Nutrient allocation to tree compartments, relationship with nutrient availability in the soil and impact on sustainable wood harvesting

GEO 511 Master's Thesis

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30.09.2022
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Abstract

Forestry in Switzerland is being intensified by the increasing wood demand. This requires sustainable wood harvesting and a better understanding of the relationship between the nutrient concentrations in and their allocation to the individual tree compartments, as well as their relationship to the nutrient availability in the soil depending on the geological substrate. If there is a relation between the nutritional status of the trees and the geological substrate, an adaptation of the forest management to the soil conditions would be essential. For this purpose, trees of the species *Fagus sylvatica* were cut at the four sites Waldlabor, Arisdorf, Bülach and Irchel in Switzerland. The tree compartments leaves, branches with different diameters, bark, stem and soil samples including fine roots were sampled to analyse the macronutrients N, P, S, K, Mg and Ca. It is investigated whether the macronutrient concentrations in the tree compartments differ at the sites and whether there is a relationship between the nutrient allocation to the tree compartments of *Fagus sylvatica*, focussing on leaves, and the nutrient availability in the soil. In the second part, data from literature studies with macronutrient concentrations of the tree compartments leaves/needles, branches, bark and stem of different tree species in temperate forests in Europe is analysed. It is investigated whether the nutrient concentrations in the different tree compartments differ depending on the geological substrate group. The results show a weak relationship between the different nutrient allocation strategies and the nutrient availability in the soil for a few macronutrients. Further, differences in nutrient concentrations could be detected in the different tree compartments depending on the geological substrate group. The results confirm findings from previous studies that to some degree, tree nutrition can be balanced by nutrient supply via precipitation, weathering of minerals and nutrient recycling processes. The topic needs to be further investigated using a broader data base and including other stand characteristics and environmental factors to better understand the relationship between nutritional status of trees and geological substrate and to determine the influence of each factor in the Central Plateau in Switzerland.

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Abbreviations

ρ	Density
AD	Arisdorf
Al	Aluminium
ANOVA	Analysis of variance
BD	Bulk density
BS	Base saturation
C	Carbon
$CaCl_2$	Calcium chloride
CEC	Cation exchange capacity
CL	Carbonaceous loose
Cl	Chlorine
CO_2	Carbon dioxide
C_{org}	Organic carbon
CS	Carbonaceous solidified
DBH	Diameter at breast height
DW	Dry weight
Fe	Iron
H	Hydrogen
K	Potassium
LAI	Leaf area index
Mg	Magnesium
MLCF	Mass loss correction factor
N	Nitrogen
Na	Sodium
NaHCO3	Sodium bicarbonate
NH_4^+	Ammonium
NH_4Cl	Ammonium chloride
NUE	Nutrient use efficiency
P	Phosphorus
P_{inorg}	Inorganic phosphorus
P_{org}	Organic phosphorus
PSA	Particle-size analysis
S	Sulphur
SL	Siliceous loose
SO_4^{2-}	Sulphate
SLA	Specific leaf area
SS	Siliceous solidified
TLA	Total leaf area
TLS	Terrestrial laser scanner
Tukey HSD	Tukey Honest Significant Differences
V	Volume
WC	Water content
WL	Waldlabor
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research
WW	Wet weight

1. Introduction

1.1 Macronutrient cycling in the forest

Nutrients are chemical elements that are essential for the functioning of biological processes in organisms such as plants (Barnes et al. 1998). The so-called macronutrients include nitrogen (N), phosphorus (P), sulphur (S), potassium (K), magnesium (Mg) and calcium (Ca). These nutrients are part of the nutrient cycle and are moved, transformed and (re)used by plants and organisms in the forest and are essential for the forest ecosystem (Rahman et al. 2013). In general, nutrient input to the biosphere and soil occurs through geological, hydrological and biological processes (Likens 2013). Input via precipitation is particularly relevant for nutrients where input through weathering is low, such as N, S and Cl (Art et al. 1974; Likens 2013). Nutrients provided by hydrological processes are N, P and Cl. Simultaneously, there is a loss of silica, Ca, Na, Al, Mg and K due to these processes (Likens 2004, 2013). These losses are compensated by the release of nutrients through weathering of primary minerals from the parent material, dry deposition and mineralisation of soil organic matter (Drever 2005; Likens 2013). The depth of these nutrient stocks, and thus soil fertility, results from input minus output fluxes (Ranger and Turpault 1999; Ponette et al. 2014). Nutrients in the soil can be taken up by plant roots and their mycorrhizae (Figure 2). Nutrients are then allocated to the different tree compartments. During the phenological year, nutrients are reabsorbed from the senescent tissue and reallocated or translocated within the tree, or they are returned to the soil by the shedding of leaves and needles. The litter is microbially decomposed into organic material and finally the inorganic nutrients are released back into the soil, which is known as mineralisation (Rahman et al. 2013).

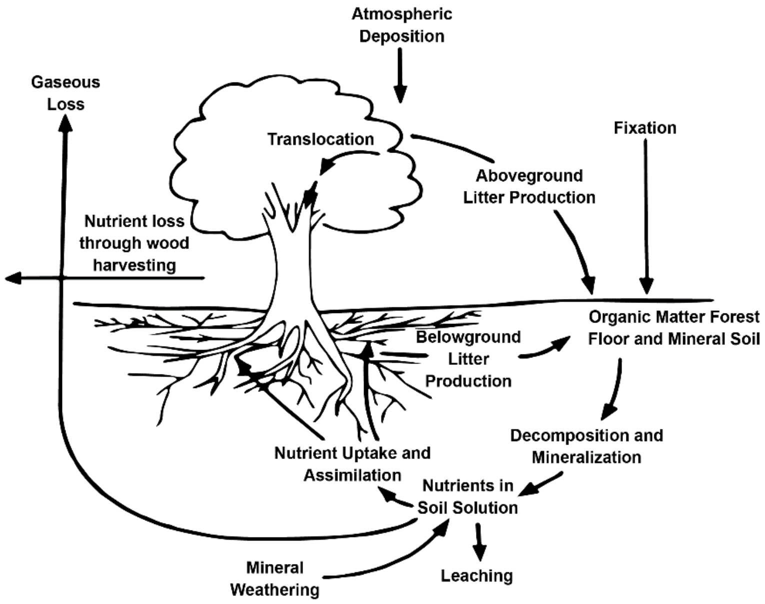

Figure 2: A schematic diagram of the nutrient cycle in a forest ecosystem (adapted from Rahman et al. (2013) after Barnes et al. (1998)).

Nitrogen is an essential primary plant nutrient and is present in many of a plant's organic N compounds. However, the bedrock is a minor source of N and input to soil occurs primarily through biological N_2 fixation from the transformation of plant and microbial residues, where the N_2 is converted to (inorganic) ammonium (NH_4^+) and organic compounds. N is mainly present in organic form in the topsoil and is transformed by mineralisation (Amelung et al. 2018).

Calcium, potassium and magnesium are taken up by plants from the soil solution as Ca^{2+}, K^{+} and Mg^{2+} cations. Ca and Mg are essential components of compounds in plants. Mg additionally stimulates enzymes and K drives the regulation of osmotic pressure and water balance, among other things. Ca and Mg supply succeeds in humid climatic regions through minerals of the silicate group or carbonates in the parent material. In the case of K, the primary source are mica or illite. A high proportion of Ca in the soil is usually present in exchangeable form and increases with pH, while the amount of available clay minerals increases with silt and especially clay content. In general, the availability of Ca, K and Mg in the soil increases with increasing total concentration, as the solid material weathers and releases nutrients in solution for plant supply (Amelung et al. 2018).

Phosphorus is important for plants because it drives energy transfer and the synthesis of organic and cellular components. It is taken up by plant roots as dissolved phosphate, and when its concentration in the soil solution is low, the P pool is continuously replenished from solids, originating from apatites in alkaline soils from the parent material and in acidic soils as Al- and Fe-phosphates (variscit, strengit) (Mellert and Ewald 2014; Amelung et al. 2018). In general, the higher the total P concentration in the soil, the better the P supply of the plants (Amelung et al. 2018).

Sulphur is an important element for plants, including amino acids, proteins, enzymes, vitamins, etc. S is absorbed by plants mainly as sulphate (SO_4^{2-}) from the soil. S occurs in humid climatic regions mainly in alkaline rocks in minerals in the form of metal sulphides. Under oxidising conditions, they are oxidised by sulphides to sulphates (gypsum) and bound to organic matter in the H, O and A horizons (Amelung et al. 2018).

1.2 Nutrient allocation on tree level

Depending on the physiological processes that take place in the tree compartments, different amounts of nutrients are needed to maintain the supply. Due to that, the allocated amount of macronutrients varies depending on the compartment (Marschner 2012). The stem biomass usually has the lowest nutrient concentrations compared to the other aboveground compartments (Augusto et al. 2000), but the stem is allocated a high proportion of the total nutrients due to its proportion of the biomass. In a fertilisation experiment, there has been no effect on the nutrient concentration in the heartwood, suggesting that different tree components react differently to varying environmental conditions. For compartments other than the stem, fertilisation experiments resulted in higher nutrient allocation to the needles and lower allocation to the bark and branches (Heilman and Gessel 1963; Nilsson and Wiklund 1995). The bark usually has higher nutrient concentrations than other components of the stem (Hagen-Thorn et al. 2004). Due to the physiological activity of the crown, it is sensitive to environmental conditions such as climate and soil fertility (Augusto et al. 2000).

In practice, foliar concentrations are commonly used to assess the nutritional status of trees (Göttlein 2020). Normal ranges for the macronutrients N, P, S, Mg, K and Ca were developed for the in European temperate forests important tree species *Fagus sylvatica* (beech), *Picea Abies* (spruce), *Pinus sylvestris* (pine), *Quercus robur/ petraea* (oak) (Mellert and Göttlein 2012). In addition, nutrient ratios can provide information about nutritional imbalances in trees (Duquesnay et al. 2000). Jonard et al. (2015) found that foliar nutrient concentrations decreased for P and observed decreasing trends over time for Mg, K, S and Ca in some of the species sampled. They attributed this trend to increased demand due to increased tree productivity. Flückiger and Braun (1999) attributed the decrease in P, K, Mg and Ca to increased atmospheric N deposition in *Fagus sylvatica* and *Picea abies*. Not all nutrients need to be in an optimal range, but at least in a physiologically acceptable range (Meller et al. 2019). As a result of these nutrient allocation strategies in the different tree compartments, different amounts of nutrients are removed from the nutrient cycle in the forest depending on the number and completeness of the harvested trees (Rumpf et al., 2018). A recent experimental study by Meller et al. (2019) has shown that the complexity of nutrient allocation may be due to trees trying to optimise leaf biomass based on the available nutrient supply. For P, for example, Netzer et al. (2017) found that adult *Fagus sylvatica* growth rates do not always reflect soil P availability, but that trees adjust their internal P allocation efficiency to low soil P availability (Meller et al. 2019). Nevertheless, little is known about the allocation process and its relationship to soil nutrient availability.

If leaf concentrations are higher, this can lead to a higher nutrient input via the litter layer and influence the nutrient status of the upper soil layer (Hagen-Thorn et al. 2004). In this context, nutrient use efficiency (NUE) is a key concept and is defined by Achat et al. (2018, p. 408, after Bridgham et al. (1995); Paoli et al. (2005)) as "[...] the ratio of net primary production to the quantity of nutrients acquired during the same period." By remobilising nutrients from foliage in senescing or young leaves and needles (Binkley et al. 2004; Fife et al. 2008), plants are able to store nutrients that support faster and better ensured growth at the beginning of the next growing season (Proe et al. 2000; Weatherall et al. 2006; Netzer et al. 2017). When nutrient availability is low, one strategy of plants is to enhance NUE by adapting leaf longevity or leaf nutrient remobilisation (Vitousek 1982; Eckstein et al. 1999), which allows the production of large amounts of biomass on soils with low nutrient availability (Augusto et al. 2000). Increased NUE is thus an adaptation to nutrient-poor soils (Vitousek 1982; Eckstein et al. 1999). Studies have shown that this may be particularly relevant for the nutrients N and P (Reed et al. 2012; Tully et al. 2013; Hayes et al. 2014; See et al. 2015; Tsujii et al. 2017). Little is known about the relationship between nutrient availability and remobilisation for other nutrients (Brant and Chen 2015), but Achat et al. (2018) hypothesise that this relationship also applies for other nutrients.

1.3 Relationship between nutrient concentration in trees, soil and the geological substrate and potentials of stem wood harvesting

The species composition and productivity of forests is influenced by the soil properties (Binkley 1986; Schoenholtz et al. 2000; Abbott and Murphy 2003; Higman et al. 2005; Binkley and Fisher 2019). and the parent material of the soil (Binkley and Fisher 2019). Therefore, these factors can influence the to forest productivity associated potential for forest management. The interaction of nutrient uptake, plant growth, nutrient relocation and loss determines the nutrient concentration in the plant biomass (Hagen-Thorn et al. 2004). However, the loss of nutrients through harvesting and leachate output can lead to nutrient depletion in forest soils (Blanco et al. 2005). Research from fertilization trials showed that in one third of all studies, tree growth was limited by a single nutrient (Binkley and Fisher 2019). Furthermore, fertilisation is not common in forestry, this is why maintaining soil fertility through sustainable thinning and harvesting management is of great importance (Augusto et al. 2000).

The lower the nutrient stocks in the soil, the more severe the consequences of nutrient losses through wood harvesting could be for the maintenance of site potential and nutrient balance and thus for the sustainability of nutrient supply. Therefore, plant-available nutrient stocks in the soil should be used to assess nutrient balance of the forest ecosystem and the intensity of wood harvesting. To meet the demand for energy wood, whole trees are harvested (“whole-tree harvesting”), i.e. the branches are removed in addition to the stem wood from the forest (Block et al. 2016; Zimmermann et al. 2020). Since a large part of the nutrients is stored in the crown, nutrient removal from conventional wood harvesting (stem wood) to whole-tree harvesting increases by a factor of 1.4 to almost 3, depending on the nutrient, tree species and yield class. This means that nutrient export is considerably higher when other tree compartments are exported from the forest in addition to stem wood (Block et al. 2016). Higher nutrient export from the forest due to intensified wood harvesting can have an impact on the forest soil and its fertility, as well as on plant and animal biodiversity (Zimmermann et al. 2020).

If a positive correlation between nutrient concentrations in tree compartments and the underlying geological substrate exists, wood harvesting could be organised more sustainably by extracting only as many trees and tree compartments as necessary to prevent the excessive removal of nutrients from the soils (Hagen-Thorn et al. 2004). A consistent relationship between nutrient concentrations in plant compartments and non-fertilised forest soils is often not observed, but Ca and sometimes Mg and N show consistent patterns (Andersson et al. 1989; Påhlsson 1989).

1.4 Research questions and hypotheses

The relationship between nutrient concentrations in tree compartments and nutrient availability in the soil has been researched in several European countries (e.g. Alriksson and Eriksson 1998). Based on the state of the art described in the previous chapters, it can be stated that the relationship between nutrient concentrations and nutrient availability in the soil is often poorly described (Hagen-Thorn et al. 2004), especially in Switzerland. Globally, little is known particularly about nutrient allocation to individual tree compartments and their relationship to nutrient availability and the geological substrate. The relationships between tree nutrient and growth status, soil resources and plant response to water and nutrient deficiencies are complex, and variations in nutrient status between soil and biomass are difficult to assess because input and output fluxes need to be determined (Calvaruso et al. 2017).

The aim of this Master's thesis is an approach to better understand the relationship between nutrients in tree compartments on the one hand and nutrients in soil and parent material in Swiss forests on the other. With the ambition to replace fossil fuels with renewable energies and to reduce CO_2 emissions, wood is becoming increasingly important as an energy source, which is why sustainable use of forest resources is of great importance. It is therefore expected that the demand for wood in Switzerland will increase due to a higher demand for wood energy. In Switzerland, especially on forest sites in the Central Plateau, where wood harvesting is most intensive, there are soils where weathering and leaching processes are advanced compared to other sites and which are susceptible to nutrient depletion (Zimmermann et al. 2020). Currently, it is not sufficiently known how the allocation to biomass compartments and the nutrient availability in the soil adapts when also nutrient-richer compartments (branches) are removed from the forest. A better understanding of these mechanisms would therefore enable to adapt wood harvesting to the nutrient status of forest soils in Switzerland and to adapt the amount and type of tree compartments according to the sustainability of the forest nutrient cycle. In particular, the influence of site or soil properties can be observed in the tree species *Fagus sylvatica*, which grows on nutrient-rich and on nutrient-poor sites due to its habitat requirements (Jacobsen et al. 2003; Joosten and Schulte 2003; Rumpf et al. 2018).

Parameters such as nutrient concentrations in and allocations to biomass compartments and their relationship to soil and geological conditions are evaluated using data from four sites in Switzerland for *Fagus Sylvatica*. The data from the Waldlabor and Arisdorf sites, which are used to answer the first hypothesis, were collected as part of WSL's Swiss Biomass project. For the second hypothesis, data from another project in which the WSL is involved, the project "Holzernte und Nährstoffnachhaltigkeit in Buchenbeständen” (Wood harvesting and nutrient sustainability in beech stands) (Zimmermann et al. 2020), were added. In a second step, the data from all four sites were integrated into the meta-analysis with data from studies in temperate forests in Europe dating from 1958 – 2019. The following research question and underlying hypotheses frame this thesis:

How can the relationship between macronutrients in soil and tree compartments be characterised based on site geology, and how are nutrients allocated to different tree compartments depending on nutrient availability in the soil?

1. The relative nutrient allocation to the leaves is most sensitive to the nutrient availability in the soil.
2. The allocation of a given nutrient to a particular tree compartment depends on the parent material of the soil.

2. Materials and Methods

2.1 Study sites

The four sites studied (with the short names in brackets) are Waldlabor at Hönggerberg in Zurich (Waldlabor) (canton of Zurich), Arisdorf (Arisdorf) (canton of Basel), Bülacher Hard in Bülach (Bülach) (canton of Zurich) and Irchelplateau in Irchel (Irchel) (canton of Zurich). The study sites are marked in Figure 3. Figure 4 shows the geological substrates and the topography and Table 1 summarises the site characteristics. A more detailed comparison of the site characteristics follows below. The soil descriptions are based on Walthert et al. (2004) and on the soil profile description by (Zimmermann 2021).

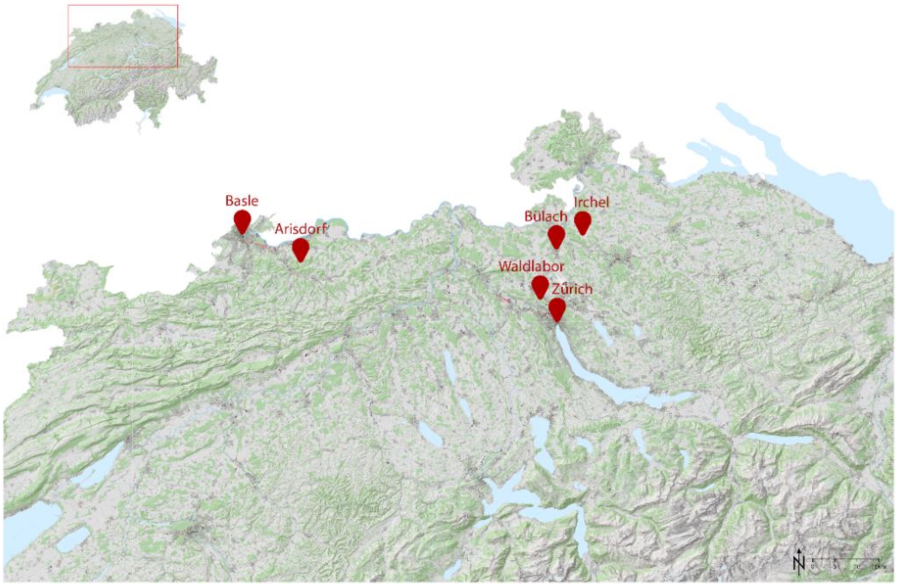

Figure 3: Study sites of this thesis including the cities Basel and Zurich on a map of Switzerland (Swisstopo 2022b).

