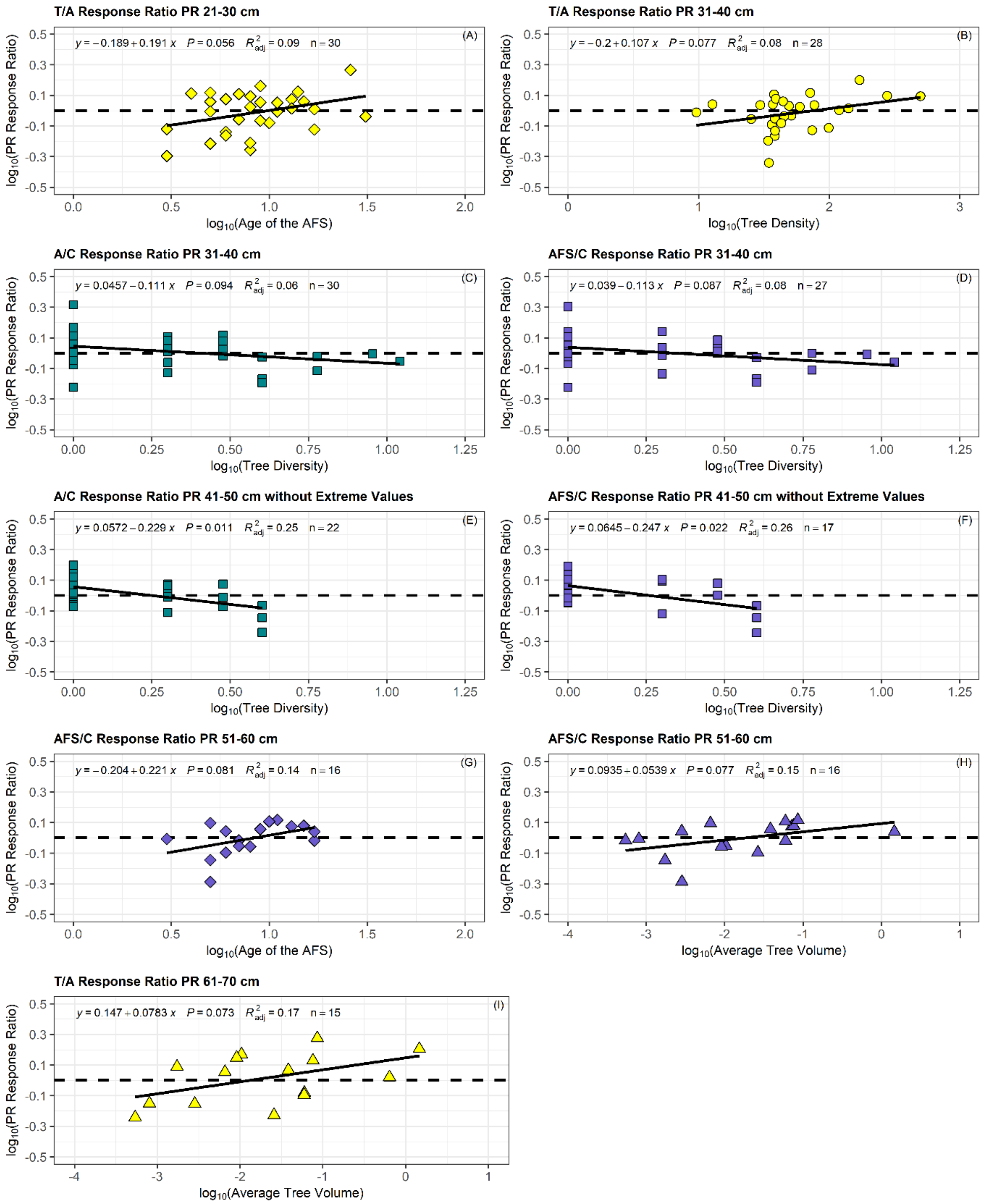

Figure 14: Significant penetration resistance (PR) log_{10} response ratios sorted by ascending soil depth (yellow = tree / alley ratio, turquoise = alley / control, purple = AFS / control). The slope of the linear regression, the p-value, the R2-adj value and the number of observations (n) are displayed in the respective graph. The different symbols represent the variables (dot = tree density, square = tree diversity, diamond = age of agroforestry system, triangle = average tree volume).

4. Discussion

4.1. Influence of Agroforestry Systems on Soil Properties

4.1.1. Bulk Density

The change in bulk density values with depth is caused by differences “in organic matter content, porosity and compaction” (Panagos et al. 2024: p. 4). With increasing organic matter content, the bulk density decreases, which lead to increasing porosity (Minasny & McBratney 2018). Panagos et al. (2024) reported between the 0-10 cm and 10-20 cm soil layers, a bulk density increase of 10% for the deeper layer. For this study, a significant difference was visible between the two soil depths (0-20 and 20-40 cm), as the absolute subsoil bulk density values were higher than the topsoil bulk density values. The results seem coherent, as Cardinael et al. (2017) and Cardinael et al. (2015) also reported a significant increase in bulk density as the soil depth increased in their studies.

Within this study, no significant differences regarding the absolute values of the bulk density between the different plots (tree, alley, control) in the topsoil and the subsoil were found. The same applied to the $\log_{10}$ response ratios of the bulk density, as no significant differences were reported between the response ratios. This seems like a consistent result, as nor the absolute bulk density values nor the response ratios showed differences. Cardinael et al. (2017) reported similar results in their study, which was conducted at six different agroforestry sites in France and assessed among other things the bulk density in a depth of 0-30 cm with three depth subsets of 10 cm each. The authors did not find significant differences between the plots, except for some exceptions in a depth of 0-10 cm (Cardinael et al. 2017). Upson et al. (2013) did not find differences either between the agroforestry plot (tree and alley plots combined) and the control plot in their agroforestry site in England at a depth of 0-40 cm. This corresponds to the results of this study, as the median of the agroforestry-control response ratio for the bulk density did not deviate greatly from 0 in the topsoil and subsoil. Additionally, there was no difference between the tree and the alley plot reported for this study (tree-alley response ratio), although Upson et al. (2013) showed higher bulk density values in the alley plot than in the tree plot. The authors argue that this could be due to compaction caused by machinery used for the cultivation of the crops, and pruning of the trees (Upson et al. 2013). Cardinael et al. (2015) stated that in their study conducted in a 20-year-old agroforestry system in Southern France, the significantly lowest bulk densities occurred in the tree rows, followed by the alley plots and the control plots for the depths of 0-10 and 10-30 cm. For the 30-50 cm depth, the alley plot had the lowest bulk density, followed by the tree and the control plot (Cardinael et al. 2015). The synthesizing study of Kim et al. (2016) reported a reduction in the alley cropping system bulk density of 3.9% compared to a treeless arable field, which is, however, based on one observation. The average difference in bulk density over all assessed types of agroforestry was stated to be -9.6% (± 4.8%) compared to treeless fields (Kim et al. 2016). Even though only one observation was reported in the latter study, it seems that alley cropping systems have a smaller impact on the bulk density than other types of agroforestry systems.

Therefore, the impact of trees on the bulk density is not always clearly given, and within this study, the trees did not seem to have an impact on the bulk density. This can have various reasons. Some of the mentioned aspects leading to changes in bulk density were not assessed within this study, including tillage type, used machinery, organic matter or soil texture. The latter was commissioned; however, the results were not available in time. Souza et al. (2021) argue that bulk density as an indicator for soil compaction should only be utilized in connection with soil texture, as different textures must be interpreted alternatively. Afterwards, “more information about the soil and the effects of management practices" (Souza et al. 2021: p. 5) could be obtained. To exclude the missing parameters, the response ratios were calculated to compare only plots of the same sites with each other, which have assumingly the same soil characteristics (e.g. soil texture). Thus, the uncertainty of comparing different soils was reduced.

Another reason for no significant difference between the bulk density of the different plots could be the tree age. The authors of several studies including Cardinael et al. (2017) and Pardon et al. (2017) mentioned that there were not many mature agroforestry systems, as most of them were younger than ten years. They suggested that long-term experiments should be carried out (Cardinael et al. 2017; Pardon et al. 2017). Young agroforestry systems were also present in this study, as two thirds of the sites were younger than ten years and only three of them were older than 20 years. As root systems grow with increasing age (Vetterlein & Doussan 2016), their impact on soil properties increases too (Ling et al. 2019). Therefore, it is assumed that older tree root systems have a bigger impact on the soil properties, which could be assessed in older agroforestry systems. A possible solution would be to repeat the measurements in a few years' time when more agroforestry systems are mature. This could be beneficial, as the root systems would have grown, as well as the crown of the trees, which impacts the soil bulk density positively through the input of leaves as litter and organic matter (Thomas et al. 2020). There were no correlations between the bulk density and any of the assessed variables. Regarding the bulk density and the tree density, Cardinael et al. (2017) reported also no impact of the distance from the trees on the bulk density. The other non-existent correlations could also be due to the young age of the trees and the associated limited influence.

The non-existent difference between the plots could be because most agroforestry systems were created on former pure arable land. As soil compaction lasts for a long time (Hamza & Anderson 2005), it could be that the roots were, to the date the sampling was conducted, not yet able to loosen the compacted soil. Another reason could be that by planting the trees, the soil was compacted, even though not on purpose. Upson et al. (2013) argue that for the pruning of the trees additional machinery is used, which could lead to further compaction. Discussions with some farmers during sampling indicated that they also use additional machinery to plant, maintain and irrigate the trees in the first years after implementation. This could lead to compaction of the tree plot. In addition, Kunakh et al. (2022) argued that the weight of the trees is transferred through the roots into the soil, which could lead to compaction if the trees get older.

Regarding the study design, no clear difference was noticed between this study and other studies on temperate alley cropping systems such as Cardinael et al. (2017) and Upson et al. (2013). Both studies used three plots for their analysis (tree, alley, control) and compared only the plots from the same site. The depth from which the bulk density samples were taken, is the only difference between the two mentioned studies and this study. Therefore, the results seem comparable.

4.1.2. Gravimetric Water Content

Regarding the absolute gravimetric water content values, a significant difference between the two soil depths was visible: in the subsoil (20-40 cm) the absolute gravimetric water content values were lower than in the topsoil (0-20 cm). This finding is supported by literature, as Seobi et al. (2005, as cited in Jacobs et al. 2022) found a higher moisture content in the topsoil than the subsoil of oak tree rows. The difference was caused by the increased porosity through the roots (Seobi et al. 2005, as cited in Jacobs et al 2022), as the living roots develop channels which persist, even if the roots decay (Rolo et al. 2023). The differences between the three plots (tree, alley, control) in the topsoil and subsoil gravimetric water content values were not significant, but the boxes of Figure 11 (A) had a greater range in the topsoil than those of the subsoil. This was also stated by Jacobs et al. (2022), as the differences in soil moisture content were higher in the upper soil layers than the deeper ones. The greater variability was explained through the increased response rate to precipitation (Jacobs et al. 2022), the vegetation growth and the management type (Zimmermann & Schwab 2023).

No additional significant differences regarding the absolute values of the gravimetric water content were observed, and the corresponding response ratio median values were located close to zero. This led to the inference of a limited influence of the trees on the gravimetric water content property in this study. This is likely due to the chosen sampling date in February and March, as the spatial variability of soil moisture is lower during times with high precipitation (Jacobs et al. 2022). Other authors like Sarto et al. (2022) proposed that the porosity, the infiltration and the storage of water in agroforestry systems was enhanced through the root growth of trees. As the distance to the trees increased, the soil moisture increased too in their study. Additionally, near the trees, the soil moisture was lower due to the enhanced soil structure through the roots and the increased infiltration, as well as the increased water uptake of the trees (Sarto et al. 2022). The results of this study do not agree with the results of Sarto et al. (2022). It could be explained by different pedo-climatic conditions at the sampling location, as the study of Sarto et al (2022) was conducted in an agroforestry system in the tropics in Brazil. In addition, as Jacobs et al. (2022) stated, there is only limited scientific evidence for soil moisture gradients in agroforestry systems (tree and alley plot).

The tree density had a significant negative effect on the gravimetric water content subsoil tree-alley response ratio when the densest agroforestry systems were excluded. When the tree density exceeded 60 trees/ha, the gravimetric water content tended to be lower in the tree plot than in the alley plot. Everson et al. (2009) found in their study conducted in an agroforestry system with four different tree species in South Africa that the water content in the tree row was mostly higher when the trees of each species were planted with a wider spacing between the trees (1 m) compared to a narrower planting of the trees (0.5 m). For one of the species, the values did not vary between the wide and the narrow treatment (Everson et al. 2009). Although, in this study, the tree spacings were greater than in the study of Everson et al. (2009), it could lead to the assumption that through the denser planting of the trees, other soil properties are affected, which impact the gravimetric water content.