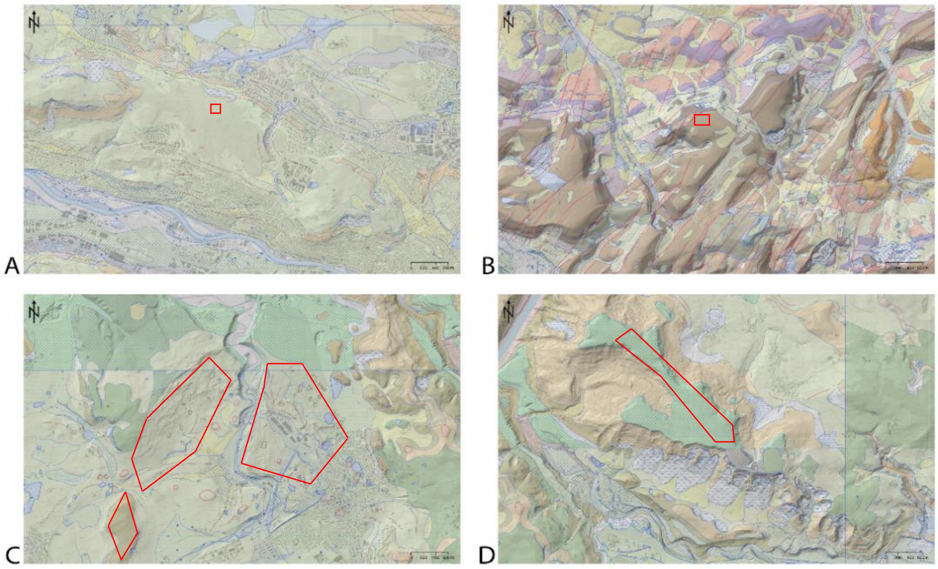

Figure 4: Geological map with underlying topography model of the sites A Waldlabor, B Arisdorf, C Bülach and D Irchel. The red bordered areas mark roughly the area, where the samples were taken. The geology of each site is described in Table 1 (Swisstopo 2022b, 2022a).

Table 1: Study site characterisation with mean values of the soil parameters of the soil profiles at Waldlabor, Arisdorf, Bülach and Irchel, [a] MeteoSchweiz (2022c, 2022b, 2022a), [b] WRB (1998), [c] Pavoni et al. (2015), [d] Pfirter et al. (2019) , [e] Haldimann et al. (2017) . All data, which is not marked with a superscript letter is obtained by the WSL.

	Waldlabor	**Arisdorf**	**Bülach**	**Irchel**
General				
Coordinates	679444.1/ 252523.3	625820/ 261610	NA	NA
Area [m^2]	6466	14591	NA	NA
MAN [mm/a]	800-1100[a]	800-1100[a]	1000[a]	1000[a]
Forest type	Aro-Fagetum	Pulmonario-Fagetum typicum/ Galio odorati-Fagetum	Fagetum	Fagetum
Stand age [yr]	75–95	110–130	70 –90	80–100
Soil and geology				
Soil type	Slightly pseudo-gleyed luvisol[b]	Rendzic Leptosol[b]	Cambisol / Luvisol, more or less pseudo-gleyed[b]	Cambisol / Luvisol, more or less pseudo-gleyed[b]
Geology	Moraine from late Pleistocene (Quaternary: Würm)[c]	Marlstone and Oolitic limestoned of the Hauptrogenstein formation (Jura: Dogger)[d]	Moraine from the late Pleistocene (Quaternary: Würm)[e]	Deckenschotter from the early Pleistocene (Quaternary)[e]
Corg [%]	1.3	7.4	2.9	6.6
C:N	10.9	17.2	13	11.8
pH	6	7.5	4.9	4.2
BS [%]	88.6	99.9	56.4	44.1
CEC [mmol_c/kg]	158.8	300.7	103.4	118.8

In Waldlabor, the soil is classified as slightly acidified. The base saturation is very high and the cation exchange capacity high. The trees still reach the base-saturated subsoil and thus the nutrients they take up in their biomass and release again via the litter, which leads to a neutralisation capacity that, among other things, prevents severe acidification (Zimmermann 2021). In Arisdorf, the soil has a neutral pH value that is quite stable with the depth of the soil profile and is classified as slightly acidified. The base saturation is very high and the cation exchange capacity again is high. The measurements show that the soil in Waldlabor is more acidified and decarbonisation is more advanced than in Arisdorf.

In Bülach, the soil is classified as medium acid. The average base saturation is classified as high. The cation exchange capacity is low to medium. The C:N ratio in the upper horizon is medium close. In Irchel, the pH values of the upper soil horizons are predominantly in acid class 5 (and partly in class 4). Since the majority of the soil (> 50% of the fine soil) is in acid class 4, the soil is classified as strongly acidic. Base saturation is medium to high and the average cation exchange capacity is medium. The C:N ratio is medium. These measurements show that the older soil – Irchel – is more acidified and more nutrients have been leached out than the soil in Bülach. Furthermore, the cation exchange sites in Bülach are more strongly occupied by calcium, whereas in Irchel aluminium is the dominant cation (Zimmermann et al. 2020).

2.2 Sampling

Waldlabor and Arisdorf

The different tree species at each site were studied and *Fagus sylvatica* trees that were close to each other were selected. In Waldlabor, two trees a few meters apart and three trees arranged in a triangle a few meters apart were chosen. In Arisdorf, five trees standing next to each other were sampled.

Around each *Fagus sylvatica* tree, three to six soil samples were taken in November 2020 in a random direction at a distance of 1 m, 3 m, and 5 m from the stem using a Humax corer (tube length 25 cm). In Waldlabor, soil cores were taken at two depths (0 – 25 cm and 25 – 50 cm). In Arisdorf, only soil cores at 0 – 25 cm depth could be sampled due to the shallow soil with stones in the subsoil.

Hemispherical photographs of the crown were taken in September 2020 to determine the leaf area index (LAI). In September 2020, tree climbers sampled the green leaves at three different heights. Two litter traps per site were placed between the *Fagus sylvatica* trees to sample litterfall. These were emptied every two weeks, and the litter was pooled into three sets of samples with three time points (early October, late October, and late November). The sampled litterfall data were attributed to the *Fagus sylvatica* trees next to the litter traps.

Before harvesting, all trees were measured using traditional non-destructive measurement methods such as diameter at breast height (DBH), diameter at 7 m height, tree height and various crown parameters. In addition, all trees were measured with a terrestrial laser scanner (TLS). These measurements on the standing trees were carried out in November and December 2020. During the wood harvest at the sites in December 2020 (Waldlabor) and January 2021 (Arisdorf), 30 selected trees were weighed in the field with a crane scale. Attempts were made to measure the entire crown to determine the fresh weight of the total aboveground woody biomass. Afterwards, the crown was cut off and the stem wood alone was weighted. In addition, the diameter of the lying stems was measured every two metres. This is a so-called section-by-section diameter determination. From the number of measurement sections and the length of the end section, the total length of the stem could be calculated.

Figure 5: Scraping bark of a stem wood (left). Two members of the staff weigh a stem disk in the field. In the car, the already sampled stem disks are visible (right) (Speich 2021).

Bülach and Irchel

In the Bülacher Hard and on the Irchelplateau, four *Fagus sylvatica* trees were sampled at five locations per site in winter 2019/2020 (Figure 6). Each site is assigned a soil profile at a distance of less than 300 m, and where no soil profile was available from previous investigations, a new soil profile was excavated. Thus, an additional soil profile had to be excavated on Irchel, while no additional soil profile was needed on Bülacher Hard. Trees were selected to be distributed throughout the site and to ensure that on Irchel, gravel and on Bülacher Hard, moraine was the underlying substrate.

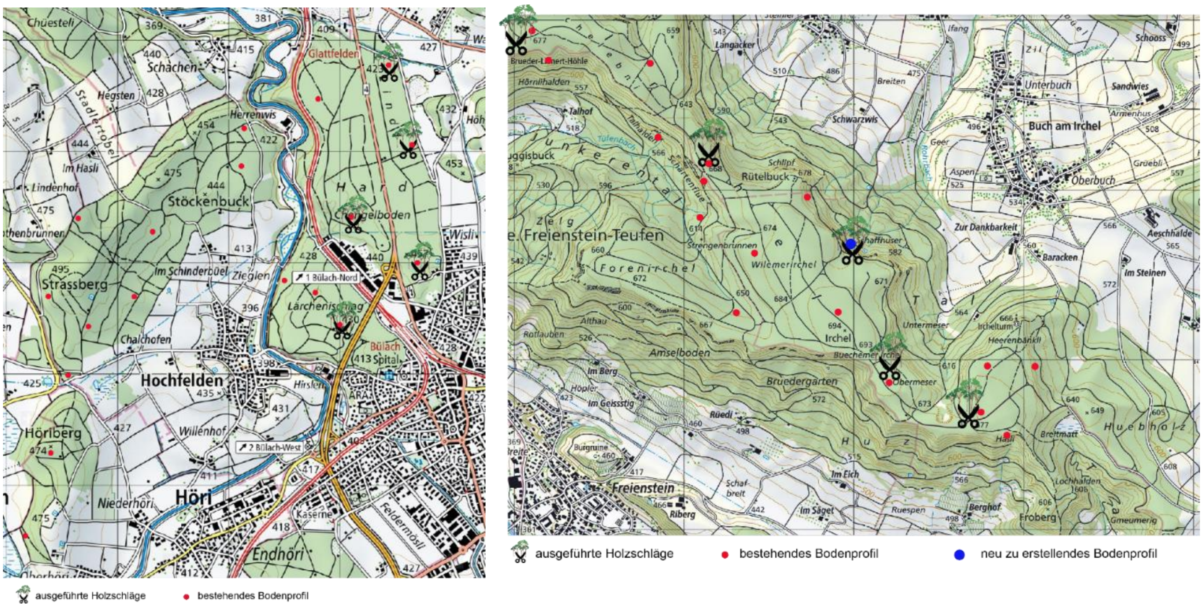

Figure 6: Sampling site Bülacher Hard (left) and sampling site Irchelplateau (right). On the maps, position of cut trees (ausgeführte Holzschläge), existing soil profiles (bestehendes Bodenprofil) and new excavated soil profile (neu zu erstellendes Bodenprofil) are presented (Zimmermann et al. 2020, adapted from swisstopo 2020).

Compartment sampling

Figure 7 is a visualisation of the samples taken in Waldlabor and Arisdorf. At these sites, five disks (diameter >250 mm) were taken from each stem at different heights (but distributed as evenly as possible over the stem). In Bülach and Irchel, three stem compartment classes were sampled: Ø 20 – 70 mm, Ø 120 – 250 mm and >250 mm. In this analysis, these three classes are taken together. Three disks were sampled from each stem (Ø >70 mm), each in the middle of the respective diameter class (e.g. disk 0.07 – 0.12 m: in the middle of the stem section with a minimum diameter of 0.07 m and a maximum diameter of 0.12 m) This was done at all sites in consultation with the forester, as the stem was further processed into wood products after sampling. As a result, some irregular spacing between stem disks resulted. Branches of different diameters were sampled from the lower, middle, and upper parts of the crown, respectively, when possible: fine branches (Ø <5 mm), medium branches (Ø 5 – 20 mm), thick branches (Ø 20 – 70 mm), thin volume (Ø 70 – 120 mm), and medium volume (Ø 120 – 250 mm). In addition, some bark was scraped from each stem in two spots with an axe to obtain a composite sample, taking care not to include any wood from the stem (Figure 5).

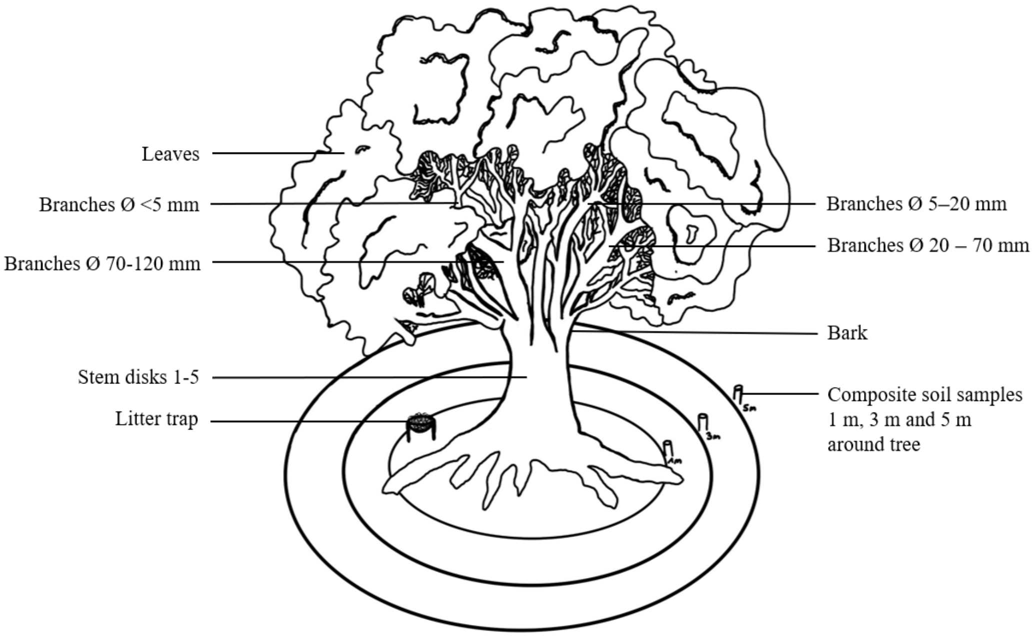

Figure 7: Visualisation of the sampled tree compartments and additional samples at Waldlabor and Arisdorf (Berrocoso 2022).

2.3 Laboratory work

Preprocessing

Waldlabor and Arisdorf

According to the soil samples taken in the field, the described analyses are performed separately for 0 – 25 and 25 – 50 cm. First, the samples were weighed (moist). The fine roots of the tree species *Fagus Sylvatica* were picked out and separated into roots with diameter <2 mm and >2 mm. The roots were washed and then weighed, while the roots of the other tree species were disposed. Subsequently, the roots were dried in an oven at 65 °C and the soil samples at 40 °C. In the next step, the root samples were ground using a ball or disk mill. After drying, the soil samples were weighed again to calculate the water loss and, based on this, the gravimetric water content. The soil sieved to 2 mm was used for further analysis. For the measurement of total C and N, the soil samples were ground using the disk mill.

Of the leaves sampled, 100 whole green leaves were selected, weighed and photographed. Of these 100 leaves, 30 were set aside, weighed and again photographed. The same was done with the remaining 70 leaves, which served as a reserve. The 30 leaves were used to determine the specific leaf area (SLA) by scanning the leaves with an Epson scanner (Epson Perfection V800) and the software Silverfast8 and WINSEEDLE (Version 2006) to measure the area of the 30 leaves. After scanning, all leaves were oven dried at 65 °C and weighed again. The scanning process was repeated for the dried leaves. A proportion of the leaves were then ground using a ball mill (Retsch MM 400) for chemical analysis. The same procedure was used for the leaves from the litter samples.

The branch and bark samples were weighed (moist), dried in the oven at 65 °C and then ground in the ball or disk mill. The stem disks were weighed at WSL and the circumference of the disks and thickness of the bark were measured. Of the large disks, a wedge was cut out and the wedge weighed again. A second wedge was put aside as a reserve. The stem disks and wedges were dried at 60 °C, weighed and ground with the ball or disk mill.

Bülach and Irchel

The bark on the stem samples was cut off. The branch, bark and stem samples were weighed (moist), dried in the oven at 80 °C, weighed again and then ground in the Fritsch Vibrating Cup Mill pulverisette 9.

Laboratory analysis

In the sieved soil samples of Waldlabor and Arisdorf, total C and N were measured using an Elemental Analyzer NC-2500 (CE Instruments). C_{org} was measured after removing carbonate with strong mineral acid (Walthert et al. 2010).

Hydrogencarbonate extractable P ("Olsen P") was determined according to (Kuo 1996). The soil samples were extracted with 0.5 M $NaHCO_3$ in a soil:extractant ratio of 1:60 for 16 hours. Part of the filtered extracts was digested with persulfate dissolved under strongly acidic conditions at 120 °C in an autoclave. Phosphate in the untreated ("inorganic P") and digested ("total P") extracts was analysed colorimetrically using Malachite Green (Ohno and Zibilske 1991). Organic P was defined as the difference between total P and inorganic P.

With the NH_4Cl-extract method, the available cation concentrations of Ca, K and Mg in soil samples of Waldlabor and Arisdorf were determined. To the dried and milled samples, nitric acid and hydrofluoric acid was added. The mixture was digested under pressure and microwave technique in the Ultraclave IV (MLS GmbH). The digestion was done twice for each sample (double determination). The digested solutions were diluted and measured with the ICP–OES Optima 7300 DV (Perkin Elmer). For the steps, certified reference materials and blank samples are included in the analysis.

The grain size distribution was conducted according to the particle-size analysis (PSA) by sedimentation using the pipette method according to Gee and Bauder (1986). The principle of PSA is the destruction or dispersion using chemical, physical, or ultrasonic tools and the separation of the particles into the different size classes sand (<200 – 50 μm), silt (<50 – 2 μm) and clay (<2 μm) by sieving and sedimentation.

The pH was measured potentiometrically in a 1:2 slurry of soil in 0.01 M $CaCl_2$ with using a Metrohm 691 pH meter (electrode: Bioblock scientific).

For all sites, including Bülach and Irchel, ground plant samples were analysed for C and macronutrients (N, P, S, K, Mg, Ca). Total element concentrations in ground plant samples were determined by inductively-coupled-plasma optical-emission-spectrometry of acid digests (ICP-OES Optima 7300 DV, Perkin Elmer).

2.4 Literature review

Since the framework of this master thesis is limited to four sites and there has been little research on this topic in Switzerland, the data analysis is complemented by a literature study. Therefore, tree-level data with macronutrient concentrations in g/kg or mg/g were collected from studies conducted in temperate regions. For the purpose of this thesis, the geological underground had to be indicated in the study. In the collected dataset of the 128 studies are 7 tree species (respectively 8 tree species if black pine and pine are separated) investigated. The tree species are *Abies alba* (fir), *Fagus sylvatica*, *Larix decidua* (larch), *Picea abies*, *Pinus nigra* (black pine), *Pinus sylvestris*, *Pseudotsuga menziesii* (douglas fir) and *Quercus petraea* / *Quercus. robur L.*.

In the appendix (Table A 12), there is a list of all studies included in the analysis with the origin country, tree species studied, geological substrate, attributed geological substrate group and soil type. Most of the data is based on the collection of Jacobsen et al. (2003), a considerable part is from Block et al. (2016). Further sources originate from individual papers and the four sample sites from Switzerland. Some studies are repeated measurements at the same site. Details on the methods can be found in the respective papers. Each study was assigned to a geological substrate group based on the geological substrate group given in the paper or in a few cases found with the coordinates in the geological atlas. Jacobsen et al. (2003) divided some of the studies into three classes: carbonaceous sites, other nutrient-rich sites and nutrient-poor siliceous sites. For studies where assignment to one of the four groups used in this paper was difficult at first glance, the classification of some of the papers in Jacobsen et al. (2003), a look at the site descriptions of the available papers, a geological map or a comparison of the soil of the site provided support for decision-making. The substrate groups were differentiated into carbonaceous and siliceous substrates and further subdivided into consolidated rocks and unconsolidated sediments. The studied were therefore attributed to four different geological substrates: carbonaceous loose (unconsolidated), carbonaceous solidified (consolidated), siliceous loose (unconsolidated) and siliceous solidified (consolidated). In unconsolidated sediments, percolation (including nutrients) occurs depending on the grain size, while in consolidated rocks percolation occurs along fractures. In carbonaceous rocks and sediments, the chalk buffer and the associated nutrient availability is relevant for the nutrient supply of trees. However, nutrient availability is associated with weathering of the carbonaceous rock, which releases Ca. Subsequently, soils with a loose carbonaceous substrate are excellent arable soils, for example (Wiesenberg 2022).

For the studies for which values of twigs and branches were available, a mean value was calculated. For some of the studies, only values for branches were available. For some of the studies, values for stem wood including bark were available, but these were not used as the nutrient concentrations in stem wood and bark are analysed separately. For some of the tree species of Block et al. (2016), data were available for heartwood and sapwood. Again, the mean value of these different sub-compartments was used. Similarly, for the pine trees, a mean value was also calculated, as data for bark and mirroring bark were available in Block et al. (2016). If data on wood and bark was available for the stem and crown, only the data for the stem was used for the nutrient concentrations in stem and bark.

2.5 Calculations of biomass of the compartments, nutrient allocation and nutrient remobilization rates

The calculation of the biomass of the individual tree compartments, in order to subsequently calculate the allocation of nutrients to the compartments, was done using simple mathematical equations, which are presented below (equations 1 – 6). In addition, the calculation of the remobilisation rate by nutrient is presented (equation 7). Details on the calculations and the calculations of the soil properties can be found in the appendix (see chapter 6.1).

Total biomass of individual compartments

$$Total\ leaf\ biomass\ [kg] = \frac{\frac{TLA\ [m^2] \times 100}{\overline{SLA}\ [dm^2 / DW]\ (top, middle, bottom)}}{1000} \tag{1}$$

$$\begin{gathered} Total\ branch\ Ø < 70\ mm\ biomass\ [kg] = \\ WW\ branches\ Ø < 70\ mm\ [kg] \times (\overline{DW}\ branches\ [g/g]\ (Ø < 5mm;\ Ø\ 5-20\ mm;\ Ø\ 20-70\ mm)) \end{gathered} \tag{2}$$

$$\begin{gathered} Total\ bark\ biomass\ [kg] = \\ \sum |i\ \left((V\ bark / \ stem\ segment)\ \left[m^3\right] \times \overline{\rho}\ bark\ \left[g/cm^3\right] \times 1000\right) \end{gathered} \tag{3}$$

ρ represents the mean density of bark in *Fagus sylvatica* from Petráš et al. (2020)

$$\begin{gathered} Total\ stem\ wood\ biomass\ [kg] = \\ WW\ stem\ wood\ [kg] * (\overline{DW}\ [g/g]\ stem\ disk) \end{gathered} \tag{4}$$

For the fine roots, the mean characteristics from 0 – 25 cm and 25 – 50 cm are used.

$$Total\ fine\ root\ biomass\ [kg] = crown\ area\ \left[m^2\right] \times f \times root\ \rho\ \left[mg/cm^3\right] \tag{5}$$

$f = 0.25$ represents a fraction of the crown projection to estimate the horizontal fine root biomass extent.

Nutrient allocation

The amount of a nutrient allocated to a particular plant compartment was calculated according to the formula of Meller et al. (2019):

$$Nutrient\ allocation\ [\%] = \frac{Mass\ fraction\ of\ nutrient\ in\ plant\ compartment\ [g]}{Mass\ fraction\ of\ nutrient\ in\ total\ plant\ [g]}$$

6)

Nutrient remobilisation rate

The remobilisation rate of the foliage for the three time points was calculated with the formula by Achat et al. (2018):

$$Remobilization\ rate\ [\%] = \frac{((Nutrient)_{Fol} - MLCF \times (Nutrient)_{Lit}) \times 100}{(Nutrient)_{Fol}} \tag{7}$$

The MLCF is the mass loss factor that takes into account the mass loss during senescence in woody deciduous trees (Vergutz et al. 2012). A separate MLCF was calculated for each sampling date, 30.10.20 and 23./24.11.20. However, for the sampling date 09.10.20, the MLCF value of 30.10.20 had to be used because SLA data were not plausible. ($Nutrient_{Fol}$) represents the nutrient concentration in the foliage in g/kg and ($Nutrient_{Lit}$) the nutrient concentration in the litter in mg/g.

2.6 Statistical analysis

The statistical analysis as well as the data visualisation were carried out with Rstudio (Version 2022.07.1) (R Core Team 2022). The packages used for the analysis are indicated in italics in brackets.

To answer the hypothesis 1, Welch Two Sample t-tests (*stats*) were performed to evaluate whether the mean values of the nutrient concentrations in the tree compartments differ significantly and thus as a support to answer hypothesis 1. To check the prerequisites for the t-test, a Shapiro-Wilk test (*stats*) was performed to test the data for normal distribution and a Levene's test for equal variances (*car*) to check whether the variances are equal. If no normal distribution was given for a variable, a Tukey transformation (*rcompanion*) was used, which finds the best fit to a normal distribution based on the lambda value. If no normal distribution or homoscedasticity was achieved with a transformation, a non-parametric test, the pairwise Wilcoxon test (*stats*), was used.

For the second hypothesis, the data were treated in the same way as the data for the first hypothesis in order to test whether the two sites Bülach and Irchel have significantly different nutrient concentrations. In a second step, an analysis of variance (ANOVA) was performed to test whether the nutrient concentrations differed significantly between the four substrate groups. If the ANOVA indicated significant differences, a post-hoc test, Tukey Honest Significant Differences (Tukey's HSD) (*stats*), was performed to assess which groups were significantly different from each other. To check the prerequisites for the ANOVA, the residuals of the model were tested with a Shapiro-Wilk test and visually with a qqplot for normal distribution (*ggpubr*). The data was also tested for equal variances using Levene's test. Outliers were identified to assess whether the groups (classification) formed might be appropriate. For data from variables where a normal distribution or equal variances could not be obtained with the Tukey transformation, a Kruskal-Wallis test (*stats*) was performed. If the test was significant, a pairwise Wilcoxon test (*stats*) was performed to test which pairs of groups had significant differences. The Eta Squared test was used to assess how much variance is connected to the main effect in the ANOVA model (*lsr*) or Krukal Wallis test (*rstatix*).

3. Results

3.1 Nutrient concentrations and ratios in tree compartments

3.1.1 Waldlabor and Arisdorf

3.1.1.1 Nutrient concentrations in tree compartments

The boxplots in Figure 8 show the nutrient concentrations in the tree compartments by study site, and the t-test results are shown in Table 2. A significant test result by site was found for Ca, Mg and P in leaves and needles. For the nutrient concentration in the branches, the results showed significant differences for most nutrients: Ca, Mg, P and S. When looking at the differences by site and nutrient in the bark compartment, it was found that the differences were significant for the concentrations of N, Ca, Mg and P. In the case of Ca in bark, the variability in the data from Arisdorf is considerably higher than in Waldlabor. No significant difference was found between the sites for most nutrients in the stem, except for K. The high heterogeneity of the data from Waldlabor for N and Ca concentration in the stem is particular. For the nutrient concentrations in the fine roots, the t-test revealed a significant difference by site for Mg, K and P and a trend for Ca.

Table 2: T-test results per nutrient of the tree compartments at Waldlabor and Arisdorf. P-value <0.05 indicates a significant difference.

Nutrient	Plant tissue				
	Leaves	Branches	Bark	Stem	Fine roots
			p-value		
N	0.248	0.086	0.015	0.154	0.731
P	0.006	0.017	0.04	0.124	0.009
S	0.583	0.001	0.35	0.601	0.825
K	0.945	0.3	0.333	0.041	< 0.001
Mg	0.004	< 0.001	0.042	0.836	< 0.001
Ca	< 0.001	< 0.001	< 0.001	0.06	0.060

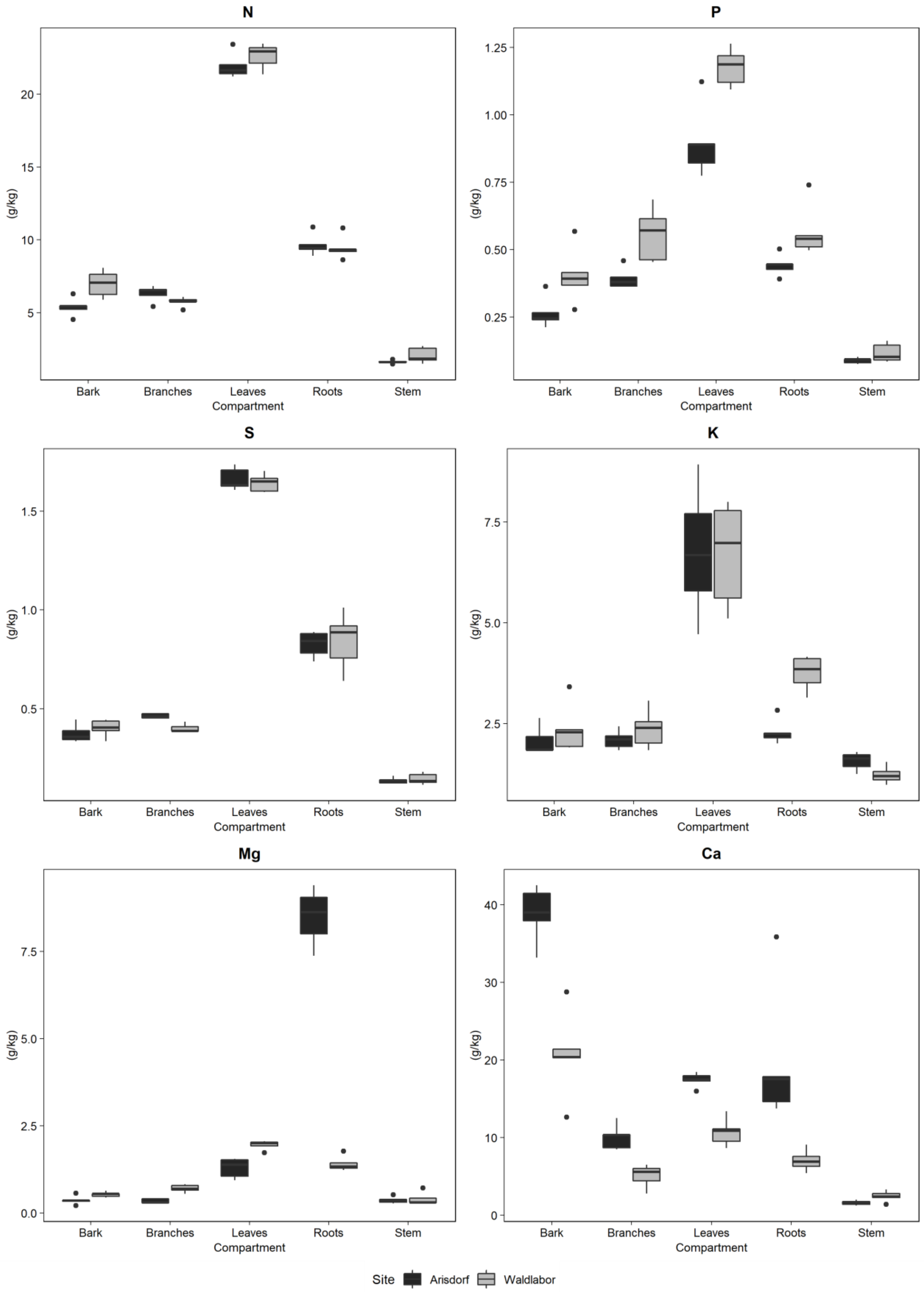

Figure 8: Boxplots with mean nutrient concentrations [mg/kg] of Fagus sylvatica including standard deviation of biomass compartments at Waldlabor and Arisdorf.

3.1.1.2 Nutrient ratios in leaves

The nutrient ratios N:X are presented in Table 3. There is a difference between Waldlabor and Arisdorf for N:P, N:Mg and N:Ca and no difference by site for N:K.

Table 3: Mean ratios of N and Ca, N and K and N and Mg in leaf biomass at Waldlabor and Arisdorf.

Mean ratio	**N:P**	**N:Ca**	**N:K**	**N:Mg**
Waldlabor	19.3	2.2	3.5	11.6
Arisdorf	24.6	1.3	3.4	17.6

3.1.2 Bülach und Irchel

In Figure 9, the mean nutrient concentrations of the different compartments at Bülach and Irchel are visualised. The p-values of the t-tests are given in Table 4. The test results show significant differences in the K concentrations in the bark. For the branches with a diameter of <5 mm, significant differences were found between the sites for the P concentration. A trend was found for P in the branches with a diameter of 5 – 20 mm. For Ca in the bark, considerable heterogeneity was present at both sites.

Table 4: T-test results per nutrient of the tree compartments at Bülach and Irchel. P-value <0.05 indicates a significant difference.

Nutrient	Plant tissue				
	Branches			Bark	Stem
	Ø < 5 mm	Ø 5-20 mm	Ø 20-70 mm		Ø 70- > 250 mm
	p-value				
N	0.384	0.862	0.629	0.493	0.688
P	0.001	0.062	0.012	0.019	0.123
S	0.689	0.59	0.44	0.126	0.1
K	0.727	0.801	0.027	0.01	0.255
Mg	0.08	0.704	0.551	0.317	0.451
Ca	0.695	0.552	0.636	0.85	0.806

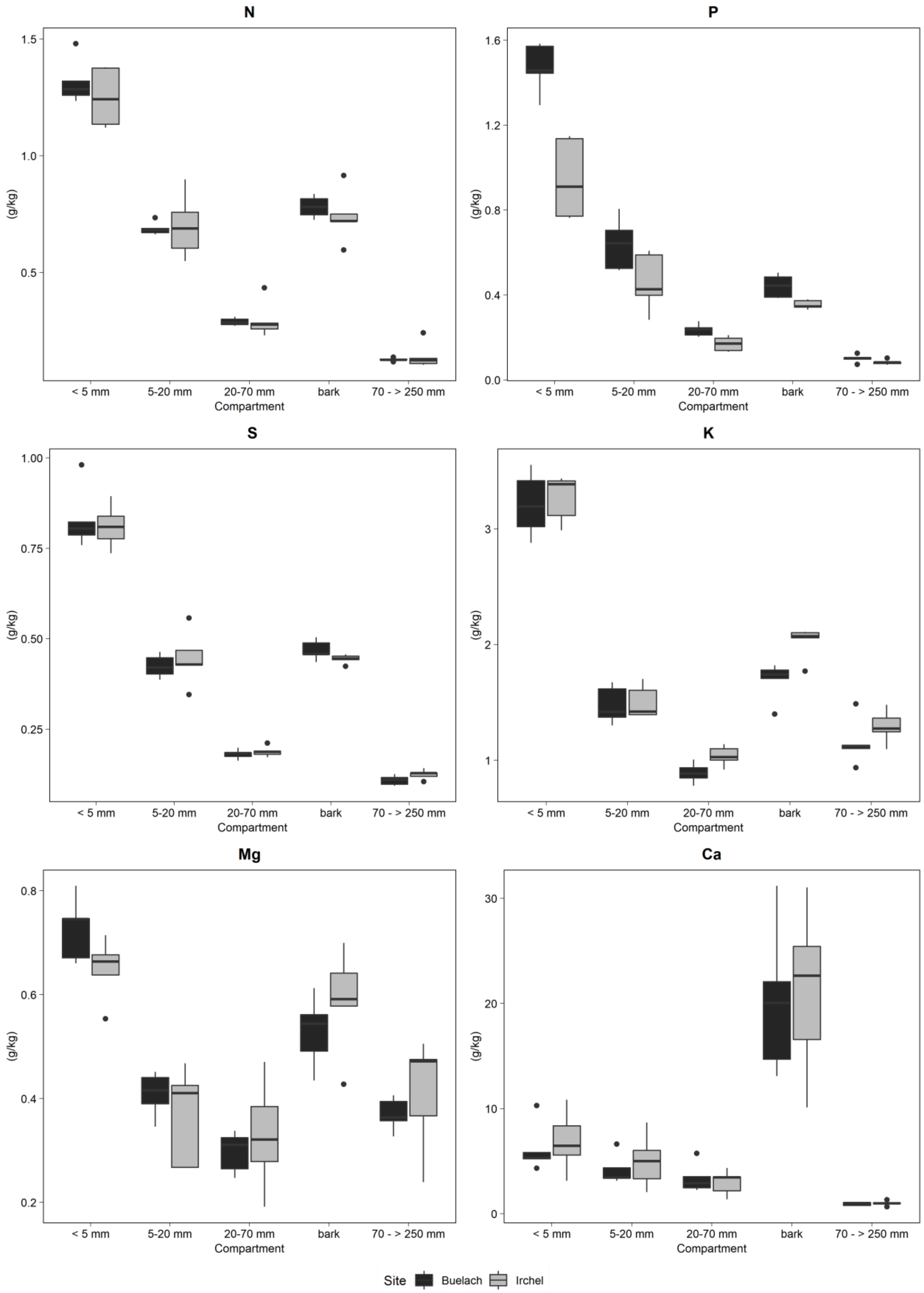

Figure 9: Boxplots with mean nutrient concentrations [mg/kg] of Fagus sylvatica including standard deviation of biomass compartments at Waldlabor and Arisdorf.

3.2 Nutrient remobilisation rates in the leaves at Waldlabor and Arisdorf

Remobilisation rates are presented by site and nutrient for three time points in October and November 2020 (Figure 10). For the remobilisation rates of N, K, P and S an increasing trend over time can be observed, while for Ca, a decreasing trend over time can be observed. For Ca, the standard deviation of the remobilisation rates is particularly large (-50 – 40 %). For Mg, no trend can be distinguished and the standard deviation is high.

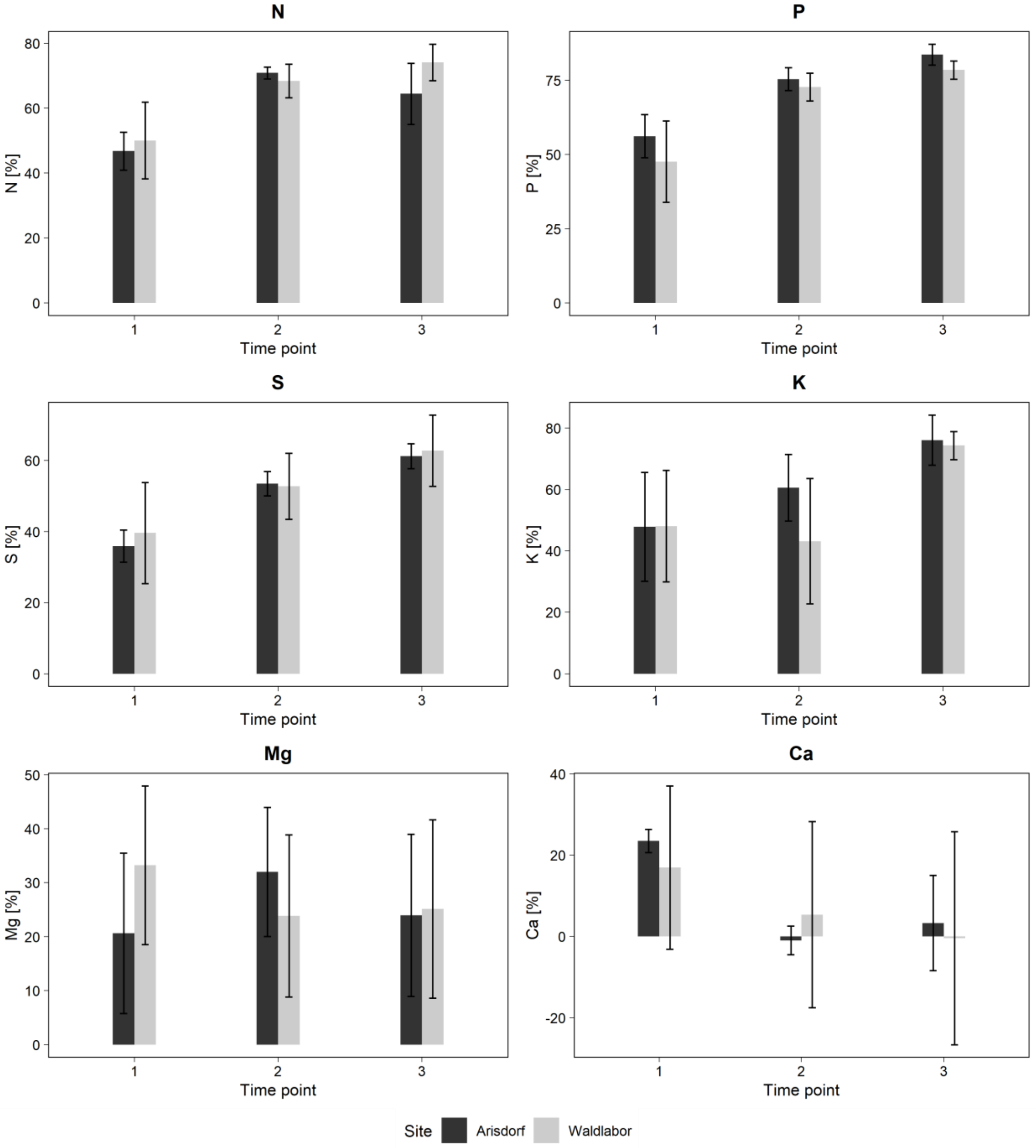

Figure 10: Mean nutrient remobilisation [%] including standard deviation in foliage of Fagus sylvatica at three time points at the sites Waldlabor and Arisdorf. The time points are 1 = 09.10.2020, 2 = 30.10.2020, 3 = 23.11.2020 (WL) / 24.11.2020 (AD).