The tree diversity showed three different significant effects on gravimetric water content when the extreme values were excluded: one was in the topsoil between the tree and alley plot, the others in the subsoil of the alley-control and agroforestry-control response ratios. In the topsoil, the effect was negative, leading to a larger decrease in gravimetric water content of the tree plot compared to the alley plot the more tree species were present. If only one tree species was planted, the gravimetric water content was higher in the tree plot. The opposite occurred in the subsoil alley-control and agroforestry-control ratios, where the gravimetric water content increased more in the alley and agroforestry plot compared to the control plot when more than one species was present. Generally, the root systems are not yet enough researched, but it is known that they depend on the environment and the species (Van Noordwijk et al. 2019), as different tree species have differing root functional traits (Clivot et al. 2022). These root functional traits include “selective root placement (…), root length density (…) or specific root length (…)" (Bayala et al. 2019: p. 18). Those characteristics are employed to assess the competition between the different species within an agroforestry system, but as the soil properties are differing within the systems, there is still research needed to define the controlling aspects of the functional traits (Bayala et al. 2019). As Jacobs et al. (2022) state, are the soil moisture dynamics affected by the tree and crop species which are planted regarding time and space, and fast-growing tree species have a greater impact on the dynamics. As agroforestry trees are deep rooted due to tillage and competition (Jacobs et al. 2022; Cardinael et al. 2017), they have access to water from deeper soil layers (Jacobs et al. 2022). In wet periods, however, trees use the water from the topsoil, and not from the deeper groundwater (Bayala et al. 2019). In the study conducted by Everson et al. (2009), the authors found different impacts of the tree species on the soil moisture. The four studied tree species differed in the amount of soil water content. This effect was larger in the wide treatment than in the narrow treatment (Everson et al. 2009), which could be even enhanced in this study, as the trees are planted even wider. The difference in tree species could therefore explain why the water content in the tree plot is lower than in the arable plot. There was for example one tree species with a 5-10% lower water content compared to the other species in the study of Everson et al. (2009).

Another reason for the differences in gravimetric water content between the tree, alley and control plots could be due to the different transpiration rates of the trees and the crops. Jacobs et al. (2022) stated that crops have lower transpiration rates than trees. But it seems unclear, whether this is also the case in February and March. Markwitz et al. (2020) assessed the evapotranspiration of different agroforestry and monoculture systems in Germany throughout one year. Although, the authors did not measure in February and March, it was visible that in January and April, the evapotranspiration rates were similar for the agroforestry systems and the adjacent monoculture. The evapotranspiration rates of the sites were between approximately 2-5 mm/week in January and 3-8 mm/week in April (Markwitz et al. 2020). It could be assumed that these findings also correspond to the months February and March, and that the trees, therefore, did not have a decisive impact on the evapotranspiration. Regarding the transpiration of the crops, Kang et al. (2003) measured the transpiration and evapotranspiration of winter wheat for 250 days during its growing season. As winter wheat is sown around beginning of November in Switzerland (Strickhof 2024), it would grow approximately 90 days until beginning of February and 150 days until end of March. Kang et al. (2003) reported for winter wheat a transpiration rate close to 0 mm/day for the 90th day of growth. This value remained close to 0 mm/day until approximately day 125, afterwards until day 150 an increase up to around 1.5 mm/day occurred. For the evapotranspiration of winter wheat, the authors reported values between 0.5 mm/day (day 90) and 1.5 mm/day (day 150) (Kang et al. 2003). Therefore, the results of Markwitz et al. (2020) and Kand et al. (2003) tend to show similar magnitudes, and it can be assumed that the evaporation rates of the trees are negligible. Consequently, the different root functional traits of the trees could explain why the gravimetric water content decreases in the topsoil tree plot compared to the alley plot, when more tree species were present. The highest density of coarse roots was found in a depth of 20-40 cm (Upson et al. 2013), which could explain why the significant results of the alley-control and agroforestry-control response ratios were obtained in the subsoil.

The reason for the significance of both ratios (alley-control and agroforestry-control) is likely to be due to the small share of the tree plot width within the agroforestry-control ratio. The alley plot has a higher weighed impact on the agroforestry plot, which is why this ratio is predominantly represented by the alley plot. The significance of the response ratios varies negligibly which supports the higher impact of the alley plot within the agroforestry-control ratio.

The response ratio of the tree-alley plots helps to understand the direct influence of the trees compared to the adjacent alley, which provides valuable insights. However, the more important ratios are the alley-control and the agroforestry-control response ratios, as they provide differences between the soil properties concerning the alley plot, which might be influenced by the trees, and the control plot without any influence of trees.

The tree-alley gravimetric water content ratio decreased with increasing age of the agroforestry systems in the subsoil. When the trees were older than approximately 18 years, the gravimetric water content in the tree plot tended to be lower than in the alley plot. In their study conducted in France in November, Clivot et al. (2022) found significant positive differences in soil water content between the agroforestry plot and the control plot after two and four years, respectively. For this study, this could not be observed. When the extreme values (the oldest trees) were removed, no significant result occurred.

A possible limitation regarding the gravimetric water content concerns the variable of the plot's slopes, which were not assessed in this study. Jacobs et al. (2022) mentioned an increased surface runoff during extreme precipitation with increasing slope. In general, the same limitations that were mentioned in the previous chapter also apply to this chapter.

4.1.3. Penetration Resistance

The penetration resistance absolute values for all plots increased rapidly between 0-40 cm, afterwards, the absolute penetration resistance values grew only slowly until 80 cm. Kunakh et al. (2022) and Murer et al. (2012) stated that with increasing depth, the penetration resistance increases too, which is also visible in this dataset. The peak was observed at a depth of 31-40 cm, which corresponds to the depth beneath the plough depth (Diserens & Spiess 2004; Zimmermann & Schwab 2023). Below the plough depth, the physical stresses such as compaction are severe (Agroscope 2021). This could explain the highest penetration resistance in the depth of 31-40 cm. Zimmermann & Schwab (2023) observed the maximum penetration resistance value at 30 cm and stated afterwards a decrease in penetration resistance in their study conducted on Swiss agricultural fields and grasslands. In their study in an Ukrainian forest, Kunakh et al. (2022) observed a sharp increase of penetration resistance at a depth of 30 cm until 75 cm, due to an alluvial horizon. Both results (Zimmermann & Schwab 2023; Kunakh et al. 2022) could not be supported in this study. However, an increased scattering of the absolute penetration resistance values was reported for all the plots in this study with increasing depth. This can be caused by soils with a lot of stones in the deeper layers, which lead to greater variability concerning the depth and the value of the measurement (Zimmermann & Schwab 2023). The increased stone content was observed at some sites, which is also why the stone correction was applied for the bulk density. Therefore, the reasoning of the increased stone content with increasing depth mentioned by Zimmermann & Schwab (2023) is likely to be depicted also in this study and was also reported in other papers like Souza et al. (2021) and Alesso et al. (2018).

Additionally, the absolute values showed that below 30 cm, all median values of the plots were below 2 MPa. For the deeper layers until 80 cm, almost all median values were between 2-2.5 MPa, with two exceptions in the alley plot which were slightly above 2.5 MPa (61-80 cm). A penetration resistance exceeding 2.5 MPa restricts the growth of roots, especially of annual crops (Souza et al. 2021). This is not the case for most of the median values of these plots and can, therefore, be interpreted positively. However, there are already from a depth of 21-30 cm onwards values of certain sites exceeding the 2.5 MPa threshold in all the three plots, which limits the root growth (Bartzen et al. 2019), and could therefore be seen on the sampled sites. Regarding the penetration resistance response ratios for each 10 cm subset, there were no significant differences reported between the plots, which aligns to the absolute values, as there were neither significant differences visible. This indicates that the trees have no or insufficient influence to be able to alter the penetration resistance, which could be caused by the young age of the agroforestry systems. Although, a study in an agroforestry system aged four years showed a lower penetration resistance in the agroforestry system than in a monoculture (Carvalho et al. 2004, as cited in Stöcker et al. 2019). This study was conducted in Brazil, which has a tropical climate, and is therefore maybe not comparable. Another reason for the non-existence of a difference between the agroforestry systems and the control plots in this study is mentioned by Kunakh et al. (2022), who state that the trees compact the soil by their weight. It could be that positive and negative influences of the trees compensate each other.

The tree-alley response ratio of the penetration resistance showed a positive correlation with the tree density variable in a depth of 31-40 cm. As the tree density increased to more than 80 trees/ha, the penetration resistance tended to be larger in the tree plot than in the alley plot. This result is only partially supported by the result of Zhukov et al. (2021), who found a decreasing penetration resistance when the tree density increased at a depth of 5-10 cm, and a non-linear trend with the lowest and highest tree densities showing the highest penetration resistance values in a depth of 35-40 cm at an urban park in the Ukraine. For this study, the densest agroforestry systems showed also the higher penetration resistance in the tree plot, which could be caused by the already mentioned own weight of the trees. Another reason could also be the roots of the trees, which could be encountered during the measurements, and could increase the penetration resistance.

The tree diversity showed significant results in the alley-control and agroforestry-control penetration resistance response ratios at the depths of 31-40 (with extreme values) and 41-50 cm (without extreme values). The penetration resistance tended to be larger in the alley and agroforestry plot, respectively, than in the control plot, when only one (41-50 cm) or two (31-40 cm) tree species were present in an agroforestry system, and if there were two or more tree species, the penetration resistance was higher in the control plot than in the alley and agroforestry plot. The influence of the trees on the agroforestry-control ratios is limited, as their weighed value is smaller than the alley weighed value. As already discussed, the root traits differ between tree species, which could lead to an improvement of the adjacent alley plot near the tree row in comparison with the control plot, when more tree species are present. Why exactly the depths of 31-50 cm showed significant results, could be explained through two reasons. On one hand, it is likely that some of the alley and control plots were tilled, which influences the soil properties of the first 30 cm, which often occurs on agricultural soils (Zimmermann & Schwab 2023). However, trees influence soil properties in vicinity, but it differs on a horizontal and vertical scale (Kunakh et al. 2022), which could explain why the 31-50 cm depth was influenced by the different root traits, in combination with the highest density of roots in a depth of 20-40 cm (Upson et al. 2013). On the other hand, with increasing depth, the effect of the trees, plants and biotic soil components decrease in favor of the weathering processes (Kunakh et al. 2022), which could explain why the lower soil layers were not as affected as the upper ones.

Regarding the impact of tree age on penetration resistance, two significant results were found: for the tree-alley ratio in a depth of 21-30 cm and the agroforestry-control ratio at 51-60 cm, both indicating a positive effect, which shows a greater increase of penetration resistance in the tree and agroforestry plot with the age of the trees. When the trees were younger than ten (tree-alley 21-30 cm) and eight years (agroforestry-control 51-60 cm), respectively, the penetration resistance was higher in the alley and control plots. For the average tree volume, also two significant results were reported: for the agroforestry-control response ratio in a depth of 51-60 cm and for the tree-alley response ratio at a depth of 61-70 cm. The indicated effect was positive: as the tree volume increased, the penetration resistance was greater in the agroforestry and tree plots compared to the control and alley plots, respectively. Interestingly, the positive effect in the agroforestry-control 51-60 cm response ratio was found in both variables. This could be explained through the only correlation of two variables which was visible in this dataset: the tree age correlated positively with the tree volume. Therefore, a property which both variables have in common is likely responsible for the occurred result. As both corresponding alley-control response ratios did not show significant results, it is likely that the difference is found in the tree plot. When the tree age and the tree volume increase, the weight of the trees increases too, which could lead to the compaction of the soil beneath the roots (Kunakh et al. 2022).

For the penetration resistance measurements, the number of observations decreased with the depth. For the depth of 21-30 cm, 30 observations or median values, respectively, were available, but for the 61-70 cm result, only 15 observations were left. This is due to the high stone contents of the soils at these depths. Therefore, the validity of the results could be limited. Zimmermann & Schwab (2023) stated that the penetration resistance is heterogeneously distributed all over Switzerland. The anthropological changes, like the agricultural management practices, are greatly influencing the penetration resistance in agricultural soils. For example, the use of heavy machinery or tillage on those soils, impedes the interpretation and thus the significance of the results (Zimmermann & Schwab 2023).

4.2. Influence of External Variables on Soil Properties

Trees are able to alter the microclimate within an agroforestry system, which could stabilize the yield in context of climate change by providing shade and wind protection. This effect is depending on the design of an agroforestry system and its characteristics (e.g. topography, climate) (Jacobs et al. 2022). For this study, the influence of the external variables (altitude, annual precipitation amount and annual average temperature) was very low. No influence of the altitude was found for any of the three parameters bulk density, gravimetric water content and penetration resistance. Varga et al. (2018) reported in their study conducted in Slovakia that they found significant differences between two of their three study sites regarding the soil moisture, the penetration resistance and the altitude. The latter ranged between 418-950 m a.s.l. However, they did not find significant differences between two study sites where the difference in altitude was only about 170 m (418-597 m a.s.l.), but the authors pointed out that the physical soil properties underlie a spatial and temporal variability, but also regarding the land use (Varga et al. 2018). As the altitude in this study varied between 408-771 m a.s.l., the differences in altitude could be too small to make differences visible.

No significant influence of the annual precipitation amounts on the bulk density, gravimetric water content and penetration resistance response ratios was found. As the trees increase the water uptake in agroforestry systems compared to treeless systems (Jacobs et al. 2022), there should be differences visible between the ratios. But as the precipitation amount in winter 2023/24 was at all the study sites above the average between the years 1911-2020 (MeteoSchweiz 2024b), it could be assumed that the soils were approximately at field-capacity. Therefore, the distribution between the different plots was similar, which is also stated in literature by Jacobs et al. (2022). This is supported by the sampling date in February and March, as the trees and the crops then did not have a high moisture demand due to lower temperatures and therefore lower transpiration than in summer. Although for the precipitation variable, the most suitable precipitation stations were chosen, the extent of the considered time period for the precipitation could be a limitation and could have been chosen narrower (e.g. only data from the three last months before sampling).

Air temperature impacts the growth of crops and is lower in the tree row than on the alley land, on parts of the latter which is not affected by the trees' shade (Jacobs et al. 2022). The annual average air temperature significantly influenced the tree-alley penetration resistance response ratio in a depth of 21-30 cm. It seems unclear why the annual average air temperature affects the penetration resistance at this depth, as it would be more logical if the upper soil layer was affected by the air temperature. During literature review, no similar result was found, which is why the significance of this result could be coincidental.

4.3. Limitations of this Study

Some of the limitations concerning this study have already been discussed, such as the missing data on soil texture, organic matter content and management practices. The use of the response ratios neutralized the impact of these limitations. In this chapter, the other limitations are mentioned that haven't been addressed yet. Regarding the age of the agroforestry systems within this study, only three sites were older than 25 years and two thirds of the sites were younger than ten years. Therefore, the presence of mature agroforestry systems is scarce in this study's data. This issue was also mentioned in other studies like Pardon et al. (2017) and Cardinael et al. (2017), where agroforestry systems older than 15 and 40 years, respectively, were rarely found. Cardinael et al. (2017) mention that more long-term experiments are needed. With those long-term experiments, gradients of the tree influence could become visible.

There is a research gap for temperate agroforestry systems compared to tropical agroforestry systems, which is also stated by authors like Honfy et al. (2023) and Jacobs et al. (2022). For some aspects of this study, like the penetration resistance, there were only a few comparable studies.

The average temperature and the annual precipitation amounts may not reflect the actual values of each site, as some meteorological stations rather far away from a site had to be considered. Generally, the error margin regarding those two parameters is seen as rather small, but overall noteworthy.

In general, it had to be considered that different persons of the sampling teams and other helping persons were taking the samples (bulk density, gravimetric water content) and conducted the measurements (penetration resistance). Even though they were instructed in the same way, it could lead to inaccuracy in handling and therefore, a source of uncertainty.

5. Conclusion

The aim of this thesis was to provide an overview of the impact of agroforestry on soil physical properties in 33 different silvoarable alley cropping systems in Switzerland with the following research questions:

i. Is there a difference between soil physical properties in silvoarable agroforestry plots and soils in arable plots without trees in Switzerland in regard to:
    a. the bulk density,
    b. the gravimetric water content at sampling time, and
    c. the penetration resistance?
ii. Does the tree density, tree diversity, age of trees and/or average tree volume of the alley cropping systems have an impact on the soil's physical properties?

The hypotheses were stated as follows:

I. The bulk density is lower in the silvoarable agroforestry systems compared to the arable plots without trees.
II. The gravimetric water content at sampling time is higher in the agroforestry plots than in the arable plots without trees.
III. Penetration resistance is lower in the tree plot than in the alley and control plots.
IV. Increasing tree density, diversity, age and tree volume impact physical soil properties positively.

There were no differences between the physical soil properties of the agroforestry systems and the treeless arable control plots in terms of bulk density, gravimetric water content and penetration resistance. Therefore, the first research question (i.) must be denied. The same applies to the first three hypotheses (I.-III.).

For the second research question (ii.), the answers differ between the soil properties. The bulk density was not affected at all by the tree density, diversity, age or average tree volume of the agroforestry systems. The tree density was positively influencing the gravimetric water content response ratio. The more tree species were present, the higher the gravimetric water content in the agroforestry plot compared to the control plot. The tree diversity positively affected the penetration resistance alley-control and agroforestry-control response ratios at depths of 31-40 and 41-50 cm. The other variables showed no or negative impacts on the penetration resistance in different depths and response ratios. Therefore, only the tree diversity variable showed positive impacts on the penetration resistance of the agroforestry plot. Despite the few above mentioned exceptions, the hypothesis that internal variables such as tree density, diversity, age of the trees or average tree volume impact physical soil properties (IV.) must be rejected. Reasons for the few positive effects of the internal variables could be the relatively young age of the agroforestry systems, but also the influence of other important variables for physical properties such as the soil texture or the organic matter content that were not considered in the present study.

To be able to draw more detailed conclusions, it is important to assess further variables that influence soil physical properties. For example, farmers could be asked in future studies about the farming practices they apply in their agroforestry and control plots. This information could lead to insights into the usage of heavy machinery or tillage, which could both cause soil compaction. In addition, the soil texture and organic matter should be considered for further analyses to correct the bulk density. The results of the physical soil properties should be compared to chemical and biological properties within the parent project to see, whether these variables explain certain relations. It would be interesting to repeat this monitoring in some years from now, when the younger trees have become mature. It could open new insights into how the soil properties change over time and what effect mature trees have on soil properties in silvoarable agroforestry systems in Switzerland.

References

Abbass, K.; Qasim, M.Z.; Song, H.; Murshed, M.; Mahmood, H. & Younis, I. (2022): A review of the global climate change impacts, adaptation, and sustainable mitigation measures. In: *Environmental Science and Pollution Research*, 29, p. 42539-42559. DOI: 10.1007/s11356-022-19718-6.

Agroscope (2021): Physical investigations. URL: <https://www.agroscope.admin.ch/agroscope/en/home/topics/environment-resources/soil-bodies-water-nutrients/nabo/monitoring/physical-investigation.html> (available online, accessed 20.09.2024).

Alesso, C.A.; Masola, M.J.; Carizzo, M.E.; Cipriotti, P.A. & Del Imhoff, S. (2018): Spatial variability of short-term effect of tillage on soil penetration resistance. In: *Archives of Agronomy and Soil Science*, 65(6), p. 822-832. DOI: 10.1080/03650340.2018.1532076.

Bartzen, B.T.; Hoelscher, G.L.; Oliveira Riberio, L.L. & Pereira Seidel, E. (2019): How the Soil Resistance to Penetration Affects the Development of Agricultural Crops? In: *Journal of Experimental Agriculture International*, 30(5), p. 1-17. DOI: 10.9734/JEAI/2019/46589.

Bayala, J. & Prieto, I. (2020): Water acquisition, sharing and redistribution by roots: applications to agroforestry systems. In: *Plant and Soil*, 453, p. 17-28. DOI: 10.1007/s11104-019-04173-z.

Bilskie, J. (2001): Soil water status: content and potential. Published by: Campbell Scientific, Inc. App. Note: 2S-I.

Bundesamt für Landestopografie (swisstopo) (2024): swissBOUNDARIES3D. URL: <https://www.swisstopo.admin.ch/de/landschaftsmodell-swissboundaries3d> (available online, accessed 27.09.2024).

Cardinael, R.; Cadisch, G.; Gosme; M. Oelbermann, M. & van Noordwijk, M. (2021): Climate change mitigation and adaptation in agriculture: Why agroforestry should be part of the solution. In: *Agriculture, Ecosystems and Environment*, 319, p. 1-7. DOI: 10.1016/j.agee.2021.107555.

Cardinael, R.; Mao, Z.; Chenu, C. & Hinsinger, P. (2020): Belowground functioning of agroforestry systems: recent advantages and perspectives. In: *Plant and Soil*, 453, p. 1-13. DOI: 10.1007/s11104-020-04633-x.

Cardinael, R.; Chevallier, T.; Cambou, A.; Béral, C.; Barthès, B.G.; Dupraz, C.; Durand, C.; Kouakoua, E. & Chenu, C. (2017): Increased soil organic carbon stocks under agroforestry: A survey of six different sites in France. In: *Agriculture, Ecosystems and Environment*, 236, p. 243-255. DOI: 10.1016/j.agee.2016.12.011.

Cardinael, R.; Chevallier, T.; Barthès, B.G.; Saby, N.P.A.; Parent, T.; Dupraz, C.; Bernoux, M. & Chenu, C. (2015): Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon – A case study in a Mediterranean context. In: *Geoderma*, 259-260, p. 288-299. DOI: 10.1016/j.geoderma.2015.06.015.

Castle, S.E.; Miller, D.C.; Merten, N.; Ordonez, P.J. & Baylis, K. (2022): Evidence for the impacts of agroforestry on ecosystem services and human well-being in high-income countries: a systematic map. In: *Environmental Evidence*, 11(10), p. 1-27. DOI: 10.1186/s13750-022-00260-4.

Clivot, H.; Petitjean, C.; Marron, N.; Dallé, E.; Genestier, J.; Blaszczyk, N.; Santenoise, P.; Laflotte, A. & Piutti, S. (2019): Early effects of temperate agroforestry practices on soil organic matter and microbial enzyme activity. In: *Plant and Soil*, 453, p. 189-207. DOI: 10.1007/s11104-019-04320-6.

Den Herder, M.; Burgess, P.; Mosquera-Losada, M.; Herzog, F.; Hartel, T.; Upson, M.A.; Viholainen, I. & Rosati, A. (2015): Preliminary stratification and quantification of agroforestry in Europe. Milestone report 1.1 for UF FP7 AGFORWARD Research Project (613520). DOI: 10.13140/RG.2.1.4258.4482.

Diserens, E. & Spiess, E. (2004): Wechselwirkung zwischen Fahrwerk und Ackerboden. In: *FAT Berichte*, 613, p. 1-16.

Dmuchowski, W.; Baczewska-Dabrowska, A.H. & Gworek, B. (2024): The role of temperate agroforestry in mitigating climate change: A review. In: *Forest Policy and Economics*, 159, p. 1-11. DOI: 10.1016/j.forpol.2023.103136.

Dollinger, J. & Jose, S. (2018): Agroforestry for soil health. In: *Agroforestry Systems*, 92, p.213-219. DOI: 10.1007/s10457-018-0223-9.

Don, A.; Schumacher, J.; Scherer-Lorenzen, M.; Scholten, T. & Schulze, E.-D. (2007): Spatial and vertical variation of soil carbon at two grassland sites – Implications for measuring soil carbon stocks. In: *Geoderma*, 141(3-4), p. 272-282. DOI: 10.1016/j.geoderma.2007.06.003.

Everson, C.S.; Everson, T.M. & van Niekerk, W. (2009): Soil water competition in a temperate hedgerow agroforestry system in South Africa. In: *Agroforestry Systems*, 75, p. 211-221. DOI: 10.1007/s10457-008-9174-x.

Fahad, S.; Chavan, S.B.; Chichaghare, A.R.; Uthappa, A.R.; Kumar, M.; Kakade, V.; Pradhan, A.; Jinger, D.; Rawale, G.; Yadav, D.K.; Kumar, V.; Farooq, T.H.; Ali, B.; Sawant, A.V.; Saud, S.; Chen, S. & Poczai, P. (2022): Agroforestry Systems for Soil Health Improvement and Maintenance. In: *Sustainability*, 14, p. 1-25. DOI: 10.3390/su142214877.

Food and Agriculture Organization of the United Nations (FAO) (2024): Agroforestry. URL: <https://www.fao.org/agroforestry/about-agroforestry/overview/en> (available online, accessed 10.07.2024).

Ghale, B.; Mitra, E.; Sodhi, H.S.; Verma, A.K. & Kumar, S. (2022): Carbon Sequestration Potential of Agroforestry Systems and Its Potential in Climate Change Mitigation. In: *Water, Air, & Soil Pollution*, 233(228), p. 1-27. DOI: 10.1007/s11270-022-05689-4.

Hamza, M.A. & Anderson, W.K. (2005): Soil compaction in cropping systems: A review of the nature, causes and possible solutions. In: *Soil and Tillage Research*, 82, p. 121-145. DOI: 10.1016/j.still.2004.08.009.

Hernández-Morcillo, M.; Burgess, P.; Mirck, J.; Pantera, A. & Plieninger, T. (2018): Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. In: *Environmental Science and Policy*, 80, p. 44-52. DOI: 10.1016/j.envsci.2017.11.013.

Herzog, F. (1998): Streuobst: a traditional agroforestry system as a model for agroforestry development in temperate Europe. In: *Agroforestry Systems*, 42, p. 61-80. DOI: 10.1023/A:1006152127824.

Honfy, V.; Pödör, Z.; Keserű, Z.; Rásó, J.; Ábri, T. & Borovics, A. (2023): The Effect of Tree Spacing on Yields of Alley Cropping Systems – A Case Study from Hungary. In: *Plants*, 12(595), 0. 1-19. DOI: 10.3390/plants12030595.

Jacobs, S.R.; Webber, H.; Niether, W.; Grahmann, K.; Lüttschwager, D.; Schwartz, C.; Breuer, L. & Bellingrath-Kimura, S.D. (2022): Modification of the microclimate and water balance through the integration of trees into temperate cropping systems. In: *Agricultural and Forest Meteorology*, 323, 109065, p. 1-13. DOI: 10.1016/j.agrformet.2022.109065.

Jäger, M. (2017): Agroforstsysteme: Hochstamm-, Wildobst- und Laubbäume mit Kulturpflanzen kombinieren. AGRIDEA (Hrsg.).

Kang, S.; Gu, B.; Du, T. & Zhang, J. (2003): Crop coefficient and ratio of transpiration to evatranspiration of winter wheat and maize in a semi-humid region. In: *Agricultural Water Management*, 59, p. 239-254. DOI: 10.1016/S0378-3774(02)00150-6.