3.3 Nutrient allocation to tree compartments at Waldlabor and Arisdorf

Overall, the following allocation pattern results for all nutrients (rough estimates are given in brackets): The stem accounts for most of the total (ca. 60 – 80 %), followed by the branches (ca. 20 – 30 %), leaves (ca. 3 – 6 %) and fine roots (ca. 1 – 3 %) and finally bark (ca. 0.1 – 1 %). The allocation patterns is shown in Figure 11.

For Ca, more is allocated to the branches, leaves and roots in Arisdorf, while more Ca is allocated to the bark and stem in Waldlabor. Comparing the allocation of K and Mg to the compartments of the sites, more K and Mg is allocated to the stem in Waldlabor, while less K and Mg is supplied to the branches. A greater proportion of the total P is allocated to the leaves, fine roots and branches in Arisdorf. In Waldlabor, on the other hand, more P is allocated to the stem and slightly more to the bark.

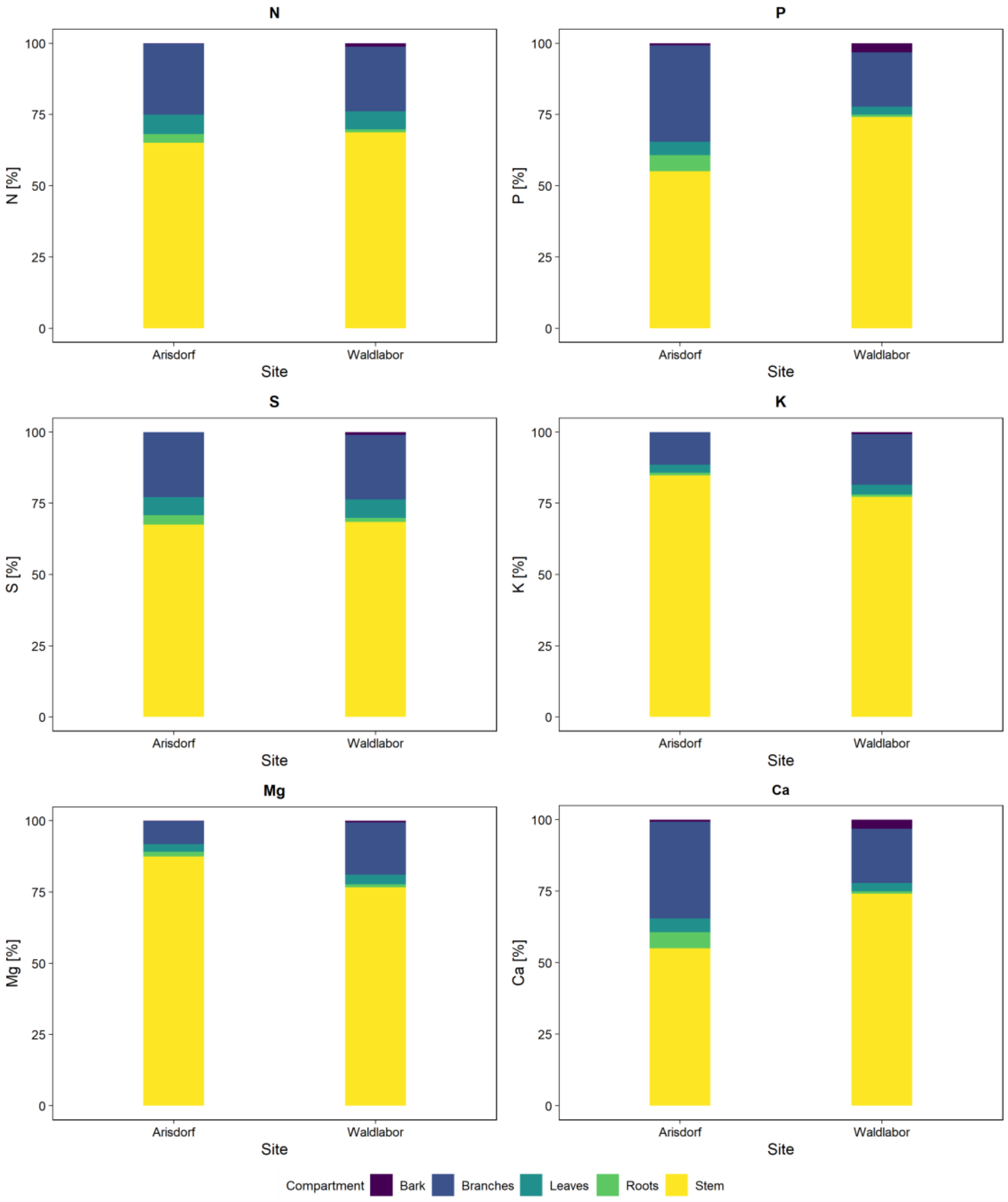

Figure 11: Mean nutrient allocation [%] to tree compartments of Fagus sylvatica at Waldlabor and Arisdorf.

3.4 Soil properties at Waldlabor and Arisdorf

In Table 5, the mean values including standard deviation of the pH, organic C content, the C:N ratio, the cation exchange capacity (CEC), the base saturation (BS) and the nutrient stocks of Ca, Mg and K in the soil are presented per site and depth.

In Figure 12, the nutrient concentrations in the soil including standard deviation at Waldlabor and Arisdorf are presented. The total N, total P, inorganic P, available K and available Ca concentrations are significantly different by site with the same tendency of Waldlabor showing lower concentrations for these nutrients than Arisdorf. The available Mg concentration by site is significantly different with Waldlabor showing higher concentration than in Arisdorf.

Table 5: Mean values of pH, C_{org} [%], C:N, CEC [$mmol_c$/kg], BS [%] and Ca, Mg and K stocks [kg/ha] including standard variation around Fagus sylvatica at Waldlabor and Arisdorf. Stocks of Ca, Mg and K refer to a soil depth of 50 cm.

Site	Soil depth [cm]	pH $CaCl_2$	C_{org} [%]	C:N	CEC [$mmol_c$/kg]	BS [%]
Waldlabor	0–25	4.6 ± 0.2	2.3 ± 0.2	11.8 ± 0.6	87.9 ± 14.8	88.3 ± 4.4
	25–50	5.1 ± 0.4	0.8 ± 0.05		115 ± 17.2	93 ± 3.8
Arisdorf	0–25	6.9 ± 0.1	7.74 ± 1.65	14.4 ± 0.3	411 ± 20.6	100 ± 0.02
	25–50	NA	NA		NA	NA

Site	Soil depth [cm]	Ca [kg/ha]	Mg [kg/ha]	K [kg/ha]
Waldlabor	0–25	4026 ± 715.8	727 ± 117.8	202.2 ± 18.2
	25–50			
Arisdorf	0–25	2442.5 ± 594.5	28.6 ± 8.2	38.9 ± 11.3
	25–50			

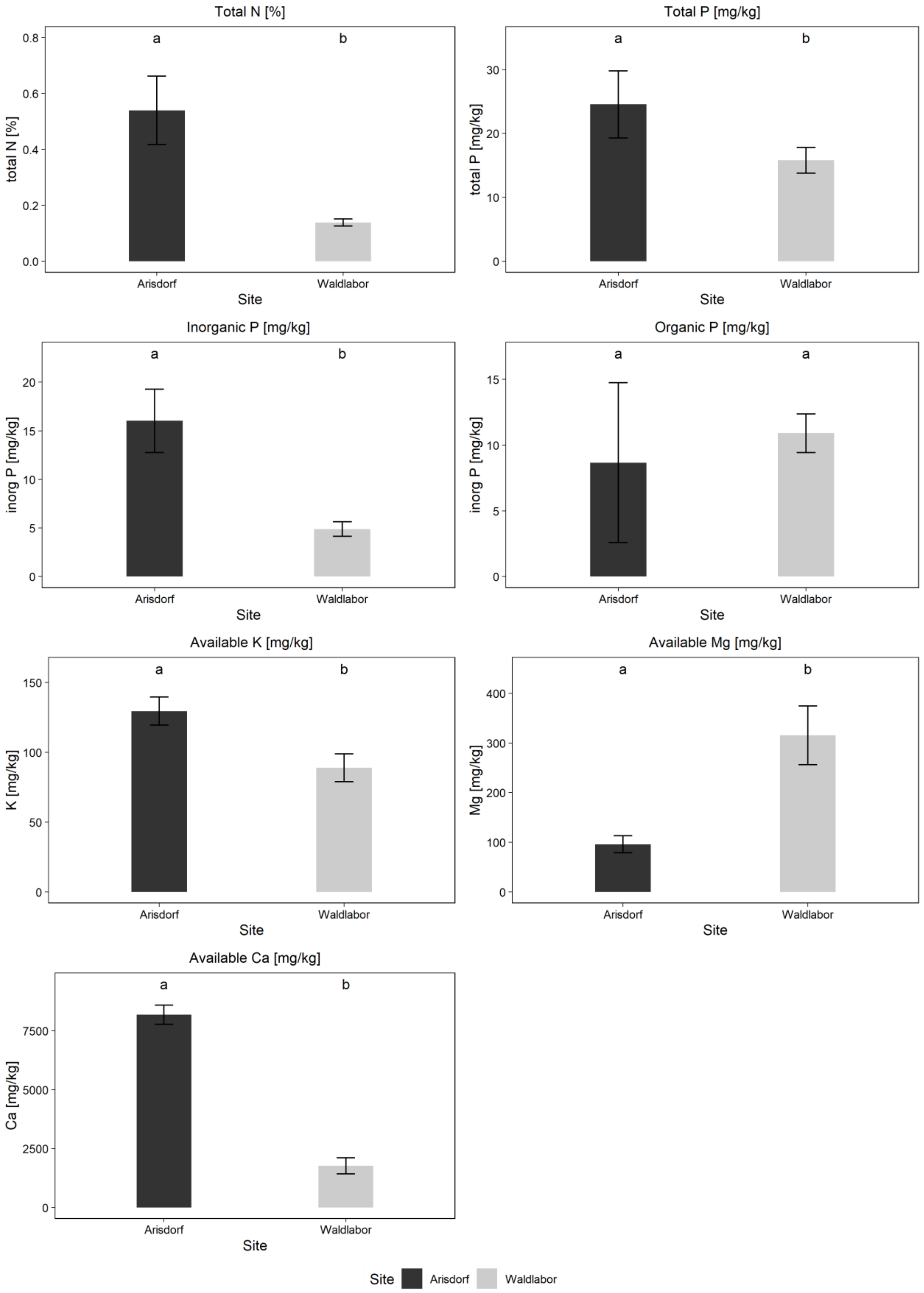

Figure 12: Mean nutrient concentrations [% or mg/kg] in the soil around Fagus sylvatica including standard variation at Waldlabor and Arisdorf.

3.5 Analysis of variance of nutrient concentrations in tree compartments and relationship to geological substrate in temperate climates

In this section, the results of the ANOVA and the Kruskal-Wallis test are presented along with the post-hoc Tukey HSD and Wilcoxon results represented by letters. The nutrient concentrations by geological substrate group are shown in Figure 13-16.

The mean Ca concentrations by geological substate group in leaves and needles is significantly different. Group-specifically, the substrates in carbonaceous solidified was significantly different from the other substrate groups. The Kruskal-Wallis test revealed significant differences in Mg concentrations in leaves and needles. The difference was found between the same groups as for Ca, however there are some extreme outliers in the carbonaceous consolidation group that probably influenced the test result. This might be reflected in the Eta square which indicates a moderate effect size. For P in leaves and needles, the result is significant over all geological substrate groups, however not between individual substrate groups.

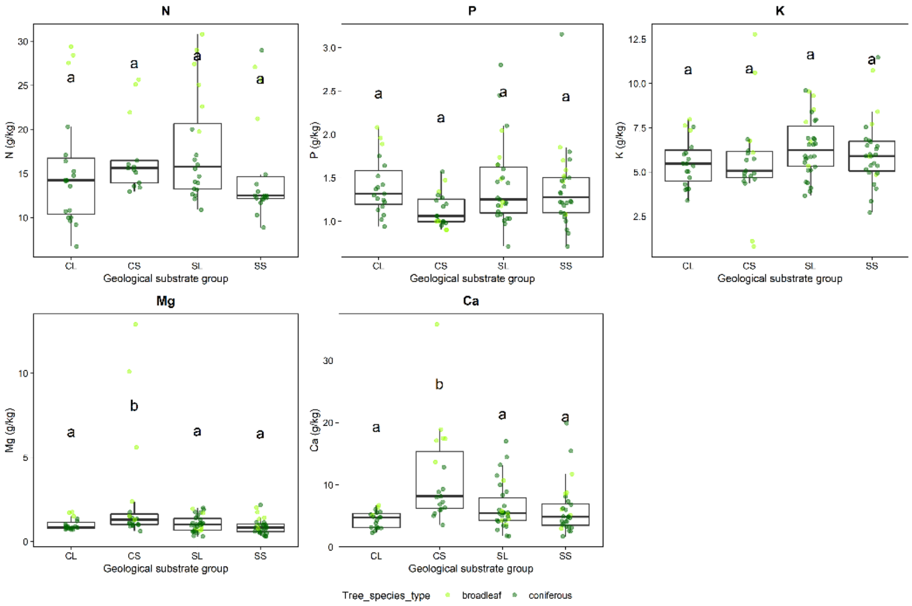

Figure 13: Boxplots with nutrient concentrations [g/kg] in leaves and needles by geological substrate. The geological substrate groups are CL = carbonaceous loose, CS = carbonaceous solidified, SL = siliceous loose, SS = siliceous solidified. Light green = broadleaf, dark green = coniferous.

The test results showed significant differences in Ca and K concentrations in the branches by geological substrate group. Ca showed in the group carbonaceous solidified significant differences to all other groups and in the group siliceous loose to all other groups. Eta square for Ca in the branches indicated a medium effect size. For K, the substrate groups carbonaceous solidified and siliceous solidified showed significant differences to each group. Significant differences were revealed for P in the branches. There, the carbonaceous loose group showed significantly different concentrations to all other groups and the same is the case for siliceous loose. As for Ca, the effect size is medium.

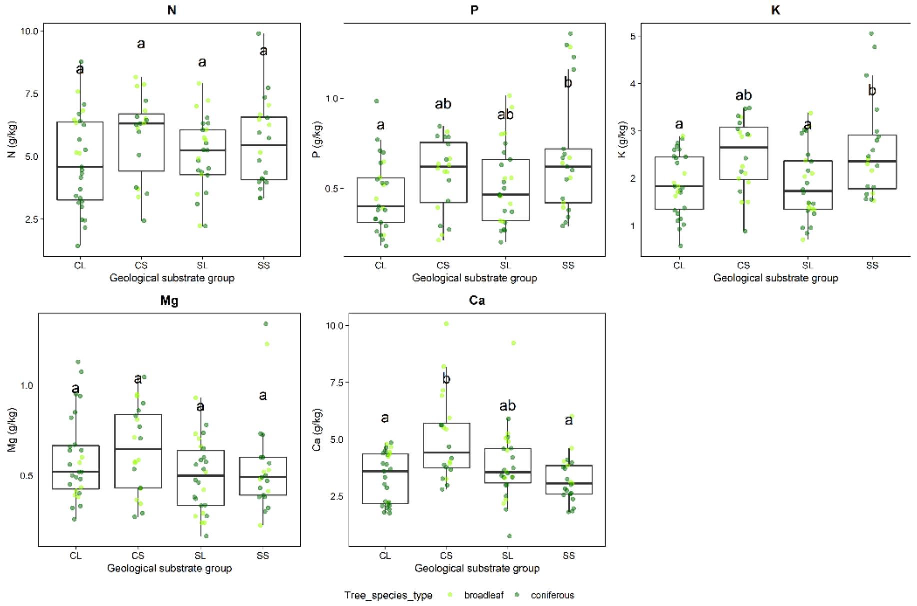

Figure 14: Boxplots with nutrient concentrations [g/kg] in branches by geological substrate. The geological substrate groups are CL = carbonaceous loose, CS = carbonaceous solidified, SL = siliceous loose, SS = siliceous solidified. Light green = broadleaf, dark green = coniferous.

The ANOVA revealed significant differences in N, K, Mg and P concentrations in bark. For all these nutrients, the differences occurred in the same group combinations: the substrate group carbonaceous differed from the other groups. For Mg and P, the effect size is medium. The Kruskal-Wallis test showed significant differences in Ca concentrations in the bark by geological substrate group. The tests revealed that the carbonaceous solidified and siliceous loose groups were affected. However, the Eta square indicates a small effect size.

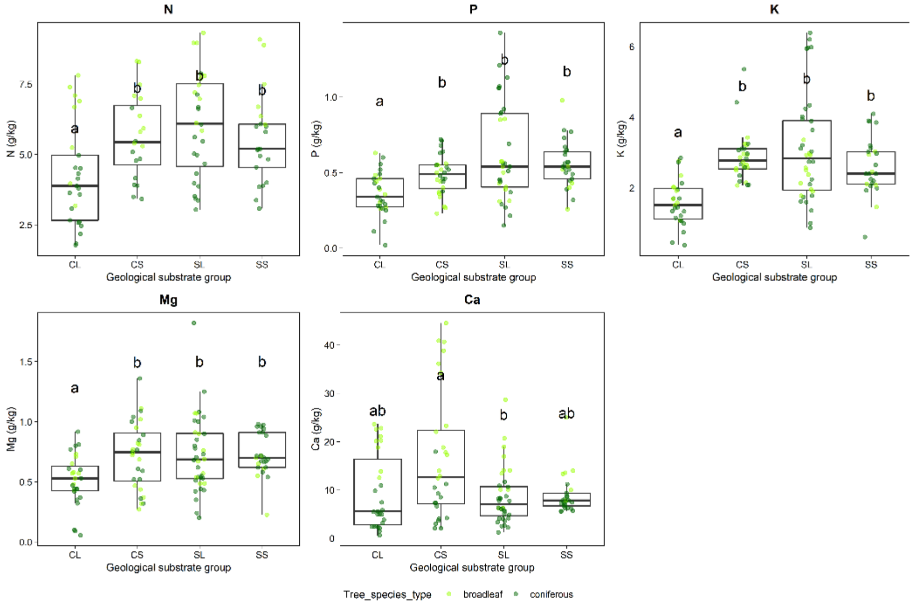

Figure 15: Boxplots with nutrient concentrations [g/kg] in bark by geological substrate. The geological substrate groups are CL = carbonaceous loose, CS = carbonaceous solidified, SL = siliceous loose, SS = siliceous solidified. Light green = broadleaf, dark green = coniferous.

Finally, a statistical difference was found for P in the stem. The siliceous loose and solidified groups were each different from all other substrates. The Eta square indicated a medium effect size for all nutrients.