Kay, S.; Jäger, M. & Herzog, F. (2020): Moderne Agroforstsysteme in der Schweiz, Partizipative Entwicklung und künftige Herausforderungen. In: *Berichte über Landwirtschaft – Zeitschrift für Agrarpolitik und Landwirtschaft*, 98(2), p.1-22. DOI: 10.12767/buel.v98i2.299.

Keller, U.O. (2022): Es war einmal ein Obstbau-Paradies … In: *UFA Revue*. URL: <https://www.ufarevue.ch/landleben/es-war-einmal-ein-obstbaum-paradies> (published 23.09.2022, accessed 12.07.2024).

Kim, D.-G.; Kirschbaum, M.U.F. & Beedy, T.L. (2016): Carbon sequestration and net emissions of CH_4 and N_2O under agroforestry: Synthesizing available data and suggestions for future studies. In: *Agriculture, Ecosystems and Environment*, 226, p. 65-78. DOI: 10.1016/j.agee.2016.04.011.

Kumar, P.; Singh, R.P.; Kumar Singh, A. & Kumar, V. (2014): Quantification and distribution of agroforestry systems and practices at global lebel. In: *HortFlora Research Spectrum*, 3(1), p. 1-6. ISSN: 2250-2823.

Kunakh, O.; Zhukova, Y.; Yakovenko, V. & Daniuk, O. (2022): Influence of plants on the spatial variability of soil penetration resistance. In: *Ekológia (Bratislava)*, 41(2), p. 113-125. DOI: 10.2478/eko-2022-0012.

Ling, Q.; Zhao, X.; Wu, P.; Gao, X. & Sun, W. (2019): Effect of the fodder species canola (Brassica napus L.) and daylily (Hemerocallis fulva L.) on soil physical properties and soil water content in a rainfed orchard on the semiarid Loess Plateau, China. In: *Plant and Soil*, 453, p. 209-228. DOI: 10.1007/s11104-019-04318-0.

Lu, N.; Luo, S. & Likos, W.J. (2024): Errors in Conventional Calculations of Soil Phase Relationships. In: *Journal of Geotechnical and Geoenvironmental Engineering*, 150(7), p. 1-13. DOI: 10.1061/JGGEFK.GTENG-11957.

Markwitz, C.; Knohl, A. & Siebicke, L. (2020): Evapotranspiration over agroforestry sites in Germany. In: *Biogeosciences*, 17, p. 5183-5208. DOI: 10.5194/bg-17-5183-2020.

MeteoSchweiz (2024a): Datenportal für Lehre und Forschung (IDAweb). URL: <https://gate.meteoswiss.ch/idaweb/login.do;idaweb=whXQTQtPkTSbh3dGcrWzyDnBHQ7sJJnQhz01vbZhWhdKTdHkq1h0!-1907983237> (available online, accessed 23.07.2024).

MeteoSchweiz (2024b): Klimabulletin Winter 2023/24. URL: <https://www.meteoschweiz.admin.ch/service-und-publikationen/publikationen/berichte-und-bulletins/2024/klimabulletin-winter-2023-24.html > (available online, accessed 16.09.2024).

Microsoft Corporation (2024): Microsoft Excel. URL: <https://www.microsoft.com/de-de/microsoft-365/excel?market=de> (available online, accessed 08.09.2024).

Minarsch, E.-M.L.; Middelanis, T.; Wichern, F.; Göbel, L.; Böhm, C. & Weckenbrock, P. (2022): Leitfaden: Bodenkundliche Untersuchungen in streifenförmigen Agroforstsystemen. Deutscher Fachverband für Agroforstwirtschaft (DeFAF) e.V.

Minasny, B. & McBratney, A.B. (2018): Limited effect of organic matter on soil available water capacity. In: *European Journal of Soil Science*, 69(1), p. 39-47. DOI: 10.1111/ejss.12475.

Murer, E.; Sisák, I.; Baumgarten, A. & Strauss, P. (2012): Bewertung der Unterbodenverdichtung von Ackerböden im österreichischen Alpenvorland. In: *Die Bodenkultur*, 63(1), p. 7-15.

Nerlich, K.; Graeff-Hönninger, S. & Claupein, W. (2013): Agroforestry in Europe: a review of the disappearance of traditional systems and development of modern agroforestry practices, with emphasis on experiences in Germany. In: *Agroforestry Systems*, 87, p. 475-492. DOI: 10.1007/s10457-012-9560-2.

OpenStreetMap contributors (2024): OpenTopoMap. URL: <https://www.openstreetmap.org/> (available online, accessed 27.09.2024).

Panagos, P.; De Rosa, D.; Liakos, L.; Labouyrie, M.; Borrelli, P. & Ballabio, C. (2024): Soil bulk density assessment in Europe. In: *Agriculture, Ecosystems and Environment*, 364, 108907, p. 1-14. DOI: 10.1016/j.agee.2024.108907.

Pardon, P.; Reubens, B.; Mertens, J.; Verheyen, K.; De Frenne, P.; De Smet, G.; Van Waes, C. & Reheul, D. (2018): Effects of temperate agroforestry on yield and quality of different arable intercrops. In: *Agricultural Systems*, 166, p 135-151. DOI: 10.1016/j.agsy.2018.08.008.

Petrillo, M. & Herzog, F. (2016): System report: Silvoarable agroforestry in Switzerland. AGFORWARD (613520).

Poeplau, C.; Vos, C. & Don, A. (2017): Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. In: *SOIL*, 3(1), p. 61-66. DOI: 10.5194/soil-3-61-2017.

Quandt, A.; Neufeldt, H. & Gorman, K. (2023): Climate change adaptation through agroforestry: opportunities and gaps. In: *Current Opinion in Environmental Sustainability*, 60, p. 1-7. DOI: 10.1016/j.cosust.2022.101244.

R Core Team (2024): R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. URL: <https://www.r-project.org/>.

Roberti, G.; Herzog, F. & Kay, S. (2023): 10-year Agroforestry Monitoring with Fruit and Poplar Trees in Switzerland: Comparison of measured and modelled outcomes. Unpublished.

Rolo, V.; Rivest, D.; Maillard, É. & Moreno, G. (2023): Agroforestry potential for adaption to climate change: A soil-based perspective. In: *Soil Use and Management*, 39(12), p. 1006-1032. DOI: 10.1111/sum.12932.

Royal Eijkelkamp (2022): Penetrologger, User manual. URL: <https://www.royaleijkelkamp.com/media/nrwjyah3/m-0615sae-penetrologger.pdf> (available online, accessed 22.09.2024).

Royal Eijkelkamp (2019): Sample ring kits, Manual. URL: <https://www.royaleijkelkamp.com/media/1alf3lst/sample-ring-kits-manual.pdf> (available online, accessed 22.09.2024).

Sarto, M.V.M.; Borges, W.L.B.; Bassegio, D.; Nunes, M.R.; Rice, C.W. & Rosolem, C.A. (2022): Deep Soil Water Content and Forage Production in a Tropical Agroforestry System. In: *Agriculture*, 12(3), p. 359-372. DOI: 10.3390/agriculture12030359.

Scholz, D. (n.d.): Schätzhilfen: Wieviel Festmeter und Bäume stehen in meinem Wald? Landwirtschaftskammer Niedersachsen (Hrsg.). URL: <https://www.lwk-niedersachsen.de/lwk/news/36164_Schaetzhilfen_Wieviel_Festmeter_und_Baeume_stehen_in_meinem_Wald> (available online, accessed 23.07.2024).

Schoop, J. & Carrard, E. (2022): Agro4esterie. Bundesamt für Landwirtschaft BLW (Hrsg.). URL: <https://www.blw.admin.ch/blw/de/home/instrumente/ressourcen--und-gewaesserschutzprogramm/ressourcenprogramm/projektuebersicht.html> (downloadable online, accessed 24.09.2024).

Sereke, F.; Graves, A.R.; Dux, D.; Palma, J.H.N. & Herzog, F. (2015): Innovative agroecosystem goods and services: key profitability drivers in Swiss agroforestry. In: *Agronomy for Sustainable Development*, 35, p. 759-770. DOI: 10.1007/s13593-014-0261-2.

Souza, R.; Hartzell, S.; Ferraz, A.P.F.; De Almeida, A.Q.; De Sousa Lima, J.R; Antonino, A.C.D. & De Souza, E.S. (2021): Dynamics of soil penetration resistance in water-controlled environments. In: *Soil and Tillage Research*, 205, p. 1-8. DOI: 10.1016/j.still.2020.104768.

Stöcker, C.M.; Bamberg, A.L.; Stumpf, L.; Monteiro, A.B.; Cardoso, J.H. & De Lima, A.C.R. (2020): Short-term soil physical quality improvements promoted by an agroforestry system. In: *Agroforestry Systems*, 94(5), p. 2053-2064. DOI: 10.1007/s10457-020-00524-3.

Strickhof (2024): Merkblatt Winterweizen. URL: <https://www.strickhof.ch/publikationen/merkblatt-winterweizen/> (available online, accessed 25.09.2024).

Thomas, P.; Mondai, S.; Roy, D.; Meena, M.C.; Aggarwal, B.K.; Sharma, A.R.; Behera, U.K.; Das, T.K.; Jatav, R. & Chakraborty, D. (2020): Exploring the Relationships between Penetration Resistance, Bulk Density and Water Content in Cultivated Soils. In: *Journal of Agricultural Physics*, 20(1), p. 22-29. ISSN 0973-032X.

Throop, H.L.; Archer, S.R.; Monger, H.C. & Waltman, S. (2012): When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. In: *Journal of Arid Environments*, 77, p. 66-71. DOI: 10.1016/j.jaridenv.2011.08.020.

Upson, M.A. & Burgess, P.J. (2013): Soil organic carbon and root distribution in a temperate arable agroforestry system. In: *Plant and Soil*, 373, p. 43-58. DOI: 10.1007/s11104-013-1733-x.

Van Noordwijk, M.; Rahayu, S.; Gebrekirstos, A.; Kindt, R.; Tata, H.L.; Muchungi, A.; Ordonnez, J.C. & Xu, J. (2019): Tree diversity as a basis of agroforestry. In: *Sustainable development through trees on farms: agroforestry in its fifth decade*. Van Noordwijk, M. (Ed.). World Agroforestry (ICRAF) Southeast Asia Regional Program, p. 17-44.

Varga, J.; Kanianska, R. & Spišiak, J. (2018): Impact of land use and geological conditions on selected physical soil properties in relation to the earthworm abundance and biomass along an altitudinal gradient in Slovakia. In: *Soil Science Annual*, 69(3), p. 160-168. DOI: 10.2478/ssa-2018-0016.

Vaupel, A.; Bednar, Z.; Herwig, N.; Hommel, B.; Moran-Rodas, V.E. & Beule, L. (2023): Tree-distance and tree-species effects on soil biota in a temperate agroforestry system. In: *Plant and Soil*, 487, p. 355-372. DOI: 10.1007/s11104-023-05932-9.

Vaz, C.M.P.; Manieri, J.M.; De Maria, I.C. & Tuller, M. (2011): Modeling and correction of soil penetration resistance for varying soil water content. In: *Geoderma*, 166, p. 92-101. DOI: 10.1016/j.geoderma.2011.07.016.

Vetterlein, D. & Doussan, C. (2016): Root age distribution: how does it matter in plant processes? A focus on water uptake. In: *Plant and Soil*, 407, p. 145-160. DOI: 10.1007/s11104-016-2849-6.

Walling, E. & Vaneeckhaute, C. (2020): Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. In: *Journal of Environmental Management*, 276, p. 1-16. DOI: 10.1016/j.jenvman.2020.111211.

Zhang, J.; Wang, L. & Su, J. (2018): The Soil Water Condition of a Typical Agroforestry System under the Policy of Northwest China. In: *Forests*, 9(12), p. 730-745. DOI: 10.3390/f9120730.

Zhukov, O.; Yorkina, N.; Budakova, V. & Kunakh, O. (2021): Terrain and tree stand effect on the spatial variation of the soil penetration resistance in an Urban Park. In: *International Journal of Environmental Studies*, 79(3), p. 485-501. DOI: 10.1080/00207233.2021.1932368.

Zimmermann, R. & Schwab, P. (2023): Eindringwiderstandsmessung im Boden mittels Penetrometer: Auswertung von 38 Standorten der Nationalen Bodenbeobachtung (NABO). In: *Agroscope Science*, 166, p. 1-67. DOI: 10.34776/as166g.

Appendix

S1 Site Characteristics

Table 3: Overview on site characteristics of internal and external variables.