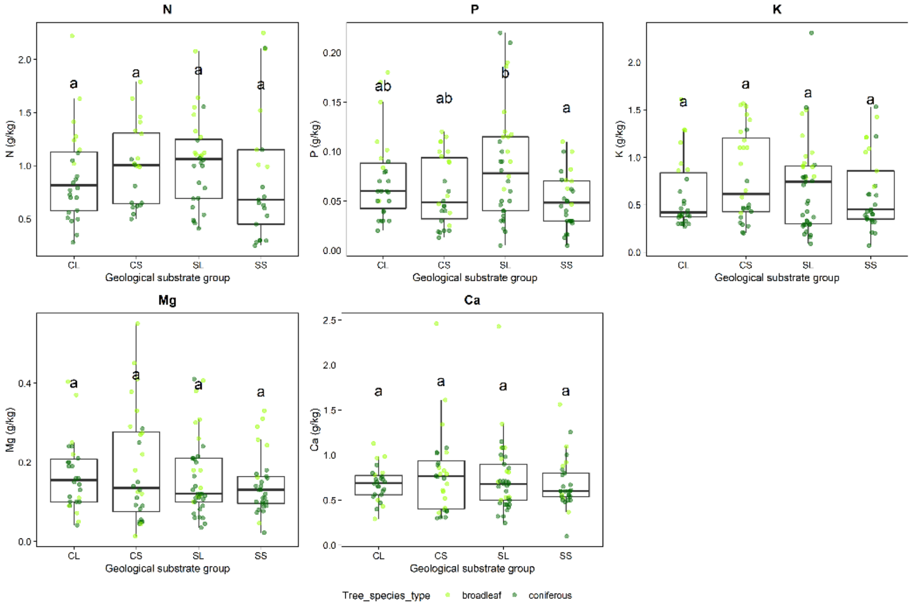

Figure 16: Boxplots with nutrient concentrations [g/kg] in stem by geological substrate. The geological substrate groups are CL = carbonaceous loose, CS = carbonaceous solidified, SL = siliceous loose, SS = siliceous solidified. Light green = broadleaf, dark green = coniferous.

4. Discussion

4.1 Nutrient allocation, concentration and (re)mobilisation with a focus on the leaves

Overall, the visual assessment of the plots considering the nutrient allocation and their relationship to the nutrient availability in the soil revealed a weak relationship between them. However, together with the evaluation of the t-test it seems that the allocation and nutrient concentrations in the tree compartments found for Ca and P show a similar tendency in relation to soil availability. For N, K and S, no or no clear tendency in allocation in relation to the nutrient availability in the soil can be found. For Mg, a weak tendency might be discernible.

The results from Waldlabor and Arisdorf are compared with the normal ranges for the evaluation of nutritional status determined by Mellert and Göttlein (2012) in a literature study (Table 6). Overall, the nutrient concentrations in the leaves at both sites are at least in the normal range, with the exception of P. For P, the concentration in Waldlabor is in the latent range and in Arisdorf even in the extreme deficiency range. In comparison to the values of leaf concentrations from other studies in temperate climates, which were examined in the ANOVA of this thesis (Figures A 1–4), leaf P is in the lower range. This finding might be in line with the results of Braun et al. (2020), who found decreasing leaf P concentrations for *Fagus Sylvatica* in Switzerland over the last decades. The K concentrations for Waldlabor and Arisdorf are also in the lower range according to Mellert and Göttlein (2012). It is remarkable that the Ca values in Arisdorf are above the suggested upper luxury limit. The Mg concentrations are in the lower normal range in Arisdorf and in the upper normal range in the forest laboratory. The leaf S concentrations are at the lower limit of the normal range.

Table 6: Nutrient ranges [g/kg] after Mellert and Göttlein (2012) from van den Burg's literature compilation (1985, 1990) with in the according range classified means of Waldlabor (WL: blue) and Arisdorf (AD: orange) for leaves in Fagus sylvatica. Ranges indicate nutrient surplus, normal range and deficiency. The table is supplemented by the normal ranges of S from Göttlein (2015).

European beech (*Fagus sylvatica*)—Critical foliar concentrations in g/kg

	Deficiency			Normal range			Surplus	
	Extreme	Deficiency	Latent	Lower	Central	Upper	Luxury	Extreme
N	< 17.0	< 18.5	18.5–18.7	18.7–20.0	20.0–22.3 AD	22.3–23.2 WL	23.2–27.5	> 27.5
P	AD	< 1.07	1.1–1.2 WL	1.2–1.4	1.4–1.9	1.7–1.9	1.9–2.0	> 2.0
S		1.35–1.5		1.5–2.25 WL, AD		> 2.25		
K	< 4.9	< 3.2	3.2–6.1	6.1–7.0 WL, AD	7.9–8.8	8.8–9.7	9.7–13.0	> 13.0
Ca			< 6.7	6.7–8.2	8.2–11.8 WL	11.8–14.0	> 14.0 AD	
Mg	< 0.7		< 1.1	1.1–1.3 AD	1.3–1.9	1.8–2.3 WL	> 2.3	

Some of the findings on the significant differences between the geological substrates in leaf concentrations from Waldlabor and Arisdorf were similar to the significant differences between the geological substrate groups in leaf and needle concentrations from studies in temperate climates examined in the ANOVA. This concerns the significant differences in leaf concentrations between groups found for Ca, Mg and P. The significant difference for P in leaves and needles in the ANOVA results is probably influenced by the lower concentrations of leaves and needles in the solidified carbonate group. Sites with high Ca concentrations in all compartments, such as Waldlabor and Arisdorf, as well as the carbonaceous solidified group from the ANOVA have lower foliar P concentrations compared to other studies with deciduous tree species. As the Eta-square test result following the ANOVA (see chapter 3.5) suggests, the significant difference of the carbonaceous consolidated group to the other groups for Mg concentrations in leaves and needles should be approach with caution, as it might be caused by the extreme outliers in the carbonaceous consolidated substrate group. In general, the results for leaves and needles from the ANOVA by substrate group should be considered with caution, as they are not differentiated by tree species, although it is known that leaf and needle concentrations can differ considerably between species, especially between coniferous and deciduous tree species (Mellert and Göttlein 2012).

Compared to the nutrient ratios compiled by Flückiger and Braun (2003), it is noticeable that the N:P ratios of the leaves from Waldlabor and Arisdorf are far above the recommended range of 7 – 12, which supports the observation that the P concentration is at the critical limit. Mellert and Göttlein (2012) and Augusto et al. (2017) presented a different range. Nevertheless, all the N:P ranges of these sources imply that N:P is unbalanced at Waldlabor and Arisdorf. For the other ratios, N:K and N:Mg, the values found in Waldlabor and Arisdorf are within the recommended range of Flückiger and Braun (2003), although N:K is at the upper limit according to Mellert and Göttlein (2012).

The pH, CEC, BS, C:N and nutrient stocks in Arisdorf were compared to the values from the soil profiles in the region of Jura in Switzerland assessed by Walthert et al. (2004). For Waldlabor, these parameters were assessed compared to the soil profiles in the Central Plateau and Prealpes by Zimmermann et al. (2006). The pH in the upper soil horizon at both sites is at Waldlabor estimated as moderately acidic and might be therefore sensitive to further pH decrease. At Arisdorf, the pH is high, which is as expected as the soil contains carbonates up to the surface. This soil is less susceptible to a pH decrease. The CEC in Waldlabor is classified in the upper horizon as low and in the lower horizon as moderate which corresponds to other soil profiles at the Central Plateau and Prealpes investigated by Zimmermann et al. (2006). In Arisdorf, the CEC and BS are very high. The high BS at Waldlabor suggests analogue to the soil profile description of Waldlabor in chapter 2.1 that nutrient supply is still ensured. The C:N ratio at Waldlabor is close and in Arisdorf moderately close. The nutrient stocks in Walthert et al. (2004) and Zimmermann et al. (2006) refer to a soil depth of 60 cm, however, it can be assumed that the bulk density in a depth of 50 cm in Waldlabor and Arisdorf is approximately the same as in a depth of 60 cm. The stocks for Ca, Mg and K are higher in Waldlabor than in Arisdorf. In Arisdorf, especially the K stock is very low. The lower nutrient stocks could be related to the root penetration depth and to the higher proportion of the soil skeleton. Also in Waldlabor, the K stock is low. There, the Mg stock in turn is classified as moderately high. The Ca stock is at both sites moderately high to high, which could entail a strong occupancy of the cation exchange sites by Ca cations at expanse of the Mg and K cations (Walthert et al. 2004). It should be noted that especially at Arisdorf, the stock calculations are an approximation, since the bulk density and the nutrient concentrations for the subsoil had to be estimated (see chapter 6.1). Overall, it seems that at both sites, K and in Arisdorf also Mg availability could be limited, as Ca cations are dominating. Lastly, a comparison with a soil index established for American forests soils by Amacher et al. (2007) suggests that total plant available P concentration is at both sites moderate.

Foliar nutrient concentrations depend not only on soil nutrient availability, but also on leaf age and development, location within the canopy, tree age and competition, and precipitation variability (Binkley and Fisher 2019). In the case of nitrogen, foliar N concentration is expected to be related to atmospheric deposition rather than soil chemistry (Braun et al. 2020). As Waldlabor is located in the agglomeration of Zurich and close to the city itself, which has much more traffic than Arisdorf, N deposition in Waldlabor is expected to be higher than in Arisdorf. For Mg and Ca, leaf concentration could be related to soil Ca and Mg pools according to the findings of Braun et al. (2020) and Ende and Evers (1997). This could be the case for the relations of leaf Mg and Ca to the nutrient availability in the soil at Arisdorf and Waldlabor. Carbonates in the parent material are a major source of Mg in the soil (Binkley and Fisher 2019). As already mentioned, the high occupation of the cation exchange sites by Ca^{2+} could be responsible for the low Mg and possibly K availability (Walthert et al. 2004) in Arisdorf. Since the parent material is the main source of Mg supply, the Mg concentration in the subsoil is usually higher than in the topsoil. However, since the Mg concentrations in the subsoil was included in the analysis in Waldlabor, but not in Arisdorf, it can be assumed that the Mg concentration at a depth of 0 – 50 cm in the soil in Arisdorf would also be slightly higher if the results from the subsoil could have been included. The differences in Ca allocation to the compartments and availability in the soil support the finding that there could be a relationship between Ca availability in the soil and allocation to the compartments. Mg and K concentrations in foliage were found to be well related to Mg and K availability in the soil exchangeable pool (Braun et al. 2020). In Waldlabor, foliar K seems to be related to the K availability in the soil considering the concentration and the stock and even if the K concentration is according to Amacher et al. (2007) sufficient, the K stock in Arisdorf support the strong relationship of K between soil and foliage. The P concentrations in the leaves, N:P ratio and P remobilisation rate suggest that the P availability in the soil is low. However, this is not necessarily due to the more acidic parent material compared to Arisdorf. For example, the availability of readily exchangeable resin P is generally higher in acidic soils than in soils on carbonaceous substrates. The pH-dependent solubility determines availability, and this solubility of P is highest in slightly acidic to slightly alkaline soils. In strongly acidic soils, P precipitates as Al or Fe phosphates (variscite, strengite) or adsorbs to Al/Fe minerals, while in strongly alkaline soils it precipitates as Ca phosphate (apatite), so P availability is limited in both strongly acidic and strongly alkaline soils (Mellert and Ewald 2014; Amelung et al. 2018; Braun et al. 2020). The low foliar P concentrations of Arisdorf could be a consequence of low P mobility and are in line with Calvaruso et al. (2017) observing low P availability for European beech stands on limestone. Duquesnay et al. (2000) suggested that increasing atmospheric CO_2 concentrations and acidification of forest soils may contribute to low foliar P levels. Similarly, atmospheric N deposition, leading to a decline in mycorrhizal abundance and diversity in European forests, plays a role in foliar P depletion (Arnolds 1991; Jaenike 1991). Nevertheless, low foliar P reflecting soil availability can be questioned as some studies have found no connection (Zavišić and Polle 2018). The low leaf S concentrations and the similar allocation pattern between sites might be due to the risk of poor S supply of substrates with calcareous, magmatic and metamorphic rocks, as atmospheric S deposition was reduced, as reported by Ricke (1960) (Göttlein et al. 2020).

Regarding the first hypothesis, few of the nutrient concentrations in the leaves and their allocation to the leaves seem to respond sensitively to the nutrient availability in the soil. Only the concentrations of Ca, P and Mg in the soil, which show significant differences, seem to be partially consistent with the allocation pattern to the tree compartments. At least for Ca and P, the allocation to the leaves is higher, while the nutrient availability in the soil is also significantly higher. For Mg, the allocation pattern to the leaves is largely indistinguishable relative to availability in the soil. In Waldlabor, more Mg is available in the soil, and more Mg is also allocated to the branches, but the allocation to the leaves does not differ by site. For N, there seems to be no or only a weak relationship between the concentrations in the soil and the allocation to the biomass compartments. Similarly, for K, there seems to be no or a negative relationship between allocation to the tree compartments and availability in the soil. In the case of S, hardly any differences in the allocation depending on the site are discernible. Herschbach and Rennenberg (1995) found in an experimental study that S allocation in *Fagus sylvatica* serves primarily for synthesis of storage substances in the stem, which could explain the small difference in allocation by site.

In addition to the significant differences in Ca, Mg, P and S concentrations in the branches, allocation to the branches was also considerably different for Ca, K, Mg and P. Higher nutrient availability in the soil seems to visually be in line with allocation to the branches, which is observed for Ca, Mg and P, but not for K. The difference in the amount of nutrient allocated to the bark by site is large, with the bark in Arisdorf mostly receiving a smaller amount. However, it remains unclear whether the amount of nutrient allocated to the bark is related to the available nutrient concentration in the soil. This applies in general for all visual relationships between nutrient availability and allocations to the individual biomass compartments. Surprising is that the stem showed a considerable difference in allocation by site for Ca, Mg and P, and to a lesser extent for K. One possible explanation for the pattern of nutrient allocation to the stem could have been the difference in age between the stands at the two sites of about 30 to 40 years, however, there was no consistent pattern per stand age and no consistent relation between the nutrient allocation to the stem and nutrient availability in the soil. Hence, this pattern remains unexplained. Finally, differences in concentration were only found for a few nutrients in the roots in Waldlabor and Arisdorf. The signal of nutrient concentration and allocation in the roots was in agreement with that of the leaves, which was in turn consistent with the results of (Poorter et al. 2012).

The moderate close to close C:N ratio at Waldlabor and Arisdorf suggests that remobilisation is not likely to play a major role for N. The wider the C:N ratio (Achat et al. 2018), the lower the N availability and the more important the remobilisation rates for N (Achat et al. 2018). Vergutz et al. (2012) compiled nutrient remobilisation rates from different studies by plant and climate type. The magnitude of the values in this thesis agreed with the values calculated by Vergutz et al. (2012). The remobilisation rates for N, K and P calculated for Waldlabor and Arisdorf were higher than the values Vergutz et al. (2012) found for deciduous tree species in temperate regions, especially in late November. This is interesting because of the hypothesis of higher remobilisation rates with low nutrient availability. The question therefore arises whether for these nutrients, the availability in the soil in the Waldlabor and in Arisdorf is lower than at the sites studied by Vergutz et al. (2012). A negative relationship between soil N and P availability and remobilisation rates of N and P in leaf biomass is observed in numerous studies (Reed et al. 2012; Tully et al. 2013; Hayes et al. 2014; See et al. 2015; Tsujii et al. 2017). Sardans et al. (2016) expected atmospheric N deposition to be negatively correlated with N remobilisation. However, this observation could not be confirmed in the present thesis. Accordingly, P remobilisation is expected to be high in soils with acidic parent material and thus in highly acidic soils, as low P availability is compensated by remobilisation (Achat et al. 2016, 2018; Augusto et al. 2017). Overall, previous studies have found that K and to a lesser extent P are the most remobilised nutrients (Vergutz et al. 2012; Achat et al. 2018), which is consistent with the calculated values for Waldlabor and Arisdorf. Alriksson and Eriksson (1998) observed a negative correlation between K concentration of aboveground biomass and K concentration in roots and litter. Soil fertility in general proved to be an important factor for the remobilisation of N, Ca, Mg and S (Vergutz et al. 2012). For these nutrients, however, no clear difference in remobilisation rates by site and relationship of the rates to nutrient availability in the soil was found at Waldlabor and Arisdorf. This could be due to the fact that, depending on the nutrient, other factors are also determine remobilisation, such as leaf lifespan and nutrient balances depending on the macronutrient (Achat et al. 2018). Fife et al. (2008) concluded from their results that remobilisation of P, K and Mg occurs during leaf lifespan, while remobilisation during senescence mainly affects N and S. Remobilisation is not common for Ca due to its function as an element of the cell wall (Marschner 2012; Vergutz et al. 2012; Kumar et al. 2015). A negative correlation between remobilisation rates and Ca concentration with increasing leaf age was observed (Liu et al. 2014; Achat et al. 2018), suggesting that there is no net remobilisation (Augusto et al. 2011; Marschner 2012). For Waldlabor and Arisdorf, even negative Ca remobilisation rates can be observed at the end of November, suggesting that Ca may be translocated from the stem to the leaves during the last phase of leaf shedding. This is in line with Vergutz et al. (2012) observing low or negative Ca remobilisation rates. Overall, the pattern of increasing remobilisation rates and thus better nutrient use efficiency with increasing scarcity found by Vitousek (1982) could be partly confirmed in this thesis. However, as expected according to literature, the relationship between remobilisation rates and nutrient availability in the soil is dependent on the nutrient. In contrast, there is a number of authors who do not support the hypothesis of Vitousek (1982) (Aerts 1996; Eckstein et al. 1999; Diehl et al. 2003).

The discussion of the nutrient dynamics in foliage confirms that according to Binkley and Fisher (2019), foliar analysis can be complex because nutrient concentrations in foliage depend not only on nutrient availability in the soil, but also on other factors such as leaf age and development, location within the canopy, age and competitive status of the tree, and annual precipitation variability.

4.2 Differences in the nutrient concentration of the harvestable compartments in relation to the geological substrate

The investigations of nutrient concentrations in the tree compartments by geological substrate in chapter 3.5 revealed some differences in the concentrations in branches, bark and stem depending on the geological substrate group or site. Overall, the signal was variable and no consistent pattern was evident for most nutrients and some compartments. Since coniferous and deciduous tree species differ in the way they deal with nutrient availability in the soil, the nutrient concentration in the biomass compartments also depends on the tree species (Hagen-Thorn et al. 2004). Consequently, the different number (across all substrate groups, compartments and nutrients: coniferous 10 – 26; hardwood 3 – 14) of studies with hardwood and softwood species per substrate group influenced the results of ANOVA and Kruskal-Wallis tests. In addition, in some studies, data were not available for some compartments or nutrients. In general, conifers, which dominate the dataset, have lower nutrient concentrations in all biomass compartments, while broadleaf species are often presented as outliers (Figure 13–16). A pattern that is common to all sites and for at least some compartments consistent with previous studies is the magnitude of nutrient concentrations by biomass compartment: leaves > roots > branches > bark > stem (Hagen-Thorn et al. 2004).

Many significant differences by geological substrate group were found for the bark compartment and to a slightly lesser extent for the branches. This was expected for Ca due to its dependence on the parent material (Meiwes and Beese 1988; Andersson et al. 1989; Påhlsson 1989). Thus, the group of carbonaceous solidified substrates generally has higher concentrations than siliceous substrates. The Ca concentrations of the solidified carbonates show higher values for the branches than those of other groups. For S, the evidence in this thesis is poor: a significant difference was found in the branches of Waldlabor and Arisdorf, but the relationship of S concentration in tree compartments to S availability in the soil was also not intensively investigated in previous studies. As indicated in a previous chapter, the S concentration in tree compartments is not only determined by the availability of S in the soil (e.g. in sulphates) (Göttlein et al. 2020), but has in the past mainly been determined by atmospheric deposition (Likens 2013) As far as the bark is concerned, this compartment seems to be sensitive to the nutrient availability and the substrate of the soil. The significant differences in N is one finding that could support this finding, but it could also be related to the higher atmospheric N deposition in Waldlabor (see Chap. 4.1). Mg, N, K and P always show significant differences between the same substrate groups. Concentrations in bark on loose carbonates are lowest for all nutrients, including Ca. In all compartments, P was the nutrient that showed the greatest differences, which is consistent with P being one of the only nutrients showing significant differences between Bülach and Irchel. The allocation pattern of P at Waldlabor and Arisdorf also seems to support that leaves, roots and branches are sensitive to P availability in the soil, which in this case suggests a link between geology and biomass compartments.

Finally, it was expected that there would be almost no significant differences in concentrations in the stem, as this compartment is considered the most robust biomass compartment to environmental factors (e.g. Augusto et al. 2000). Two exceptions in the results are in some cases P and K. While there is no obvious explanation for K, the significant difference for P could again support the evidence for the strong relationship between geology and biomass compartments observed in this thesis. For a given tree species, the variability of nutrient concentration in the stem is low (Heilman and Gessel 1963; Alban et al. 1978; Nilsson and Wiklund 1995).

Some differences in nutrient concentration could be explained by a mixed, interacting effect of tree species and geological substrate, leading to a reinforcing, positive feedback. If the substrate is nutrient-poor, conifer growth is favoured (Jacobsen et al. 2003). In various field experiments and field studies, tree species have been shown to influence soil quality and/or nutrient distribution, e.g. organic matter (Challinor 1968), pH (Nordén 1992), concentration of available base cations in topsoil (Alban et al. 1978; Binkley and Valentine 1991; Eriksson and Rosen 1994) and N mineralisation (Gower and Son 1992). Conifers influence the soil through their acidic needles (Jacobsen et al. 2003), resulting in less decomposable litter than deciduous trees (Binkley 1995), thus affecting the mineralisation of nutrients in the soil. However, the influence of plants on soil formation usually plays a minor role compared to other factors (Augusto et al. 1998). Jiang et al. (2018) argue that hardwoods can buffer the acid capacity of forest soils due to their organic matter content. Despite the data in the literature supporting the hypothesis of acidification under conifers, there are also findings that hardwoods lead to greater soil acidification, showing that the effect of the tree species has not been thoroughly researched (Mareschal et al. 2010; Mueller et al. 2012). Among other abiotic and biotic factors affecting soil nutrient pools and nutrient uptake by plants, recent studies have shown that soil chemical parameters are affected and consequently nutrient uptake is reduced when N deposition is increased (Braun et al. 2020). It is assumed that increased N deposition, climate change and the associated higher productivity of trees, together with increased fructification of *Fagus sylvatica*, lead to lower nutrient concentrations in plants (Pretzsch et al. 2014; Jonard et al. 2015; Talkner et al. 2015). Jonard et al. (2015) attribute the decrease in foliar nutrient concentrations to a dilution effect due to increased tree productivity. However, Braun et al. (2020) disagree with this explanation, and they question the findings of Jonard et al. (2015), as no growth data were provided by them. Another possible explanation for the low nutrient concentrations is a number of antagonistic effects that limit nutrient uptake (Pretzsch et al. 2014; Jonard et al. 2015; Talkner et al. 2015; Braun et al. 2020). Reduced K uptake is possible on calcareous soils due to Ca-K antagonism (Rehfuess 1995; Mellert and Ewald 2014). This pattern, which was in contrast not observed by Braun et al. (2020), could be reflected in the low foliar K concentrations at Waldlabor and Arisdorf in this thesis. In interaction with Ca, P can be limited by Ca antagonism, which seems to be true for Waldlabor and Arisdorf and is visible in the values of the leaves/needles and bark on calcareous substrates of the ANOVA results. A high Ca concentration as a limiting factor also seems to apply to Mg, which was already discussed in chapter 4.1 for Mg availability in the soil, which is reflected in the low Mg concentration in the *Fagus sylvatica* leaves and also applies to the Mg concentrations in the bark and branches of Arisdorf. As P concentrations are generally in the lower range, the concentrations in the branches and bark of the Swiss study sites in *Fagus Sylvatica* are consistent with with the low P concentrations in foliage in Waldlabor and Arisdorf and the results of Braun et al. (2020) and Jonard et al. (2015), who identified P as a limiting nutrient for forest productivity and of Mellert and Ewald (2014), who identify P as the most important nutrient (besides K) for nutritional balance and tree growth in the calcareous Alps. Compared to the spectrum of the investigated studies with deciduous tree species in the ANOVA, the four Swiss sites, visually assessed, show concentrations in the middle to upper range for Mg and P in the stem and for N and Ca in all compartments (Figure A1–4).

According to the results of this thesis, there could be a positive relationship for K between its availability in the soil and its distribution among the compartments. In general, the concentration of K in the soil correlates with the clay content of the soil (Alriksson and Eriksson 1998). Although weathering of soil minerals (mica, illite) is the main source of supply for K (Berner and Berner 2012; Osman 2013; Binkley and Fisher 2019), previous studies have shown that in soils with low K availability, the release of K from soil minerals is stimulated (Simonsson et al. 2007; Barré et al. 2008; Calvaruso et al. 2017). The relationship between P concentration (especially in foliage), allocation and soil or bedrock is often debated in the literature, as the relationship is not consistent (e.g. Bauer et al. 1997; Talkner et al. 2015; Meller et al. 2019). In contrast, the relationship between P allocation and concentrations in tree biomass, soil and geology in the data of this thesis is overall surprisingly consistent. Two nutrients in trees that are known to be related to geological substrate and soil are Ca and Mg, as carbonates are an important source of Ca and Mg (Binkley and Fisher 2019). Ca can vary over a wide range depending on soil properties and plant water use (Andersson et al. 1989; Påhlsson 1989; Stefan et al. 1997; Arthur et al. 1999). The Mg concentration in soil water and the available Mg concentration in the soil are crucial for the Mg supply of plants (Amelung et al. 2018). The relationship with soil and geological substrate for Mg in the data from Waldlabor and Arisdorf was discussed in the previous chapter 4.1 and revealed that high Ca availability might limit Mg availability in the soil in Arisdorf. The pattern of the close relationship between carbonaceous substrates and Mg concentration in the biomass compartments can again be observed in the ANOVA results, especially for the carbonaceous consolidated group, but not so clearly for the carbonaceous loose group. The lower Mg concentrations in the carbonaceous loose group compared to the carbonaceous solidified group can be explained by the parent material: While consolidated carbonate rocks contain a considerable amount of salts that were precipitated as dolomite (Ca-Mg bicarbonate) during diagenesis, such precipitation did not occur in loose carbonate sediments such as marl because the salt concentration in the oceans was lower, leading to precipitation of Ca carbonates and sedimentation of other particles such as silica (Wiesenberg 2022). Overall, it was often observed that nutrient concentrations in the compartments of the loose carbonaceous group in the results of the ANOVA and Kruskal Wallis test were lower than those of the other groups or similar to those of the siliceous groups. This was especially visible in the branches and the bark, but also in the leaves and needles. One reason for this pattern is that many substrates with progressing nutrient depletion can be assigned to this group. Nutrient uptake occurs mainly through the topsoil because of the reach of the roots, especially in shallow-rooted conifers (Göransson et al. 2006), and a decarbonised and base cation-poor topsoil may therefore influence nutrient distribution and concentration in tree compartments.

The results and their discussion showed that the nutrient status of the trees can be partially compensated (Hagen-Thorn et al. 2004), as seems to be the case especially in Bülach and Irchel, where only few significant differences in nutrient concentrations in the harvestable compartments branches, bark and stem were found. Calvaruso et al. (2017) summarise possible reasons for the compensation of nutrient concentrations in the tree compartments when soil nutrient availability is low. One explanation for the trees' ability to balance nutrients at the four Swiss sites is, firstly, the climatic regime of the sites: with the regularly distributed and sufficient precipitation, plant growth is well maintained (Calvaruso et al. 2017). Secondly, when nutrient availability in the soil is low, the release of nutrients from minerals by the roots can be stimulated (Simonsson et al. 2007; Barré et al. 2008). Finally, biochemical and biological mechanisms such as nutrient use efficiency help trees growing on nutrient-poor substrates to recycle elements efficiently (Ranger et al. 2000), thus controlling the nutrient supply of trees through internal relocation processes, recovery and mineralisation of organic material returned to the soil (Tiessen et al. 1994; Laclau et al. 2003; van der Heijden et al. 2013).

4.3 Impact on sustainable forestry

The results of this thesis confirm the conclusions of previous studies (e.g. Alriksson and Eriksson 1998; Augusto et al. 2000; Block et al. 2016) that reduced-intensity harvesting (stem wood harvesting) rather than whole-tree harvesting may be crucial for sites with low nutrient availability. The numerous significant differences in nutrient concentrations by substrate group in the bark and branches may underline the importance of the geological substrate for the nutrient balance of trees, especially for some nutrients such as P.

To assess whether conventional or whole-tree harvesting is appropriate, local site characteristics and experience must be taken into account (Block et al. 2016). To determine which forest sites are vulnerable to nutrient depletion, complete nutrient balances with input and output factors and resulting positive or negative nutrient balances are a useful tool (Zimmermann et al. 2020). These nutrient balances can then serve as an indicator for the intensity of wood harvesting. If the data basis is poor, derivable indicators such as the nutrient index or the biomass quotient can serve as an approximation. Colour changes of needles and leaves, growth retardation and needle and leaf analyses are also useful. Whole-tree harvesting should only take place on forest sites with a positive nutrient balance, where it should be limited to every second harvest (Block et al. 2016). Mellert and Ewald (2014) also suggest that on sites with poor soil P availability, management should focus on maintaining or restoring humus stocks. To ensure the nutrient sustainability of forestry, recommendations should be developed and the use of crown material for energy production should be reduced if there is evidence that whole-tree harvesting endangers soil fertility. For this, a utilisation concept taking into account the years since the forest was managed, the tree species and the intensity of wood harvesting is useful (Block et al. 2016). In addition to sustainable forest management, new technologies such as harvester heads that can debark the stem wood of conifers could support a reduction of nutrient export through wood harvesting (Bennemann et al. 2020).

4.4 Limitations of the analysis

The analysis of the data in this thesis is the evaluation of a pilot study with data from two WSL projects. For the first hypothesis, the evaluation of the 6 additional sites of the Swiss Biomass project will provide a broader data base to answer the hypothesis. For the second hypothesis, some more variables need to be determined to answer it more integrally, such as leaching output or atmospheric deposition. Overall, the sample size of the data in Switzerland is still limited at this point, and the results should be interpreted carefully.

The calculations of the biomass allocation are based on simple mathematical equations. For leaf and stem biomass, the calculations can be considered robust. The plausibility check showed that the values are in the order of magnitude of other studies when tree age, diameter and species are taken into account for leaf, branch and stem biomass (Vitousek et al. 1988; Forrester et al. 2017). Barbaroux et al. 2003 found bark biomass from *Fagus sylvatica* being around 6 % of the stem biomass. However, the bark biomass is in the case of *Fagus sylvatica* trees in Waldlabor and Arisdorf less than 1 %. Even if the biomass calculation of the bark was a rather rough approximation, this difference is surprising and suggests that the bark biomass is severely underestimated in this thesis. Since only fine roots and no coarse roots were considered in this thesis, it was difficult to compare these numbers with other results. However, calculating (fine) root biomass is a difficult task because the root system can extend vertically or horizontally over long distances (Jackson et al. 2007) and distinguishing roots belonging to individual trees is not trivial (Poorter et al. 2012). These results suggest that the use of crown projection measurements for horizontal root extension and 50 cm deep soil rooting may be inaccurate.

Furthermore, the analysis of a possible relationship between nutrient allocation in the tree compartments and nutrient availability in the soil was carried out visually for Waldlabor and Arisdorf. Consequently, a high nutrient availability together with a high allocation to the leaves does not necessarily mean that a causal relationship exists, but this might also not be the case if the data base were broader. Leaf sensitivity to soil nutrient availability may only apply to young *Fagus sylvatica* trees but not to mature trees, probably due to the role of tree physiology (Marschner 2012). This dynamic needs further investigation. Other studies suggest that roots are more reliable indicators of soil nutrient availability than leaves (Brouwer 1963; Zavišić and Polle 2018). Other reasons why the results for Waldlabor and Arisdorf should be considered with caution are the size of the data set with five trees per site and the data availability for nutrient concentrations in the subsoil. The soil samples could not be collected at a depth of 25 – 50 cm for Arisdorf, which slightly influenced the calculations of available nutrients.

The attribution of the geological substrates to four substrate groups to answer the second hypothesis is rough. The classification was made with the help of PD Dr. Guido L. B. Wiesenberg's geological knowledge. In addition to the subjectivity of the group attribution, the properties and composition of the parent material can vary greatly within short distances (Binkley and Fisher 2019). An insight into the site descriptions and the partly poor geological descriptions indicated that some substrate group attributions are not optimal. The discussion of the calcareous loose group in this thesis suggested that even calcareous substrates may already be highly weathered and base-poor, resulting in a sometimes wide range of nutrient concentrations within a geological substrate group. Furthermore, in some studies, some nutrients and compartments were not investigated and the statistical design with the number of studies per substrate group only provides a limited data base for some substrate groups. The data from the literature compilation originates from a broad time horizon and across Europe with many different sampling and processing materials and methods, which introduces indeterminate variation and uncertainty in the analysis (Jacobsen et al. 2003; Rumpf et al. 2018). Finally, the number of trees sampled per study varies considerably, which affects the validity of studies with small numbers such as Waldlabor and Arisdorf.

It is difficult to determine the influence of parent material and soil properties on tree nutrient balance and associated forest productivity without considering other ecological variables such as climate, atmospheric deposition, topography, stand composition, tree age and competition (Coomes and Allen 2007; Seynave et al. 2008), mycorrhizal association (George and Marschner 1996) and other influencing factors. The wide range of nutrient concentrations within a substrate group is probably also because the analysis was not done separately per tree species or at least separately for conifers and hardwoods. This suggest that the consideration of tree species in a two-way ANOVA would have been useful. However, the number per tree species type (coniferous / broadleaf) would not have been sufficient to conduct a two-way ANOVA. In fact, some authors of Swedish studies suggest that nutrient concentrations in the tree compartments studied depended more on tree species than on soil properties (Andersson et al. 1989; Påhlsson 1989), especially for the leaves and stem (Hagen-Thorn et al. 2004). Augusto et al. (2000) came to similar conclusions and added that stand age is also a more important influencing factor than soil fertility.

In general, all measurements represent only a snapshot of the annual variation in allocation and concentration patterns. Previous studies suggest that P allocation varies seasonally (Zavišić and Polle 2018). This is also true for nutrient concentrations in foliage (Hagen-Thorn et al. 2004; Binkley and Fisher 2019) and may also apply to other nutrient allocation dynamics to tree compartments.

Because of the unknown influence of each environmental and tree-specific factor and the simple approach with considering only geology, the spatial, methodological and temporal heterogeneity of the data, the high variation of geology within short distances and the statistical design in this thesis, the results of the ANOVA and Kruskal Wallis tests should therefore be considered with caution. To gain a deeper understanding of nutrient dynamics and sustainability of wood harvesting, long-term observations and other variables such as atmospheric deposition and leaching performance (Zimmermann et al. 2020) as well as input and output balances of the different nutrients are needed (Block and Meiwes 2013).

5. Conclusion and outlook

The results of this master thesis show that hypothesis 1, stating that leaves are most sensitive to low nutrient availability in the soil, could not be confirmed for most nutrients. Moreover, the same seems to apply to the fine roots. Only for P and Ca there could be a relationship between availability in the soil and allocation to the leaves. It was also found that the allocation of Mg, Ca and P to the branch compartments could depend on the nutrient availability in the soil. For some nutrients and compartments, the allocation patterns remain unclear. Foliar analysis revealed that *Fagus sylvatica* in Waldlabor and Arisdorf is deficient in P, possibly due to atmospheric N deposition or to an antagonistic effect of high Ca availability in the soil. The low S concentrations in leaves are possibly due to lower atmospheric S deposition. The K concentration in the foliage, which is in the lower range at both sites, and the low Mg concentration in the foliage in Arisdorf could be again in relation to an antagonistic effect due to the high Ca availability in the soil, especially in Arisdorf.

Many significant differences in nutrient concentrations by geological substrate were found for the Waldlabor / Arisdorf comparison as well as in bark and branch concentrations in temperate regions from the ANOVA / Kruskal Wallis results. The differences in nutrient concentrations between tree compartments depending on the geological substrate indicate that in many studies attributed to the loose carbonate group, soil acidification is progressing and thus lower nutrient availability was found, especially compared to trees growing on solidified carbonates. Therefore, hypothesis 2 can be partially confirmed. Comparison with literature however suggests that the validity of the results is limited.

The dynamic of the relationship between tree compartments, nutrient availability in the soil and geological substrate is complex and depends on the one hand on the macronutrient and on the other hand on the tree compartment as well as on many other biotic and abiotic factors. Tree species and other environmental factors, which were not included in the analysis of this thesis, influence tree nutrition differently in different tree compartments (Augusto et al. 2000). Overall, even on substrates with low nutrient reserves, nutrient supply in trees growing on the Central Plateau in Switzerland can be balanced to a certain extent by sufficient precipitation, nutrient release from minerals of the parent material and by recycling of macronutrients at tree level and in the forest ecosystem. However, the significant differences found for some of the nutrient concentrations in some of the harvestable compartments suggest that reduced intensity of wood harvesting is important for sites with low nutrient availability in the soil to avoid forest soil depletion. To further assess the hypotheses investigated in this Master thesis, a broader data base and consideration of other environmental aspects is crucial.

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References

Abbott, L. K., and D. v Murphy. 2003. *Soil biological fertility: a key to sustainable land use in agriculture*. Springer Science & Business Media.

Achat, D. L., N. Pousse, M. Nicolas, and L. Augusto. 2018. Nutrient remobilization in tree foliage as affected by soil nutrients and leaf life span. *Ecol Monogr*. 88(3):408–428 Available online at: https://doi.org/10.1002/ecm.1300.

Achat, D. L., N. Pousse, M. Nicolas, F. Brédoire, and L. Augusto. 2016. Soil properties controlling inorganic phosphorus availability: general results from a national forest network and a global compilation of the literature. *Biogeochemistry*. 127(2):255–272 Available online at: https://doi.org/10.1007/s10533-015-0178-0.

Aerts, R. 1996. Nutrient Resorption from Senescing Leaves of Perennials: Are there General Patterns? *Journal of Ecology*. 84(4):597–608 Available online at: http://www.jstor.org/stable/2261481.

Alban, D. H., D. A. Perala, and B. E. Schlaegel. 1978. Biomass and nutrient distribution in aspen, pine, and spruce stands on the same soil type in Minnesota. *Canadian Journal of Forest Research*. 8(3):290–299 Available online at: https://doi.org/10.1139/x78-044.

Alriksson, A., and H. M. Eriksson. 1998. Variations in mineral nutrient and C distribution in the soil and vegetation compartments of five temperate tree species in NE Sweden. *For Ecol Manage*. 108(3):261–273.

Amacher, M. C., K. P. O’Neil, and C. H. Perry. 2007. *Soil vital signs: a new soil quality index (SQI) for assessing forest soil health*. 1–12 p.

Amelung, W., H.-P. Blume, H. Fleige, R. Horn, E. Kandeler, I. Kögel-Knabner, R. Kretzschmar, K. Stahr, and B.-M. Wilke. 2018. *Scheffer/Schachtschabel Lehrbuch der Bodenkunde*. Springer-Verlag.

Andersson, M., A.-M. B. Pahlsson, G. Berlin, U. Falkengren-Grerup, and G. Tyler. 1989. Environment and Mineral Nutrients of Beech (Fagus sylvatica L.) in South Sweden. *Flora*. 183(5):405–415 Available online at: https://www.sciencedirect.com/science/article/pii/S0367253017315724.

Arnolds, E. 1991. Decline of ectomycorrhizal fungi in Europe. *Agric Ecosyst Environ*. 35(2):209–244 Available online at: https://www.sciencedirect.com/science/article/pii/016788099190052Y.

Art, H. W., H. Bormann, G. K. Voigt, and G. M. Woodwell. 1974. Reports Barrier Island Forest Ecosystem: Role of Meteorologic Nutrient Inputs. *Science (1979)*. 184(4132) Available online at: https://www.science.org.

Arthur, M. A., T. G. Siccama, and R. D. Yanai. 1999. Calcium and magnesium in wood of northern hardwood forest species: relations to site characteristics. *Canadian Journal of Forest Research*. 29(3):339–346 Available online at: https://doi.org/10.1139/x98-210.

Augusto, L., D. L. Achat, M. Jonard, D. Vidal, and B. Ringeval. 2017. Soil parent material—A major driver of plant nutrient limitations in terrestrial ecosystems. *Glob Chang Biol*. 23(9):3808–3824 Available online at: https://doi.org/10.1111/gcb.13691.

Augusto, L., P. Bonnaud, and J. Ranger. 1998. Impact of tree species on forest soil acidification. *For Ecol Manage*. 105(1):67–78 Available online at: https://www.sciencedirect.com/science/article/pii/S0378112797002703.