Site	Location	Canton	Density [Trees/ha]	Diversity [No. Tree Species]	Age [Years]	Average Tree Volume [m^3]	Altitude [m a.s.l.]	Annual Precipitation [mm/Year]	Average Annual Temperature [°C]
1	Courroux	JU	37.04	1	4	0.00280016	468	848.7	11.61
2	Romanel-sur-Morges	VD	49.26	4	6	0.013276041	464	1’089.3	11.3
3	Schenkon	LU	99.26	1	17	0.059825123	507	1’246.1	11.21
5	Arnex-sur-Orbe	VD	38.31	1	13	0.072033389	546	924	8.39
6	Feusisberg	SZ	47.17	2	31	2.40142647	699	1’988.6	9.02
7	Meinier	GE	33.44	2	8	0.041877823	434	1’070.2	12.11
8	Wollerau	SZ	59.52	3	17	1.463373493	617	1’988.6	9.02
9	Fey	VD	119.05	3	31	0.638929985	670	1’129.3	10.6
10	Montanaire	VD	34.1	3	11	0.004728915	753	1’129.3	10.6
11	Démoret	VD	25.25	9	3	0.00080346	702	1’250.6	10.54
12	Ipsach	BE	74.07	2	6	0.026484538	443	1’105.8	11.39
13	Port	BE	76.92	4	5	0.002838163	450	1’105.8	11.39
14	Buus	BL	37.74	1	13	0.181227288	571	984.5	12.34
15	Ruswil	LU	58.82	1	5	0.005105563	744	1’276	11.03
16	Stadel bei Niederglatt	ZH	38.99	2	9	0.015053319	411	1’112.3	10.85
17	Goumoëns-la-Ville	VD	51.28	2	14	0.040368578	594	1’129.1	10.52
18	Lully	FR	29.63	1	15	0.075787756	488	972.4	11.82
19	Prangins	VD	38.46	3	4	0.001489057	408	1’216.1	12.63
20	Eysins	VD	34.48	3	3	0.000907529	431	1’216.1	12.72
22	Oberbalm	BE	140.85	6	7	0.0005405	748	1’171.4	11.37
23	Bussy-Chardonney	VD	277.78	2	5	0.006562379	497	1’103.7	11.35
24	Attalens	FR	36.3	11	6	0.002830379	740	1’356.5	10.62
25	Bonvillars	VD	38.31	4	7	0.010392938	771	804	8.47
26	Würenlingen	AG	9.62	1	8	0.025764994	417	1’140.5	11.72
27	Würenlingen	AG	12.78	1	8	0.009081115	415	1’140.5	11.72
29	Cressier	NE	44.4	2	11	0.085579391	435	1’104.2	12.02
30	Jussy	GE	30.3	2	3	0.003705047	506	1’070.2	12.09
31	Rickenbach	ZH	500	1	5	0.001728949	425	1’136.7	10.64
32	Grosswangen	LU	45.05	1	10	0.059395736	559	1’246.1	11.21
33	Menzingen	ZG	170.94	2	26	0.135142046	715	1’989.1	9.18
34	Belmont-Broye	FR	38.46	1	9	0.012676798	626	972.4	11.82
35	Cossonay	VD	71.43	6	9	0.038342233	557	990.4	10.49
36	Oulens-sous-Échalens	VD	43.01	1	8	0.05827939	589	1’129.1	10.51

S2 $\log_{10}$ Response Ratio Values of Bulk Density and Gravimetric Water Content

a. Bulk Density $\log_{10}$ Response Ratio Values

Table 4: $\log_{10}$ response ratio values of bulk density (topsoil and subsoil). Blank cells indicate missing values.

Site	BD T/A Top	BD T/A Sub	BD A/C Top	BD A/C Sub	BD AFS/C Top	BD AFS/C Sub
1	0.007738839	-0.03037248	0.007738839	-0.06100325	-0.000683095	-0.063946678
2	0.041092953	-0.022046006	0.041092953	-0.007287514	0.000634813	-0.00951693
3	0.048419886	0.075961884	0.048419886	-0.020701491	-0.093202961	-0.002350535
5	-0.030723801	-0.024116458	-0.030723801	0.03910604	0.091630501	0.037078982
6	0.007816222		0.007816222		0.092312188	-0.792170069
7	0.003883382	0.041968331	0.003883382	-0.043377725	0.026894571	-0.037668065
8	-0.032635885	0.005437804	-0.032635885	0.025085875	-0.011458163	0.028395511
9	-0.056121164	-0.021047756	-0.056121164	0.023699982	0.055367651	0.0202621
10	-0.005340395	-0.00965973	-0.005340395	-0.056810423	-0.01024618	-0.05868763
11	-0.001628726	-0.007736965	-0.001628726	-0.002454752	-0.005562522	-0.003152445
12	-0.012041118	0.016086494	-0.012041118	0.041946414	0.007307911	0.043037584
13	-0.02239708	0.060921007	-0.02239708	-0.027298476	0.000536759	-0.022296554
14	0.042066647	-0.038805354	0.042066647	-0.043949983	-0.089543657	-0.046760733
15	-0.008590344	0.009819603	-0.008590344	0.02068974	0.023016563	0.021856578
16	-0.018854993	0.074087338	-0.018854993	-0.019406071	-0.01254039	-0.004698337
17	-0.003827043	-0.007955674	-0.003827043	-0.032744897	-0.042672755	-0.035787549
18	-0.018955549	0.000582077	-0.018955549	0.016712173	-0.010358663	0.016802769
19	0.012117281	-0.008363664	0.012117281	-0.017798967	-0.033652228	-0.019075247
20	-0.012402926	0.016864911	-0.012402926	-0.049356998	-0.024584102	-0.044932207
22	0.006676823	-0.038265261	0.006676823	0.07399797	0.011994291	0.066189901
23	-0.014990884	-0.014111918	-0.014990884	0.015716402	-0.007178885	0.011355485
24	0.002911376	0.010763663	0.002911376	0.010716896	-0.025988302	0.011467844
25	-0.009977267	0.009149943	-0.009977267	-0.014133056	0.015958215	-0.013495799
26	0.005703852	-0.036156906	0.005703852	0.00633497	-0.025243151	0.004998581
27	-0.02600083	-0.029337175	-0.02600083	0.032564543	0.010086393	0.030847637
29	0.022253033	0.01316553	0.022253033	0.049107647	-0.015492817	0.050115316
30	0.027994922	-0.019137597	0.027994922	-0.03171311	-0.025389946	-0.032849266
31	-0.009416823	-0.046711157	-0.009416823	0.037725557	0.029327785	0.026510282
32	0.007197904	0.016007428	0.007197904	0.039515346	0.006472986	0.041713301
33	-0.00899025	-0.017968272	-0.00899025	-0.0491763	-0.046756339	-0.052574491
34	-0.022000408	-0.011203922	-0.022000408	-0.003212127	-0.009429351	-0.005772112
35	-0.000197525	-0.028748919	-0.000197525	-0.01692459	-0.023259709	-0.021117469
36	0.036399767	-0.006903269	0.036399767	0.040908289	0.007646872	0.040466213

b. Gravimetric Water Content $\log_{10}$ Response Values

Table 5: $\log_{10}$ response ratio values of gravimetric water content (topsoil and subsoil). Blank cells indicate missing values.

Site	GWC T/A Top	GWC T/A Sub	GWC A/C Top	GWC A/C Sub	GWC AFS/C Top	GWC AFS/C Sub
1	0.069985979	0.117667051	0.019222987	-0.017268471	0.026751413	-0.003959501
2	-0.04471522	-0.01919121	-0.019143776	-0.004859294	-0.023561717	-0.006805721
3	0.167562758	-0.018461172	-0.00642858	0.009632222	0.037450874	0.005531631
5	0.031623527	-0.003802482	-0.221182932	-0.158880392	-0.218364225	-0.159206884
6	-0.02576078		-0.118650123		-0.124828799	
7	-0.004545877	0.018645613	0.031348575	0.049322318	0.030758326	0.051800235
8	-0.032727616	0.009334016	0.027235915	-0.004063314	0.00766123	0.001627655
9	-0.022311354	-0.011583083	-0.056281767	-0.049783948	-0.059921634	-0.051693135
10	-0.016462882	0.039981186	-0.049869718	-0.0231762	-0.053048926	-0.015041237
11	0.019766343	0.027207178	0.012283672	0.013854567	0.014118252	0.016399593
12	-0.006658726	0.001072247	0.033589098	0.091414966	0.033148345	0.091486532
13	-0.037901585	-0.00746451	-0.006596431	0.011209966	-0.009397352	0.010640306
14	-0.008778402	0.026773186	0.101760132	0.033164046	0.101103766	0.035243261
15	-0.00350259	0.020912297	-0.036277236	-0.06780402	-0.036687842	-0.065290839
16	-0.018757582	-0.055550299	0.000359405	0.029897609	-0.003053651	0.020132277
17	0.029121065	0.04139957	0.070709005	0.071518527	0.082141655	0.087911748
18	-0.060292881	-0.050501309	0.067752989	-0.020323533	0.058906529	-0.027803797
19	-0.109649249	0.004893619	0.005222283	0.092548398	-0.009947642	0.093304861
20	0.036335275	-0.010118639	0.090410593	0.077936058	0.100102981	0.075341685
22	0.043557617	-0.023269887	-0.157974499	-0.081114298	-0.148401183	-0.085927662
23	-0.11912782	0.038716055	0.081409659	-0.053710817	0.047566435	-0.041237233
24	-0.033321676	0.031195925	0.000355133	-0.025495771	-0.001862619	-0.023270882
25	-0.038140635	-0.001843566	0.103753281	0.070524325	0.101227758	0.070397434
26	0.014862032	0.09355679	-0.028261164	-0.033302099	-0.027680043	-0.029305231
27	-0.009483577	0.102293705	0.000835083	-0.077315504	0.000268089	-0.070403643
29	0.017069286	-0.055243021	0.025810955	-0.011111179	0.027122871	-0.015043941
30	-0.031258331	0.053494349	0.02688421	0.041324986	0.025052478	0.044761564
31	-0.036498988	0.038239675	-0.056515337	-0.104667176	-0.065356558	-0.094786996
32	-0.021847973	0.01667499	0.002988538	-0.023469698	0.0000996	-0.021178556
33	-0.03745427	-0.009394283	0.051575891	-0.000706282	0.044619581	-0.002497163
34	0.034316706	0.004691884	-0.001922379	0.00948593	0.006240941	0.01057318
35	0.045250445	0.00424056	-0.008481155	0.009473519	-0.001385652	0.010112248
36	-0.006174719	-0.005100771	-0.078932737	-0.078852358	-0.079328468	-0.079179638

S3 Log$_{10}$ Response Ratio Values of the Penetration Resistance per 10 cm Subsets

a. Tree / Alley log$_{10}$ Response Ratio Values

Table 6: Tree / alley log$_{10}$ response ratio values. Blank cells indicate missing values.

Site	0-10 cm T/A	11-20 cm T/A	21-30 cm T/A	31-40 cm T/A	41-50 cm T/A	51-60 cm T/A	61-70 cm T/A	71-80 cm T/A
1	0.143906576	0.195226269	0.112529479	0.040958608	0.046743404			
2	-0.063051746	-0.06279083	0.075250952	0.031408464	0.005201194			
3	0.057991947	0.204119983	-0.123062732	-0.11270428	-0.06694679	-0.085243281	-0.081821342	-0.009984221
5	-0.012234456	0.031034234	0.074328743	-0.164586097	0.040617851			
6	0.128318477	0.094269917						
7	-0.171070458	-0.162727297	-0.256610856					
8	0.202420198	-0.026734253	0.009870754	0.025305865	0.114345663	0.16879202	0.205546238	0.211709118
9	-0.146128036	0.073107098	-0.037788561	0.003727873	-0.039024108	0.003253157	0.020203386	-0.022777215
10	0.102662342	0.334713109	-0.006160309	-0.195745947	0.022276395			
11	0.023481096	-0.171396138	-0.119975317	-0.053875381	-0.032792513	-0.089290616	-0.150723787	
12	-0.166331422	-0.22184875	-0.139046991	-0.128029814	-0.131278915	-0.020684599		
13	0.032184683	-0.019744058	0.058866659	0.036722807	-0.043156917	-0.041392685		
14	0.096910013	0.009340026	0.014240439	0.105803726				
15	-0.2155998	-0.096910013	-0.214843848					
16	0.165625825	0.251342211	0.161062269	0.078286715				
17	0.11270428	0.113943352	0.122845747	-0.03300026				
18	0.100115153	0.229674087	0.059768205	0.037324323	0.015420359	0.112226771	0.129094696	0.146128036
19	0.218495108	0.380211242						
20	-0.069080919	-0.098925304	-0.296283561	-0.341324591				
22	-0.057991947	-0.087150176	-0.057142886	0.015420359	-0.057991947	-0.14976232	-0.241592808	-0.18662925
23	-0.036722807	0	-0.00496342	0.096910013	0.152288344	0.095203549	0.054131526	-0.057624989
24	-0.096910013	-0.13683796	-0.162727297	-0.089905111	-0.199798609	-0.249000996	-0.153334108	-0.124938737
25	0.096910013	0.193820026	0.108233043	-0.052273283	-0.040533546	0.109144469	0.170141927	0.204119983
26	0.015239967	-0.009759837	-0.210853365	-0.010723865	-0.026013432	-0.235212711	-0.226783967	-0.346787486
27	0.143422142	0.152090983	0.024359346	0.041392685	0.057991947	0.096910013	0.148062535	0.162727297
29	0.057991947	-0.022276395	0.052706351	0.061136743	0.286503742	0.319401686	0.276206412	
30	0.057991947	0.065266732						
31	0.291886616	0.273706868	0.118407869	0.094885326	0.104735351	0.185391282	0.088941083	-0.09017663
32	-0.023481096	-0.149439064	-0.079181246	-0.035838425	-0.110698297	-0.064457989	-0.094975513	-0.119975317
33	0.196294645	0.190331698	0.265702033	0.200359834				
34	0.052706351	0.018483406	-0.065392962	-0.131064289	-0.160579093			
35	0.093904503	0.143090999	0.055047566	0.116505569	0.055155265	0.092943826	0.06694679	
36	0.186310424	0.101026579	0.094099036	-0.080823193	-0.134698574			

b. Alley / Control log_{10} Response Values

Table 7: Alley / control log_{10} response ratio values. Blank cells indicate missing values.