Augusto, L., J. Ranger, Q. Ponette, and M. Rapp. 2000. Relationships between forest tree species, stand production and stand nutrient amount. *Ann For Sci*. 57(4):313–324 Available online at: http://www.edpsciences.org/10.1051/forest:2000122.

Augusto, L., B. Zeller, A. J. Midwood, C. Swanston, E. Dambrine, A. Schneider, and A. Bosc. 2011. Two-year dynamics of foliage labelling in 8-year-old Pinus pinaster trees with 15N, 26Mg and 42Ca—simulation of Ca transport in xylem using an upscaling approach. *Ann For Sci*. 68(1):169–178 Available online at: https://doi.org/10.1007/s13595-011-0018-x.

Barbaroux, C., N. Bréda, and E. Dufrêne. 2003. Distribution of above-ground and below-ground carbohydrate reserves in adult trees of two contrasting broad-leaved species (Quercus petraea and Fagus sylvatica). *New Phytologist*. 157(3):605–615.

Barnes, B. v, D. R. Zak, S. R. Denton, and S. H. Spurr. 1998. *Forest ecology*. John Wiley and Sons.

Barré, P., B. Velde, C. Fontaine, N. Catel, and L. Abbadie. 2008. Which 2:1 clay minerals are involved in the soil potassium reservoir? Insights from potassium addition or removal experiments on three temperate grassland soil clay assemblages. *Geoderma*. 146(1):216–223 Available online at: https://www.sciencedirect.com/science/article/pii/S0016706108001407.

Bauer, G., E.-D. Schulze, and M. Mund. 1997. Nutrient contents and concentrations in relation to growth of Picea abies and Fagus sylvatica along a European transect. *Tree Physiol*. 17(12):777–786 Available online at: https://doi.org/10.1093/treephys/17.12.777.

Bennemann, C., J. B. Heppelmann, S. Wittkopf, A. Hauck, J. Grünberger, B. Heinrich, and U. Seeling. 2020. Debarking Heads. Entrindende Harvesterköpfe reduzieren den Nährstoffentzug, fördern den Waldschutz und ermöglichen eine Optimierung der Logistikkette. *lwf aktuell*. :44–46.

Berner, E. K., and R. A. Berner. 2012. *Global environment: water, air, and geochemical cycles*. Princeton University Press.

Berrocoso, N. 2022. Visualisation of the sampled tree compartments and additional samples at Waldlabor and Arisdorf .

Binkley, D. 1986. *Forest nutrition management*. John Wiley & Sons, New York.

Binkley, D. 1995. The Influence of Tree Species on Forest Soils: Processes and Patterns. P. 994 in *Proceedings of the trees and soil workshop*, Mead, D.J., and I.S. Cornforth (eds.). Lincoln Univ. Press, Canterbury.

Binkley, D., and R. F. Fisher. 2019. *Ecology and management of forest soils*. Fifth edition. John Wiley & Sons, New York.

Binkley, D., J. L. Stape, and M. G. Ryan. 2004. Thinking about efficiency of resource use in forests. *For Ecol Manage*. 193(1):5–16 Available online at: https://www.sciencedirect.com/science/article/pii/S0378112704000465.

Binkley, D., and D. Valentine. 1991. Fifty-year biogeochemical effects of green ash, white pine, and Norway spruce in a replicated experiment. *For Ecol Manage*. 40(1):13–25 Available online at: https://www.sciencedirect.com/science/article/pii/037811279190088D.

Blanco, J. A., M. A. Zavala, J. B. Imbert, and F. J. Castillo. 2005. Sustainability of forest management practices: Evaluation through a simulation model of nutrient cycling. *For Ecol Manage*. 213(1–3):209–228.

Block, J. 1993. *Verteilung und Verlagerung von Radiocäsium in zwei Waldökosystemen in Rheinland-Pfalz insbesondere nach Kalk-und Kaliumdüngung*. Forstl. Versuchsanst. Rheinland-Pfalz.

Block, J., J. Dieler, J. Gauer, M. Greve, R. Moshammer, J. Schuck, V. Schwappacher, and U. Wunn. 2016. Gewährleistung der Nachhaltigkeit der Nährstoffversorgung bei der Holz-und Biomassenutzung im Rheinland-Pfälzischen Wald. *Mitteilung FAWF, Trippstadt*. (79/16):230.

Block, J., and K. J. Meiwes. 2013. Erhaltung der Produktivität der Waldböden bei der Holz-und Biomassenutzung. P. 1–50 in *Bodenschutz–Ergänzbares Handbuch der Maßnahmen und Empfehlungen für Schutz, Pflege und Sanierung von Böden, Landschaft und Grundwasser*, Bachmann, G., W. Konig, and J. Utermann (eds.). Erich Schmidt Verlag Berlin.

Brant, A. N., and H. Y. H. Chen. 2015. Patterns and Mechanisms of Nutrient Resorption in Plants. *CRC Crit Rev Plant Sci*. 34(5):471–486 Available online at: https://doi.org/10.1080/07352689.2015.1078611.

Braun, S., C. Schindler, and B. Rihm. 2020. Foliar Nutrient Concentrations of European Beech in Switzerland: Relations With Nitrogen Deposition, Ozone, Climate and Soil Chemistry. *Frontiers in Forests and Global Change*. 3:1–33 Available online at: https://www.frontiersin.org/articles/10.3389/ffgc.2020.00033.

Bredemeier, M. 1987. *Stoffbilanzen, interne Protonenproduktion und Gesamtsäurebelastung des Bodens in verschiedenen Waldökosystemen Norddeutschlands Reihe A, Bd. 33*. Ber.Forschungszentr. Waldökosysteme/Waldsterben. Reihe A, Bd. 33. 1–183 p.

Brouwer, R. 1963. *Some aspects of the equilibrium between overground and underground plantparts*. 31–39 p.

Bundesamt für Landestopografie swisstopo. 2022a. Geologische Vektordatensätze GeoCover. Available online at: https://map.geo.admin.ch/; last accessed September 22, 2022.

Bundesamt für Landestopografie swisstopo. 2022b. Karte swissTLM (farbig). Available online at: https://map.geo.admin.ch/; last accessed September 25, 2022.

Calvaruso, C., G. Kirchen, L. Saint-André, P. O. Redon, and M. P. Turpault. 2017. Relationship between soil nutritive resources and the growth and mineral nutrition of a beech (Fagus sylvatica) stand along a soil sequence. *Catena (Amst)*. 155:156–169.

Challinor, D. 1968. Alteration of surface soil characteristics by four tree species. *Ecology*. 49:286–290.

Coomes, D. A., and R. B. Allen. 2007. Effects of size, competition and altitude on tree growth. *Journal of Ecology*. 95(5):1084–1097 Available online at: https://doi.org/10.1111/j.1365-2745.2007.01280.x.

Diehl, P., M. J. Mazzarino, F. Funes, S. Fontenla, M. Gobbi, and J. Ferrari. 2003. Nutrient conservation strategies in native Andean-Patagonian forests. *Journal of Vegetation Science*. 14(1):63–70 Available online at: https://doi.org/10.1111/j.1654-1103.2003.tb02128.x.

Dietrich, H.-P., S. Raspe, M. Schwarzmeier, and S. Ilg. 2002. Biomasse-und Nährstoffinventuren zur Ermittlung von Ernteentzügen an drei bayerischen Fichtenstandorten. *Forstliche Forschungsberichte München*. 186:59–72.

Drever, J. I. 2005. *Surface and Ground Water, Weathering, and Soils: Treatise on Geochemistry, Volume 5*. Elsevier.

Duquesnay, A., J. L. Dupouey, A. Clement, E. Ulrich, and F. le Tacon. 2000. Spatial and temporal variability of foliar mineral concentration in beech (Fagus sylvatica) stands in northeastern France. *Tree Physiol*. 20(1):13–22 Available online at: https://doi.org/10.1093/treephys/20.1.13.

Eckstein, R. L., P. S. Karlsson, and M. Weih. 1999. Leaf life span and nutrient resorption as determinants of plant nutrient conservation in temperate-arctic regions. *New Phytologist*. 143(1):177–189 Available online at: https://www.cambridge.org/core/article/leaf-life-span-and-nutrient-resorption-as-determinants-of-plant-nutrient-conservation-in-temperatearctic-regions/BB2680BCBA0D791903AD0F426A7DD4C9.

Ellenberg, H., R. Mayer, and J. Schauermann. 1986. *Ökosystemforschung: Ergebnisse des Sollingprojekts 1966-1986*. Ulmer, Stuttgart. 1–507 p.

Ende, H.-P., and F. H. Evers. 1997. Visual magnesium deficiency symptoms (coniferous, deciduous trees) and threshold values (foliar, soil). P. 3–21 in *Magnesium Deficiency in Forest Ecosystems*, Hüttl, R.F., and W. Schaaf (eds.). Springer Netherlands, Dordrecht. Available online at: https://doi.org/10.1007/978-94-011-5402-4_1.

Eriksson, H. M., and K. Rosen. 1994. Nutrient distribution in a Swedish tree species experiment. *Plant Soil*. 164(1):51–59 Available online at: https://doi.org/10.1007/BF00010110.

Feger, K. H., S. Raspe, M. Schmid, and H. W. Zöttl. 1991. Verteilung der Elementvorräte in einem schlechtwüchsigen 100jährigen Fichtenbestand auf Buntsandstein. *Forstwissenschaftliches Centralblatt vereinigt mit Tharandter forstliches Jahrbuch*. 110(1):248–262 Available online at: https://doi.org/10.1007/BF02741260.

Fife, D. N., E. K. S. Nambiar, and E. Saur. 2008. Retranslocation of foliar nutrients in evergreen tree species planted in a Mediterranean environment. *Tree Physiol*. 28(2):187–196 Available online at: https://doi.org/10.1093/treephys/28.2.187.

Flückiger, W., and S. Braun. 2003. Critical limits for nutrient concentrations and ratios for forest trees– a comment. P. 273–280 in *Empirical critical loads for nitrogen. Swiss Agency for the Environment, Forests and Landscape (SAEFL), Berne*, Achermann, B., and R. Bobbink (eds.). Berne.

Flückiger, W., and S. Braun. 1999. Nitrogen and Its Effect on Growth, Nutrient Status and Parasite Attacks in Beech and Norway Spruce. *Water Air Soil Pollut*. 116(1):99–110 Available online at: https://doi.org/10.1023/A:1005298609109.

Forrester, D. I., I. H. H. Tachauer, P. Annighoefer, I. Barbeito, H. Pretzsch, R. Ruiz-Peinado, H. Stark, et al. 2017. Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. *For Ecol Manage*. 396:160–175.

Gee, G. W., and J. W. Bauder. 1986. Particle-Size Analysis. P. 383–411 in *Methods of Soil Analysis. Part I, Physical and Mineralogical Methods*, SSSA Book Series. Klute, A. (ed.). American Society of Agronomy, Madison (Wisconsin).

Gehrmann, J. 2002 (unpublished). *Makronährelemente und Schwermetalle in Biomassekompartimenten auf Flächen des Level II – Umweltmonitoringprogramms Level II in Nordrhein-Westfalen*.

George, E., and H. Marschner. 1996. Nutrient and water uptake by roots of forest trees. *Zeitschrift für Pflanzenernährung und Bodenkunde*. 159(1):11–21 Available online at: https://doi.org/10.1002/jpln.1996.3581590103.

le Goaster, S., E. Dambrine, and J. Ranger. 1991. Croissance et nutrition minérale d'un peuplement d'épicéa sur sol pauvre. I: Evolution de la biomasse et dynamique d'incorporation d'éléments minéraux. *Acta oecologica:(1990)*. 12(6):771–789.

Göransson, H., H. Wallander, M. Ingerslev, and U. Rosengren. 2006. Estimating the relative nutrient uptake from different soil depths in Quercus robur, Fagus sylvatica and Picea abies. *Plant Soil*. 286(1):87–97 Available online at: https://doi.org/10.1007/s11104-006-9028-0.

Göttlein, A. 2020. Derivation of nutritional threshold values from cumulative concentration distributions. *Journal of Plant Nutrition and Soil Science*. 183(4):403–405 Available online at: https://doi.org/10.1002/jpln.201900562.

Göttlein, A. 2015. Grenzwertbereiche für die ernährungsdiagnostische Einwertung der Hauptbaumarten Fichte, Kiefer, Eiche, Buche. *Allg Forst Jagdztg*. 186(5/6):110–116.

Göttlein, A., J. Fäth, M. Rau, and K. H. Mellert. 2020. Schwefel–vom Überschuss zum Mangel. *AFZ-DerWald*. (9):31–33.

Gower, S. T., and Y. Son. 1992. Differences in Soil and Leaf Litterfall Nitrogen Dynamics for Five Forest Plantations. *Soil Science Society of America Journal*. 56(6):1959–1966 Available online at: https://doi.org/10.2136/sssaj1992.03615995005600060051x.

Hagen-Thorn, A., K. Armolaitis, I. Callesen, and I. Stjernquist. 2004. Macronutrients in tree stems and foliage: A comparative study of six temperate forest species planted at the same sites. *Ann For Sci*. 61(6):489–498.

Haldimann, P., H. R. , Graf, and J. Jost. 2017. *Blatt 1071 Bülach. – Geol.Atlas Schweiz 1:25000, Erläuterungen 151*.

Hayes, P., B. L. Turner, H. Lambers, and E. Laliberté. 2014. Foliar nutrient concentrations and resorption efficiency in plants of contrasting nutrient-acquisition strategies along a 2-million-year dune chronosequence. *Journal of Ecology*. 102(2):396–410 Available online at: https://doi.org/10.1111/1365-2745.12196.

van der Heijden, G., A. Legout, B. Pollier, L. Mareschal, M. P. Turpault, J. Ranger, and E. Dambrine. 2013. Assessing Mg and Ca depletion from broadleaf forest soils and potential causes - A case study in the Morvan Mountains. *For Ecol Manage*. 293:65–78.

Heilman, P. E., and S. P. Gessel. 1963. The Effect of Nitrogen Fertilization on the Concentration and Weight of Nitrogen, Phosphorus, and Potassium in Douglas-Fir Trees. *Soil Science Society of America Journal*. 27(1):102–105 Available online at: https://doi.org/10.2136/sssaj1963.03615995002700010034x.

Heinsdorf, D., and H.-H. Krauß. 1990. Schätztafeln für Trockenmasse und Nährstoffspeicherung von Kiefernbeständen. *IFE-Berichte aus Forschung und Entwicklung* . 18:1–77.

Herschbach, C., and H. Rennenberg. 1995. Long-distance transport of 35S-sulphur in 3-year-old beech trees (Fagus sylvatica). *Physiol Plant*. 95(3):379–386 Available online at: https://doi.org/10.1111/j.1399-3054.1995.tb00852.x.

Higman, S., J. Mayers, S. Bass, N. Judd, and R. Nussbaum. 2005. *The Sustainable Forestry Handbook*. 2nd Edition. Earthscan Publications Ltd., London.

Hochbichler, E., N. Putzgruber, and A. Krapfenbauer. 1994. Biomassen-und Nährstoffuntersuchungen in einem 40jährigen Buchenbestand (Fagus sylvatica L.). *Centralblatt für das gesamte Forstwesen*. 111:1–22.

Huber, C., H. Borchert, J. Kremer, W. Weis, D. Metthies, and A. Göttlein. 2011. *Biomasse-und Abschlußbericht zum Forschungsprojekt B65: Nährelementverschiebungen bzw.-verluste bei Harvesterdurchforstungen und deren Auswirkungen auf Bodeneigenschaften und Stoffhaushalt von Waldökosystemen*. 95 p.

Ingerslev, M., and L. Hallbäcken. 1999. Above ground biomass and nutrient distribution in a limed and fertilized Norway spruce (Picea abies) plantation: Part II. Accumulation of biomass and nutrients. *For Ecol Manage*. 119(1):21–38 Available online at: https://www.sciencedirect.com/science/article/pii/S0378112798005076.

ISSS–ISRIC–FAO. 1998. World reference base for soil resources (WRB) DAO (Food and Agriculture Organization of the United Nations) (ed.). *World Soil Resources Reports*. 84:21–22.

Jackson, R. B., W. T. Pockman, W. A. Hoffmann, T. M. Bleby, and C. Armas. 2007. Structure and function of root systems. P. 151–174 in *Functional plant ecology,* CRC Press.

Jacobsen, C., P. Rademacher, H. Meesenburg, and K. J. Meiwes. 2003. Gehalte chemischer Elemente in Baumkompartimenten. Literaturstudie und Datensammlung. *Berichte des Forschungszentrums Waldökosysteme, Reihe B*. 69:1–81.

Jaenike, J. 1991. Mass extinction of European fungi. *Trends Ecol. Evol.* 6:174--175.

Jiang, J., Y.-P. Wang, M. Yu, N. Cao, and J. Yan. 2018. Soil organic matter is important for acid buffering and reducing aluminum leaching from acidic forest soils. *Chem Geol*. 501:86–94 Available online at: https://www.sciencedirect.com/science/article/pii/S0009254118305126.

Jonard, M., A. Fürst, A. Verstraeten, A. Thimonier, V. Timmermann, N. Potočić, P. Waldner, S. Benham, K. Hansen, P. Merila, Q. Ponette, A. C. De La Cruz, P. Roskams, M. Nicolas, L. Croisé,

M. Ingerslev, G. Matteucci, B. Decinti, M. Bascietto, and P. Rautio. 2015. Tree mineral nutrition is deteriorating in Europe. *Glob Chang Biol*. 21(1):418–430 Available online at: https://doi.org/10.1111/gcb.12657.

Joosten, R., and A. Schulte. 2003. Schätzung der Nährstoffexporte bei einer intensivierten Holznutzung in Buchenwäldern (Fagus sylvatica). *Allgemeine Forstund Jagdzeitung*. 174(9):157–168.

Kumar, A., U. M. Singh, M. Manohar, and V. S. Gaur. 2015. Calcium transport from source to sink: understanding the mechanism(s) of acquisition, translocation, and accumulation for crop biofortification. *Acta Physiol Plant*. 37(1):1–14 Available online at: https://doi.org/10.1007/s11738-014-1722-6.

Kuo, S. 1996. Phosphorus. P. 869–920 in *Methods of Soil Analysis, Part 3: Chemical Methods*, Sparks, D., A. Page, P. Helmke, and R. Loeppert (eds.).

Laclau, J., P. Deleporte, J. Ranger, J. Bouillet, and G. U. Y. Kazotti. 2003. Nutrient Dynamics throughout the Rotation of Eucalyptus Clonal Stands in Congo. *Ann Bot*. 91(7):879–892 Available online at: https://doi.org/10.1093/aob/mcg093.

Lamersdorf, N. 1988. *Verteilung und Akkumulation von Spurenstoffen in Waldökosystemen*. Reihe A, Bd. 36. Berichte des Forschungszentrums Waldökosysteme/ Waldsterben. 1–205 p.

Likens, G. E. 2013. *Biogeochemistry of a forested ecosystem*. Springer Science & Business Media.

Likens, G. E. 2004. Some perspectives on long-term biogeochemical research from the Hubbard Brook ecosystem study. *Ecology*. 85(9):2355–2362 Available online at: https://doi.org/10.1890/03-0243.

Liu, C., Y. Liu, K. Guo, S. Wang, and Y. Yang. 2014. Concentrations and resorption patterns of 13 nutrients in different plant functional types in the karst region of south-western China. *Ann Bot*. 113(5):873–885 Available online at: https://doi.org/10.1093/aob/mcu005.

Mareschal, L., P. Bonnaud, M. P. Turpault, and J. Ranger. 2010. Impact of common European tree species on the chemical and physicochemical properties of fine earth: an unusual pattern. *Eur J Soil Sci*. 61(1):14–23 Available online at: https://doi.org/10.1111/j.1365-2389.2009.01206.x.

Markan, K. 1993. Biomasse und Elementgehalte von Berliner Eichen auf grundwasserfernen Sandstandorten. In Eichensterben – ein Problem in Berlin? *Arbeitsmaterialien der Berliner Forsten 2*. :61–70.

Marschner, H. 2012. *Marschner's mineral nutrition of higher plants*. Third Edition. Elsevier, Academic press, London.

Meiwes, K.-J., and F. Beese. 1988. *Ergebnisse der Untersuchung des Stoffhaushaltes eines Buchenwaldökosystems auf Kalkgestein*. Reihe B. Ber. Forschungszentr. Waldökosysteme. 1–141 p.