Site	0-10 cm A/C	11-20 cm A/C	21-30 cm A/C	31-40 cm A/C	41-50 cm A/C	51-60 cm A/C	61-70 cm A/C	71-80 cm A/C
1	0.06694679	0.187990482	0.012409258	0.06694679	0.06366908	0.115795357	0.140375707	0.144492273
2	0.036722807	-0.062147907	-0.126403475	-0.16879202	-0.145379897			
3	0	-0.054357662	0.178920549	0.021189299	-0.03407979	0	-0.004364805	
5	0.064940807	0.069635928	0.142667504	0.315853772	0.145277312	0.113943352	0.153814864	0.109144469
6	0.057991947	0.120573931	0.071175591	0.096910013				
7	0.186310424	0.204119983	0.164553346					
8	0	-0.00643411	-0.028963696	-0.017033339	-0.072147983	-0.070037867	-0.096910013	-0.099131473
9	0.243038049	0.134698574	0.118948373	0.055857817				
10	-0.014240439	0.014240439	0.271474752	0.118579992	0.074633618			
11	0.024823584	0.340538537	0.119975317	-0.003604124	-0.011685758	0	0.023481096	
12	-0.019305155	-0.032184683	-0.066096066	-0.127242692	-0.111759134	-0.094885326	-0.035472318	0
13	-0.076388346	-0.11021548	-0.110698297	-0.192796953	-0.241357991	-0.284259785		
14	-0.2155998	-0.093117024	-0.054357662	-0.075421097	-0.05999793	-0.08795517	-0.104088598	-0.135255005
15	-0.069635928	-0.065817284	0.02171925					
16	-0.029963223	-0.075250952	0	0.010857928	0.050490992	0.055047566	0.057991947	0.044582133
17	0.051152522	0.124938737	0.113943352					
18	-0.159700843	-0.313994973	-0.106764768	0.034762106	0.067819744	0.05958569	0.034762106	0.057991947
19	-0.04742465	-0.118689787	-0.113231977	0.034762106	-0.010995384	-0.010465434		
20	0.054357662	0.00811789	0.072550667	0.078083156				
22	-0.157607853	-0.096910013	-0.034304231	-0.114345663	-0.00415596	0.010995384	0.100544298	
23	0.036722807	0.015239967	0.131569316	0.107905397	0.040958608	0.0641175	0.089290616	0.273644195
24	0.045757491	0.043156917	0.13013993	-0.053109689	0.051831638	0.056115942		
25	0.032184683	-0.118099312	-0.194802223	-0.02606549	-0.063864488	-0.061596071	-0.115983894	-0.176091259
26	-0.084320886	-0.071063356	-0.076388346	-0.222906715				
27	0.06069784	0.044203662	0.197489404	0.064240896	0.006248949	-0.063051746	-0.045078375	-0.025554104
29	0.015794267	0.033858267	0.169142399	0.031408464	0.074633618	0.082410216	0.134698574	0.143422142
30	-0.029963223	-0.044582133	0.042289062	0.08345403	0.064859835	0.010219165		
31	-0.034762106	-0.086186148	-0.098204483	-0.047772782	-0.072550667	-0.199869106	-0.285966249	-0.152861418
32	0.023481096	0.058778001	0.037788561	0.004321374	0.120139854	0.115067983	0.10969877	0.124938737
33	0.015794267	0.045757491	0.04275198	-0.060480747	-0.009340026	-0.029963223	-0.016705694	
34	0	-0.053245512	0.093421685	0.167061943	0.01608682			
35	-0.014723257	0.08130494	0.07684003	-0.02171925	0.068457381	0.041392685	0.0641175	-0.06694679
36	0.06694679	0.146128036	0.179607833	0.111492013	0.198367654			

c. Agroforestry / Control log_{10} Response Values

Table 8: Agroforestry / control log_{10} response ratio values. Blank cells indicate missing values.

Site	0-10 cm AFS/C	11-20 cm AFS/C	21-30 cm AFS/C	31-40 cm AFS/C	41-50 cm AFS/C	51-60 cm AFS/C	61-70 cm AFS/C	71-80 cm AFS/C
1	0.083681747	0.211965516	0.025068286	0.071220909	0.068576414			
2	0.030608753	-0.06823828	-0.117985875	-0.165435498	-0.144838945			
3	0.013788284	0.000823307	0.154022042	-0.001825064	-0.048320229	-0.017838591	-0.021539678	
5	0.063899583	0.072400384	0.149600516	0.303880557	0.148932395	0.074791228	0.11466274	0.069992345
6	0.093147828	0.145659541						
7	0.167464112	0.186046869	0.138514808					
8	0.133695696	-0.022468518	-0.022944027	-0.001493963	0.000790633	0.040010442	0.039011352	0.041191203
9	0.22184875	0.147769983	0.112874225	0.056481356				
10	0.007894006	0.103334105	0.270273716	0.086528616	0.079092533			
11	0.02701147	0.327469512	0.110339228	-0.008234879	-0.014566661	-0.007399923	0.011746759	
12	-0.028616573	-0.043923087	-0.074101721	-0.134698574	-0.119378531	-0.096234068	-0.065435542	-0.029963223
13	-0.073826129	-0.111702791	-0.105875731	-0.189859211	-0.244529691	-0.287307478		
14	-0.20748191	-0.092405066	-0.05326647	-0.066472021				
15	-0.090103854	-0.076158118	0.001308117					
16	0.005858138	-0.016390416	0.034686346	0.026460665				
17	0.098022163	0.172363387	0.165381313					
18	-0.142530047	-0.269291596	-0.096910013	0.040782978	0.070254721	0.079062958	0.057539321	0.08420733
19	-0.00579841	-0.033976053						
20	0.037518083	-0.015386317	0.013122256	0.012193486				
22	-0.169231058	-0.11392111	-0.045766094	-0.111041911	-0.015779164	-0.016625742	0.059518467	
23	0.025576913	0.015239967	0.130024332	0.140574514	0.0945172	0.096169107	0.10694251	0.256443787
24	0.039725526	0.034985566	0.120677803	-0.058746773	0.040644216	0.042845568		
25	0.039608701	-0.101570254	-0.186407094	-0.029475386	-0.066541654	-0.053121764	-0.101851916	-0.158482314
26	-0.083724737	-0.071434706	-0.082860813	-0.223314312				
27	0.070843321	0.055067394	0.199000189	0.066856261	0.009980381	-0.056542631	-0.034550053	-0.013790971
29	0.020451625	0.03221632	0.173351222	0.036335069	0.104222909	0.116635046	0.162897977	
30	-0.026219282	-0.04033472						
31	0.058513622	0	-0.065441435	-0.02203836	-0.043905486	-0.145594395	-0.261965973	-0.173711557
32	0.020381193	0.041346289	0.02789532	-0.000352273	0.106730039	0.106896632	0.098014917	0.110536368
33	0.061074249	0.089421992	0.108055128	-0.014090132				
34	0.012743051	-0.048909757	0.079181246	0.140136035	-0.016051143			
35	0.000723222	0.106010812	0.085555262	-0.002123694	0.077190588	0.056666686	0.074841365	
36	0.081703401	0.153405037	0.186334263	0.106707815	0.190830901			

S4 $\log_{10}$ Values of Internal and External Variables

Table 9: $\log_{10}$ values of internal and external variables.

Density	Diversity	Age	Tree Volume	Altitude	Precipitation	Temperature
1.568670978	0	0.602059991	-2.552817153	2.670245853	2.928754202	1.06483222
1.692494408	0.602059991	0.77815125	-1.876931415	2.666517981	3.037147504	1.053078443
1.996774271	0	1.230448921	-1.2231164	2.705007959	3.095552896	1.049605613
1.583312152	0	1.113943352	-1.142466152	2.737192643	2.965671971	0.923761961
1.673665876	0.301029996	1.491361694	0.380469293	2.844477176	3.298547435	0.955206538
1.524266269	0.301029996	0.903089987	-1.378015903	2.63748973	3.029464947	1.083144143
1.774662923	0.477121255	1.230448921	0.165355184	2.790285164	3.298547435	0.955206538
2.0757294	0.477121255	1.491361694	-0.19454673	2.826074803	3.052809328	1.025305865
1.532754379	0.477121255	1.041392685	-2.325238492	2.876794976	3.052809328	1.025305865
1.402261382	0.954242509	0.477121255	-3.09503574	2.846337112	3.097118424	1.022840611
1.869642345	0.301029996	0.77815125	-1.577007599	2.646403726	3.043676586	1.056523724
1.886039276	0.602059991	0.698970004	-2.546962666	2.653212514	3.043676586	1.056523724
1.576801896	0	1.113943352	-0.741776409	2.756636108	2.99321572	1.09131516
1.76952502	0	0.698970004	-2.29195636	2.871572936	3.105850674	1.042575512
1.590953235	0.301029996	0.954242509	-1.822367735	2.613841822	3.046221937	1.035429738
1.709948017	0.301029996	1.146128036	-1.393956549	2.773786445	3.052732407	1.02201574
1.471731651	0	1.176091259	-1.120400952	2.688419822	2.98784495	1.072617477
1.58500928	0.477121255	0.602059991	-2.827088677	2.610660163	3.084969288	1.101403351
1.537567257	0.477121255	0.477121255	-3.042139488	2.63447727	3.084969288	1.104487111
2.148756851	0.77815125	0.84509804	-3.267204302	2.873901598	3.06870522	1.055760465
2.443700974	0.301029996	0.698970004	-2.182938691	2.696356389	3.042851043	1.054995862
1.559906625	1.041392685	0.77815125	-2.548155407	2.86923172	3.132419798	1.026124517
1.583312152	0.602059991	0.84509804	-1.983261664	2.887054378	2.905256049	0.92788341
0.983175072	0	0.903089987	-1.588969954	2.620136055	3.05709529	1.068927612
1.106530854	0	0.903089987	-2.041860825	2.618048097	3.05709529	1.068927612
1.64738297	0.301029996	1.041392685	-1.067630808	2.638489257	3.043047743	1.079904468
1.481442629	0.301029996	0.477121255	-2.431206278	2.704150517	3.029464947	1.082426301
2.698970004	0	0.698970004	-2.762217817	2.62838893	3.05564586	1.026941628
1.653694795	0	1	-1.226244732	2.747411808	3.095552896	1.049605613
2.2328437	0.301029996	1.414973348	-0.86920951	2.854306042	3.298656617	0.962842681
1.58500928	0	0.954242509	-1.89699043	2.796574333	2.98784495	1.072617477
1.85388065	0.77815125	0.954242509	-1.416322598	2.745855195	2.995810632	1.020775488
1.633569443	0	0.903089987	-1.234485003	2.770115295	3.052732407	1.021602716

S5 Overview Maps of Variables

For all maps in this chapter, the OpenTopoMap was used as the base map (OpenStreetMap contributors 2024) in QGIS. National and cantonal boundaries were derived from the SwissBOUNDARIES3D dataset (Bundesamt für Landestopografie swisstopo 2024).

a. Internal Variables

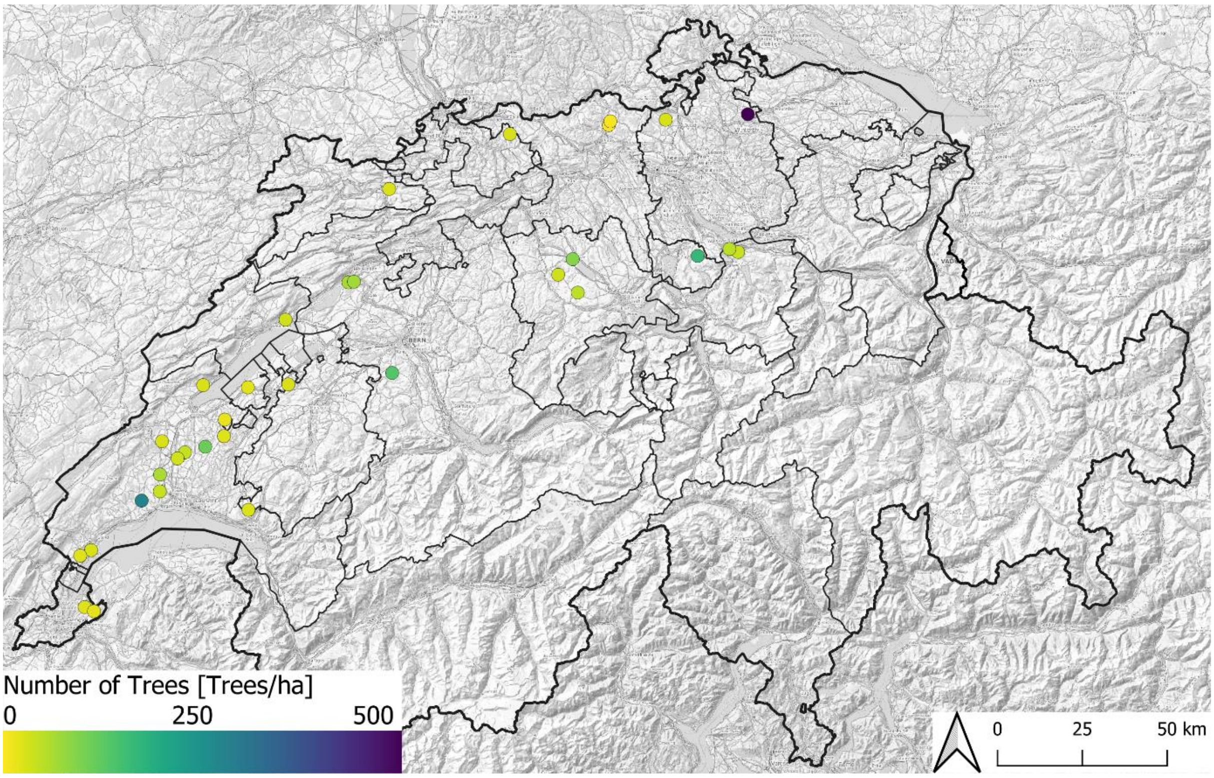

Figure 15: Overview map of the tree density variable in trees per hectare.

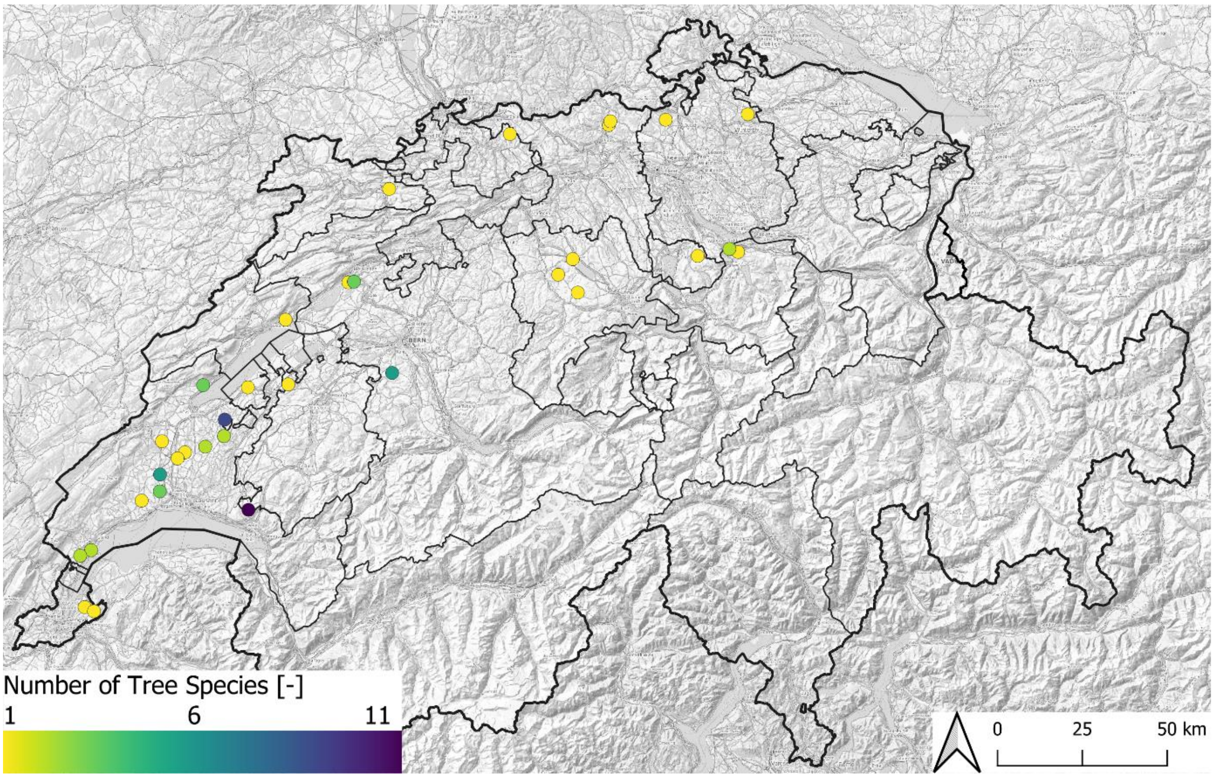

Figure 16: Overview map of the tree diversity variable, assessed by number of different tree species within one agroforestry system.

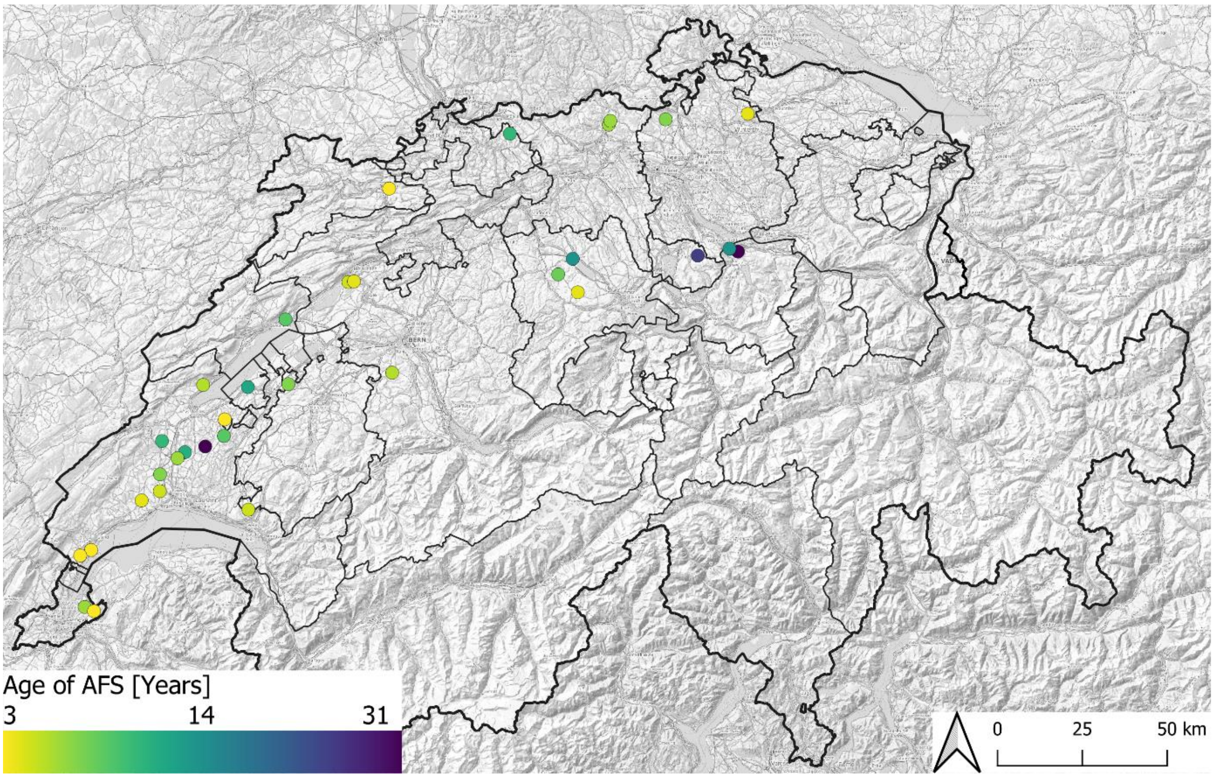

Figure 17: Overview map of the agroforestry system (AFS) age variable in years.

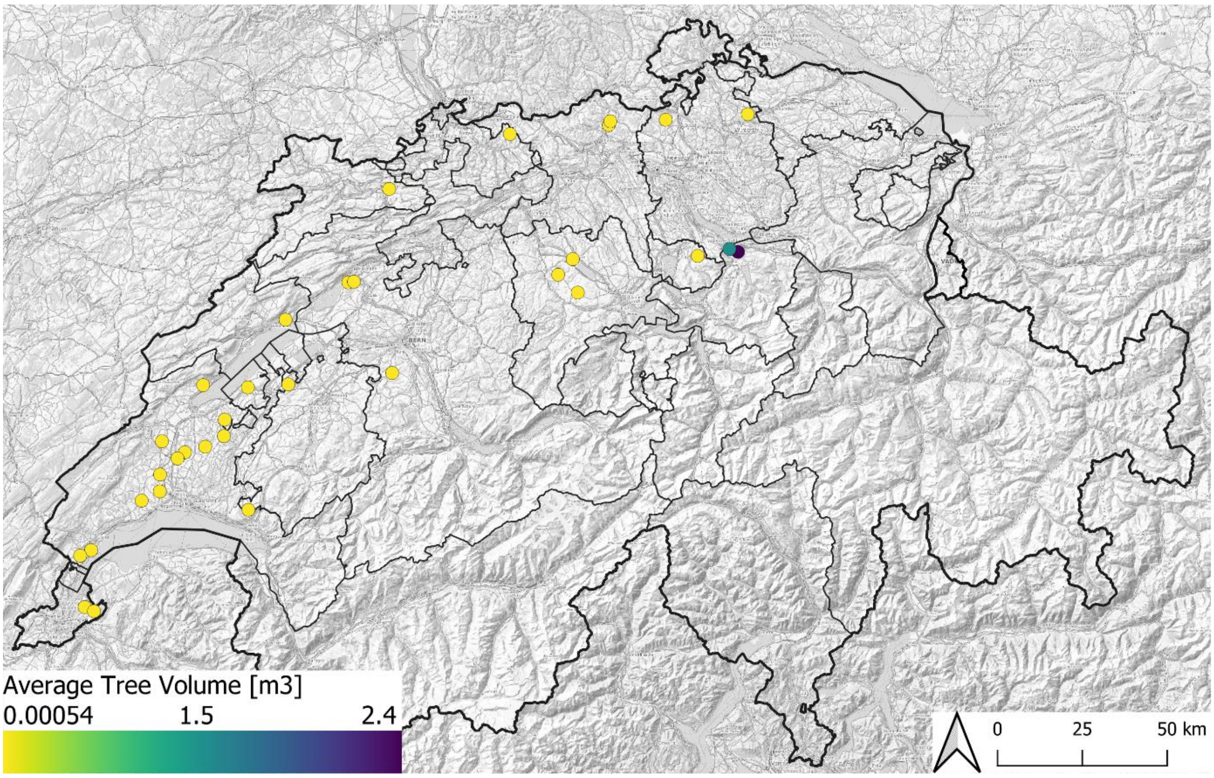

Figure 18: Overview map of the tree volume variable, measured in m³.

b. External Variables

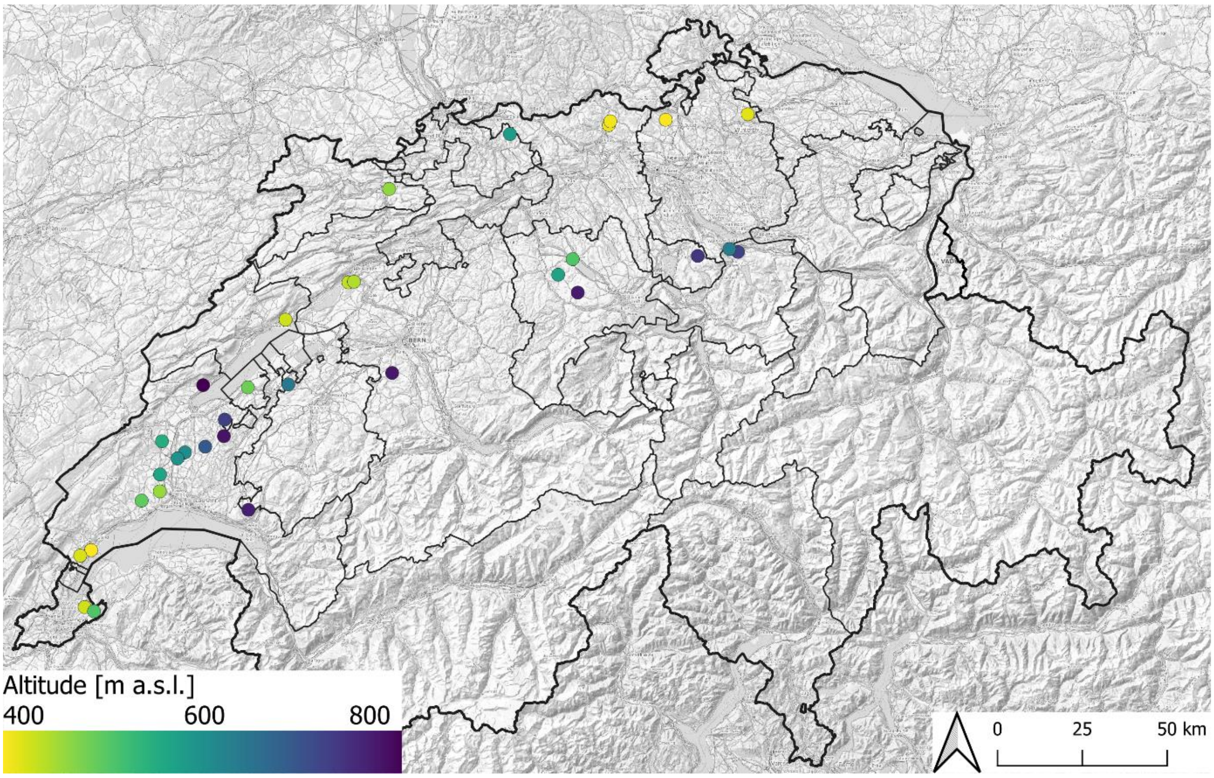

Figure 19: Overview map of the altitude variable, displayed in m a.s.l.

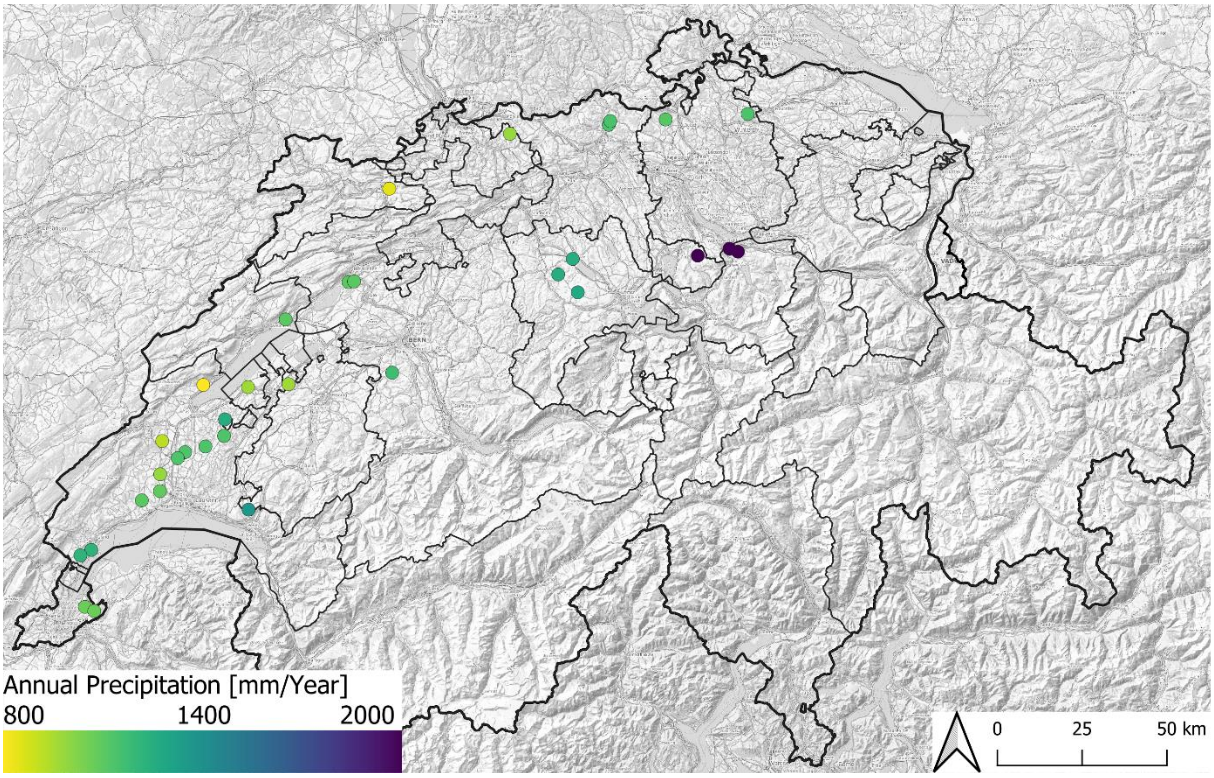

Figure 20: Overview map of the precipitation variable, assessed in annual precipitation amount in mm/year.

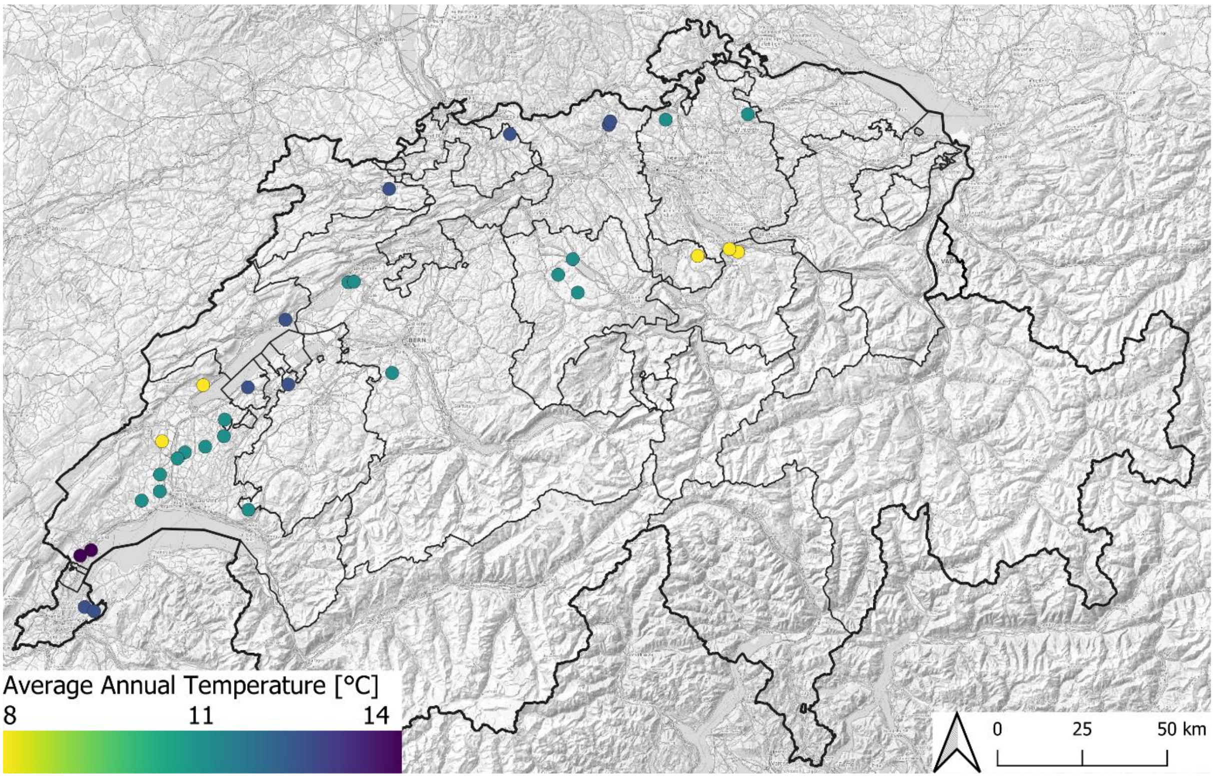

Figure 21: Overview map of the temperature variable, assessed as average annual temperature in °C.

S6 Exemplary Codes from R

a. Penetration Resistance Median Calculation per Centimetre

```r
###### Summarizing PR data in median per site per cm (exemplary for plot 1: tree strip)
side_sum_data_df_p1 <- matrix(nrow=0,ncol=84)              # creation of matrix for data
side_sum_data_df_p1 <- as.data.frame(side_sum_data_df_p1) # conversion into a data frame

# function to calculate the median of all replicates per site, plot and cm
side_sum_df_p1 <- function(sites){
  site_data_n4_p1 <- as.data.frame(subset(pen_data_n4, pen_data_n4$Site == j & Plot == 1))
  median_p1 <- t(as.matrix(apply(na.pass(site_data_n4_p1),2,median)))
  median_df_p1 <- as.data.frame(median_p1)
  side_sum_data_df_p1 <- data.frame()
  side_sum_data_df_p1 <- bind_rows (side_sum_data_df_p1, median_df_p1)
}

#loop to calculate median for each site
for (j in sites){
  side_sum_data_df_p1 <- bind_rows(side_sum_data_df_p1, side_sum_df_p1(j))
}
View(side_sum_data_df_p1)
```

Figure 22: Penetration resistance median calculation for each site, plot and centimetre.

b. Penetration Resistance Median Calculation 10 cm Subsets

```r
### median calculation for penetration resistance subsets of 10 cm (exemplary for plot 1: tree strip) ###
PenR_per10_p1 <- matrix(nrow=0,ncol=8) # creation of matrix for storing 10 cm medians

#function to calculate the median for each  10 cm depth, site and plot
PenRper10_p1 <- function(site) {
  site_data_n4_p1 <- subset(side_sum_data_df_p1, Site == j)
  d10_p1 <- apply(site_data_n4_p1[,2:11], 1, median, na.rm = TRUE)
  d20_p1 <- apply(site_data_n4_p1[,12:21], 1, median, na.rm = TRUE)
  d30_p1 <- apply(site_data_n4_p1[,22:31], 1, median, na.rm = TRUE)
  d40_p1 <- apply(site_data_n4_p1[,32:41], 1, median, na.rm = TRUE)
  d50_p1 <- apply(site_data_n4_p1[,42:51], 1, median, na.rm = TRUE)
  d60_p1 <- apply(site_data_n4_p1[,52:61], 1, median, na.rm = TRUE)
  d70_p1 <- apply(site_data_n4_p1[,62:71], 1, median, na.rm = TRUE)
  d80_p1 <- apply(site_data_n4_p1[,72:81], 1, median, na.rm = TRUE)
  PenR_p1 <- cbind(d10_p1, d20_p1, d30_p1, d40_p1, d50_p1, d60_p1, d70_p1, d80_p1)
  return(PenR_p1)
}

# loop through each site and calculationg median per 10 cm subset of penetration resistance
for (j in sites) {
  PenR_per10_p1 <- rbind(PenR_per10_p1, PenRper10_p1(j))
}

PenR_per10_df_p1 <- as.data.frame(PenR_per10_p1) # conversion into data frame
colnames(PenR_per10_df_p1) <- c("d10", "d20", "d30", "d40", "d50", "d60", "d70", "d80") # adding column names

# output of .csv-file
write.csv(PenR_per10_p1, paste(physics_outputFolder, "penetrometer_NE_median_p1.csv", sep=""))
```

Figure 23: Penetration resistance median calculation for each site, plot and 10 cm subsets.

c. ANOVA Code

```r
### exemplary calculation of ANOVA for the bulk density and the depth with all applied statistical tests ###

leveneTest(BD_Value ~ Depth, data=ratio_ANOVA)                          # calculation of Levene's test to check for normal variances.
                                                                        # If not, then:
oneway.test(BD_Value ~ Depth, data = ratio_ANOVA, var.equal = FALSE)    # calculation of Welch-ANOVA if Levene's test showed not normal
                                                                        # variances.
aov.plot.2 <- aov(BD_Value ~ Depth, data=ratio_ANOVA)                   # calculation of ANOVA if Levene's test showed normal variances.
summary(aov.plot.2)                                                     # printing out results of the ANOVA.
shapiro.test(residuals(aov.plot.2))                                     # calculating Shapiro-Wilk test to check for normal distribution
                                                                        # of residuals. If not, then:
kruskal.test(BD_Value ~ Depth, data=ratio_ANOVA)                        # calculation of Kruskal-Wallis test to check statistical
                                                                        # significance between medians of groups.
TukeyHSD(aov.plot.2, conf.level=.95)                                    # calculation of the TukeyHSD test to check which groups
                                                                        # significantly differ from each other.
plot(aov.plot.2)                                                        # plotting graphs of residuals vs fitted, Q-Q residuals,
                                                                        # scale-location, residuals vs leverage.
ggplot(ratio_ANOVA, aes(x=Depth, y=BD_Value, fill=Ratio)) + geom_boxplot() # plotting boxplots of the ANOVA's results.
```

Figure 24: Exemplary code to calculate the ANOVAs for bulk density, gravimetric water content and penetration resistance to see if there were differences between the response ratios and depths.

d. Linear Regression Code

```
### exemplary linear regression calculation for the topsoil A/C log10 response ratio of the bulk density for the variable age ###
ratio <- read.csv("Datenanalyse_def.csv", header = TRUE, sep = ";")   # loading the file with the median data
lr.BD.AC.top.age <- lm(V_BD_T_A_C_log ~ Age_log, data=ratio)          # calculating the linear regression
summary(lr.BD.AC.top.age)                                             # printing out the results of the linear regression
shapiro.test(residuals(lr.BD.AC.top.age))                             # calculation of Shapiro-Wilk-test
ggplot(ratio, aes(x=Age_log, y=V_BD_T_A_C_log)) + geom_point() +      # plotting the linear regression to evaluate the effect slope
  stat_smooth(method=lm)
```

Figure 25: Code for linear regression calculation. It was applied to all linear regressions of log_{10} response ratios of bulk density, gravimetric water content and penetration resistance and internal variables.

e. Spearman Correlation Code

```
### exemplary calculation of the Spearman Correlation ###
cor.test(ratio$V_BD_T_AFS_C_log, ratio$Age_log, method="spearman")
```

Figure 26: Code for Spearman correlation, which was applied if the residuals of the linear regressions of bulk density, gravimetric water content and penetration resistance were not normally distributed (p-value ≤ 0.1).

f. Multiple Regression Code

```
### exemplary multiple regression analysis for the topsoil A/C log10 response ratio of the bulk density with all variables ###
lm.BD_T_A_C <- lm(V_BD_T_A_C_log ~ Age_log + Density_log + Diversity_log + TV_av_log +
        Temperature_log + Precipitation_log + Altitude_log + (1|Site),  data=ratio)  # multiple regression calculation
summary(lm.BD_T_A_C)                                                                 # printing out the results of the multiple regression
shapiro.test(residuals(lm.BD_T_A_C))                                                 # calculation of Shapiro-Wilk test
```

Figure 27: Code for calculating multiple regressions of log_{10} response ratios of bulk density, gravimetric water content and penetration resistance, as well as internal and external variables.

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.

Chur, 27.09.2024