Meller, S., E. Frossard, and J. Luster. 2019. Phosphorus Allocation to Leaves of Beech Saplings Reacts to Soil Phosphorus Availability. *Front Plant Sci*. 10 Available online at: https://www.frontiersin.org/articles/10.3389/fpls.2019.00744.

Mellert, K. H., and J. Ewald. 2014. Nutrient limitation and site-related growth potential of Norway spruce (Picea abies [L.] Karst) in the Bavarian Alps. *Eur J For Res*. 133(3):433–451 Available online at: https://doi.org/10.1007/s10342-013-0775-1.

Mellert, K. H., and A. Göttlein. 2012. Comparison of new foliar nutrient thresholds derived from van den Burg’s literature compilation with established central European references. *Eur J For Res*. 131(5):1461–1472 Available online at: https://doi.org/10.1007/s10342-012-0615-8.

MeteoSchweiz. 2022a. Klimanormwerte Basel / Binningen. Normperiode 1991−2020. climsheet 2.1.7.

MeteoSchweiz. 2022b. Klimanormwerte Zürich / Affoltern. Normperiode 1991−2020. climsheet 2.1.7. Available online at: https://www.meteoschweiz.admin.ch/product/output/climate-data/climate-diagrams-normal-values-station-processing/REH/climsheet_REH_np9120_d.pdf; last accessed June 26, 2022.

MeteoSchweiz. 2022c. Klimanormwerte Zürich / Kloten. Normperiode 1991−2020. climsheet 2.1.7. Available online at: https://www.meteoschweiz.admin.ch/product/output/climate-data/climate-diagrams-normal-values-station-processing/KLO/climsheet_KLO_np9120_d.pdf; last accessed June 26, 2022.

Miller, H. G., J. D. Miller, and O. J. L. Pauline. 1976. Effect of Nitrogen Supply on Nutrient Uptake in Corsican Pine. *Journal of Applied Ecology*. 13(3):955–966 Available online at: http://www.jstor.org/stable/2402269.

Mueller, K. E., D. M. Eissenstat, S. E. Hobbie, J. Oleksyn, A. M. Jagodzinski, P. B. Reich, O. A. Chadwick, and J. Chorover. 2012. Tree species effects on coupled cycles of carbon, nitrogen, and acidity in mineral soils at a common garden experiment. *Biogeochemistry*. 111(1):601–614 Available online at: https://doi.org/10.1007/s10533-011-9695-7.

Nebe, W., and U. J. Herrmann. 1987. Das Ökologische Messfeld der Sektion Forstwirtschaft der TU Dresden. VI: Zur Verteilung der Nährelemente in der oberirdischen Dendromasse eines 100jährigen Fichtenbaumholzes. *Wissenschaftliche Zeitschrift der Technischen Universität Dresden*. 36(6):235–241.

Neirynck, J., D. Maddelein, L. de Keersmaeker, N. Lust, and B. Muys. 1998. Biomass and nutrient cycling of a highly productive Corsican pine stand on former heathland in northern Belgium. *Ann. For. Sci.* 55(4):389–405 Available online at: https://doi.org/10.1051/forest:19980401.

Netzer, F., C. Schmid, C. Herschbach, and H. Rennenberg. 2017. Phosphorus-nutrition of European beech (Fagus sylvatica L.) during annual growth depends on tree age and P-availability in the soil. *Environ Exp Bot*. 137:194–207 Available online at: https://www.sciencedirect.com/science/article/pii/S009884721730045X.

Nihlgård, B. 1972. Plant Biomass, Primary Production and Distribution of Chemical Elements in a Beech and a Planted Spruce Forest in South Sweden. *Oikos*. 23(1):69–81 Available online at: http://www.jstor.org/stable/3543928.

Nihlgård, B., and L. Lindgren. 1977. Plant Biomass, Primary Production and Bioelements of Three Mature Beech Forests in South Sweden. *Oikos*. 28(1):95–104 Available online at: http://www.jstor.org/stable/3543328.

Nilsson, L.-O., and K. Wiklund. 1995. Nutrient balance and P, K, Ca, Mg, S and B accumulation in a Norway spruce stand following ammonium sulphate application, fertigation, irrigation, drought and N-free-fertilisation. *Plant Soil*. 168(1):437–446 Available online at: https://doi.org/10.1007/BF00029357.

Nordén, U. 1992. Soil acidification and element fluxes as related to tree species in deciduous forests of south Sweden. Ph.D Dissertation, University of Lund. 1–104 p.

Ohno, T., and L. M. Zibilske. 1991. Determination of Low Concentrations of Phosphorus in Soil Extracts Using Malachite Green. *Soil Science Society of America Journal*. 55(3):892–895 Available online at: https://doi.org/10.2136/sssaj1991.03615995005500030046x.

Oren, R., E.-D. Schulze, K. S. Werk, and J. Meyer. 1988. Performance of two Picea abies (L.) Karst. Stands at different stages of decline. VII. Nutrient relations and growth. *Oecologia*. 77:163–173.

Osman, K. T. 2013. *Soils: principles, properties and management*. Springer Science & Business Media, Dordrecht.

Ovington, J. D., and H. A. I. Madgwick. 1959. Distribution of Organic Matter and Plant Nutrients in a Plantation of Scots Pine. *Forest Science*. 5(4):344–355 Available online at: https://doi.org/10.1093/forestscience/5.4.344.

Påhlsson, A.-M. B. 1989. Mineral nutrients, carbohydrates and phenolic compounds in leaves of beech (Fagus sylvatica L.) in southern Sweden as related to environmental factors. *Tree Physiol*. 5(4):485–495 Available online at: https://doi.org/10.1093/treephys/5.4.485.

Pavlov, M. B. 1972. *Bioelement-Inventur von Buchen-und Fichtenbeständen im Solling*. Göttinger Bodenkundliche Berichte. 1–174 p.

Pavoni, N., C. Schindler, M. Freimoser, P. Haldimann, and D. Letsch. 2015. *Blatt 1091 Zürich. – Geol.Atlas Schweiz 1:25 000, Erläut. 90.*

Petráš, R., J. Mecko, D. Krupová, and A. Pažitný. 2020. Aboveground biomass basic density of hardwoods tree species. *Wood Research*. 65(6):1001–1012.

Pfirter, U., P. Jordan, H. R. . Graf, H. Burger, J. Pietsch, M. Huber, S. Kiefer, C. Grezet, C. Maise, and R. Burkhalter. 2019. *Blatt 1068 Sissach, mit Südteil von Blatt 1048 Rheinfelden – Geol. Atlas Schweiz 1: 25 000, Erläut. 161.*

Ponette, Q., A. Bispo, A. Brethes, J.-L. Dupouey, I. Feix, J.-C. Gégout, B. Jabiol, N. Pousse, and J. Ranger. 2014. Fertility indicators in temperate forest soils: issues, approaches and prospects. *Revue forestière française*. 66(5):501–515.

Poorter, H., K. J. Niklas, P. B. Reich, J. Oleksyn, P. Poot, and L. Mommer. 2012. Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. *New Phytologist*. 193(1):30–50 Available online at: https://doi.org/10.1111/j.1469-8137.2011.03952.x.

Pretzsch, H., J. Block, J. Dieler, J. Gauer, A. Göttlein, R. Moshammer, J. Schuck, W. Weis, and U. Wunn. 2014. Nährstoffentzüge durch die Holz-und Biomassenutzung in Wäldern. Teil 1: schätzfunktionen für Biomasse und Nährelemente und ihre Anwendung in Szenariorechnungen. *Allgemeine Forst-u. Jagdzeitung*. 185(11/12):261–285.

Proe, M. F., A. J. Midwood, and J. Craig. 2000. Use of stable isotopes to quantify nitrogen, potassium and magnesium dynamics in young Scots pine (Pinus sylvestris). *New Phytologist*. 146(3):461–469 Available online at: https://www.cambridge.org/core/article/use-of-stable-isotopes-to-quantify-nitrogen-potassium-and-magnesium-dynamics-in-young-scots-pine-pinus-sylvestris/FF99E8AAA89C9045AFCD7302F664D9CA.

R Core Team. 2022. A language and environment for statistical computing. . *R Foundation for Statistical Computing*. Available online at: https://www.r-project.org/; last accessed September 23, 2022.

Rademacher, P. 1994. *Qualitative und quantitative Erfassung der Stoffflüsse und der Elementvorräte in Waldbäumen und deren Umwelt*. Berichte Forschungszentrum Waldökosysteme. 161–171 p.

Rademacher, P., B. Buß, and B. Müller-Using. 1999. Waldbau und Nährstoffmanagement als integrierte Aufgabe in der Kiefern-Waldwirtschaft auf ärmeren pleistozänen Sanden. *Forst und Holz* . 54:330–335.

Rademacher, P., H. Meesenburg, and B. Müller-Using. 2001. Nährstoffkreisläufe in einem Eichenwald-Ökosystem des Norddeutschen Pleistozäns. *Forstarchiv* . 71:43–54.

Rahman, M. M., J. Tsukamoto, Y. Tokumoto, and M. A. R. Shuvo. 2013. The role of quantitative traits of leaf litter on decomposition and nutrient cycling of the forest ecosystems. *Journal of Forest and Environmental Science*. 29(1):38–48.

Raisch, W. 1983. *Bioelementverteilung in Fichtenökosystemen der Bärhalde (Südschwarzwald)*. Im Selbstverlag des Instituts für Bodenkunde und Waldernährungslehre. 1–239 p.

Ranger, J., V. Badeau, É. Dambrine, J.-L. Dupouey, and C. Nys. 2000. Evolution constatée des sols forestiers au cours des dernières décennies. *Revue forestière française*. 52(sp):49–70.

Ranger, J., G. Cuirin, J. Bouchon, M. Colin, D. Gelhaye, D. Mohamed Ahamed, L. Gelhaye, and B. Pollier. 1992. Biomasse et minéralomasse d'une plantation d'épicéa commun (Picea abies Karst) de forte production dans les Vosges (France). *Ann. For. Sci.* 49(6):651–668 Available online at: https://doi.org/10.1051/forest:19920608.

Ranger, J., R. Marques, M. Colin-Belgrand, N. Flammang, and D. Gelhaye. 1995. The dynamics of biomass and nutrient accumulation in a Douglas-fir (Pseudotsuga menziesii Franco) stand studied using a chronosequence approach. *For Ecol Manage*. 72(2):167–183 Available online at: https://www.sciencedirect.com/science/article/pii/037811279403469D.

Ranger, J., and M.-P. Turpault. 1999. Input–output nutrient budgets as a diagnostic tool for sustainable forest management1Communication presented at the IEA Bioenergy, Task XII Conference `Indicators of Sustainable Forest Management', Eddleston, Scotland, 20–25 September, 1997.1. *For Ecol Manage*. 122(1):139–154 Available online at: https://www.sciencedirect.com/science/article/pii/S0378112799000389.

Reed, S. C., A. R. Townsend, E. A. Davidson, and C. C. Cleveland. 2012. Stoichiometric patterns in foliar nutrient resorption across multiple scales. *New Phytologist*. 196(1):173–180 Available online at: https://doi.org/10.1111/j.1469-8137.2012.04249.x.

Rehfuess, K. E. 1995. Gefährdung der Wälder in Mitteleuropa durch Luftschadstoffe und Möglichkeiten der Revitalisierung durch Düngung. *Ber. d. Reinhold-Tüxen-Gesellschaft*. 7:141–156.

Ricke, W. 1960. Ein Beitrag zur Geochemie des Schwefels. *Geochim Cosmochim Acta*. 21(1):35–80 Available online at: https://www.sciencedirect.com/science/article/pii/S0016703760800038.

Rumpf, S., E. Schönfelder, and B. Ahrends. 2018. Biometrische Schätzmodelle für Nährelementgehalte in Baumkompartimenten. *Freibg. Forstl. Forsch*. 101:33–73.

Sardans, J., R. Alonso, I. A. Janssens, J. Carnicer, S. Vereseglou, M. C. Rillig, M. Fernández-Martínez, T. G. M. Sanders, and J. Peñuelas. 2016. Foliar and soil concentrations and stoichiometry of nitrogen and phosphorous across European Pinus sylvestris forests: relationships with climate, N deposition and tree growth. *Funct Ecol*. 30(5):676–689 Available online at: https://doi.org/10.1111/1365-2435.12541.

Schoenholtz, S. H., H. V. Miegroet, and J. A. Burger. 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. *For Ecol Manage*. 138(1):335–356 Available online at: https://www.sciencedirect.com/science/article/pii/S0378112700004230.

See, C. R., R. D. Yanai, M. C. Fisk, M. A. Vadeboncoeur, B. A. Quintero, and T. J. Fahey. 2015. Soil nitrogen affects phosphorus recycling: foliar resorption and plant–soil feedbacks in a northern hardwood forest. *Ecology*. 96(9):2488–2498 Available online at: https://doi.org/10.1890/15-0188.1.

Seibt, G., and W. Wittich. 1965. Ergebnisse langfristiger Düngungsversuche im Gebiet des nordwestdeutschen Dilluviums und ihre Folgerungen für die Praxis. Schriftenreihe der Forstlichen Fakultät der Universität Göttingen. *Mitteilungen der Niedersächsischen Forstlichen Versuchsanstalt*. 27(28):156.

Seynave, I., J.-C. Gégout, J.-C. Hervé, and J.-F. Dhôte. 2008. Is the spatial distribution of European beech (Fagus sylvatica L.) limited by its potential height growth? *J Biogeogr*. 35(10):1851–1862 Available online at: https://doi.org/10.1111/j.1365-2699.2008.01930.x.

Simonsson, M., S. Andersson, Y. Andrist-Rangel, S. Hillier, L. Mattsson, and I. Öborn. 2007. Potassium release and fixation as a function of fertilizer application rate and soil parent material. *Geoderma*. 140(1):188–198 Available online at: https://www.sciencedirect.com/science/article/pii/S0016706107001000.

Speich, S. 2021. Pictures of compartment sampling during field work at Arisdorf in January 2021.

Stefan, K., A. Fürst, R. Hacker, and U. Bartels. 1997. Forest Foliar Condition in Europe–Results of large-scale foliar chemistry surveys (survey 1995 and data from previous years). *EC, UN/ECE, Austrian Federal Forest Research Centre*. :1–207.

Steiner, A., A. Bolte, B. U. Schneider, and R. F. J. Hüttl. 1998. Phytomasse-und Nährelementvorräte unterschiedlich stickstoffbeeinflußter Kiefernbestände (Pinus sylvestries L.) des nordostdeutschen Tieflandes. *Verhandlungen der Gesellschaft für Ökologie*. 28:421–428.

Talkner, U., K. J. Meiwes, N. Potočić, I. Seletković, N. Cools, B. de Vos, and P. Rautio. 2015. Phosphorus nutrition of beech (Fagus sylvatica L.) is decreasing in Europe. *Ann For Sci*. 72(7):919–928 Available online at: https://doi.org/10.1007/s13595-015-0459-8.

Thürig, E. 2021. Picture of a harvester weighing a stem wood with a crane scale at Arisdorf in January 2021.

Tiessen, H., E. Cuevas, and P. Chacon. 1994. The role of soil organic matter in sustaining soil fertility. *Nature*. 371(6500):783–785 Available online at: https://doi.org/10.1038/371783a0.

Trüby, P. 1994. Zum Schwermetallhaushalt von Waldbaumen. *Freiburger Bodenkundliche Abhandlungen* . 33:1–286.

Tsujii, Y., Y. Onoda, and K. Kitayama. 2017. Phosphorus and nitrogen resorption from different chemical fractions in senescing leaves of tropical tree species on Mount Kinabalu, Borneo. *Oecologia*. 185(2):171–180 Available online at: https://doi.org/10.1007/s00442-017-3938-9.

Tully, K. L., T. E. Wood, A. M. Schwantes, and D. Lawrence. 2013. Soil nutrient availability and reproductive effort drive patterns in nutrient resorption in Pentaclethra macroloba. *Ecology*. 94(4):930–940 Available online at: https://doi.org/10.1890/12-0781.1.

Uhlig, D., and F. von Blanckenburg. 2019. Geochemical and isotope data on rock weathering, and nutrient balances during fast forest floor turnover in montane, temperate forest ecosystems. *GFZ Data Services*.

Vergutz, L., S. Manzoni, A. Porporato, R. F. Novais, and R. B. Jackson. 2012. Global resorption efficiencies and concentrations of carbon and nutrients in leaves of terrestrial plants. *Ecol Monogr*. 82(2):205–220 Available online at: https://doi.org/10.1890/11-0416.1.

Vitousek, P. 1982. Nutrient cycling and nutrient use efficiency. *Am Nat*. 119(4):553–572.

Vitousek, P. M., T. Fahey, D. W. Johnson, and M. J. Swift. 1988. *Element interactions in forest ecosystems: succession, allometry and input-output budgets*. 7–34 p.

Walthert, L., U. Graf, A. Kammer, J. Luster, D. Pezzotta, S. Zimmermann, and F. Hagedorn. 2010. Determination of organic and inorganic carbon, δ13C, and nitrogen in soils containing carbonates after acid fumigation with HCl. *Journal of Plant Nutrition and Soil Science*. 173(2):207–216 Available online at: https://doi.org/10.1002/jpln.200900158.

Walthert, L., S. Zimmermann, P. Blaser, J. Luster, and P. Lüscher. 2004. *Waldböden der Schweiz. Band 1. Grundlagen und Region Jura*. Hep Verlag, Bern. 1–768 p.

Weatherall, A., M. F. Proe, J. Craig, A. D. Cameron, and A. J. Midwood. 2006. Internal cycling of nitrogen, potassium and magnesium in young Sitka spruce. *Tree Physiol*. 26(5):673–680 Available online at: https://doi.org/10.1093/treephys/26.5.673.

Weis, W., and A. Göttlein. 2002. Vergleich von Biomasse, Elementgehalten und Elementvorräten von Fichte (Picea abies (L.) Karst.) und Buche (Fagus sylvatica L.) am Standort Höglwald zu Zeiten der Vegetationsruhe. *Forstliche Forschungsberichte Munchen*. 186:163–167.

Weis, W., A. Gruber, C. Huber, and A. Göttlein. 2009. Element concentrations and storage in the aboveground biomass of limed and unlimed Norway spruce trees at Höglwald. *Eur J For Res*. 128(5):437–445 Available online at: https://doi.org/10.1007/s10342-009-0291-5.

Wiesenberg, G. L. B. 2022. Personal communication.

Wright, T. W., and G. M. Will. 1958. The nutrient content of Scots and Corsican pines growing on sand dunes. *Forestry: An International Journal of Forest Research*. 31(1):13–25 Available online at: https://doi.org/10.1093/forestry/31.1.13.

Zavišić, A., and A. Polle. 2018. Dynamics of phosphorus nutrition, allocation and growth of young beech (Fagus sylvatica L.) trees in P-rich and P-poor forest soil. *Tree Physiol*. 38(1):37–51.

Zimmermann, S. 2021 (unpublished). *Bodenprofil auf der Testpflanzungsfläche Zürich*. Birmensdorf.

Zimmermann, S., J. Luster, P. Blaser, L. Walthert, and P. Lüscher. 2006. *Waldböden der Schweiz. Band 3. Regionen Mitteland und Voralpen.* Hep Verlag, Bern. 1–848 p.

Zimmermann, S., J. Schweier, S. Holm, Stadelmann. G., D. Kurz, U. Gasser, N. Barengo, H. Beereuter, and T. Kuhn. 2020 (unpublished). *Nährstoffentzüge durch die Holzernte und ihr Einfluss auf den Nährstoffhaushalt saurer Standorte mit Buchenbestockung. Projektantrag an den Wald- und Holzforschungsfonds*.

6. Appendix

6.1 Calculations

In the following, calculations are presented that preceded the calculations in chapter 2.5 as well as additional calculations.

General tree characteristics

$$\begin{gathered}\text{Total biomass branches } \text{Ø} < 7\ \text{cm fresh [kg]} = \\ \text{Total tree biomass fresh [kg]} - \text{stem wood fresh [kg]}\end{gathered}$$

$$\text{Total leaf area } \left[m^2\right] = \text{Crown area } \left[m^2\right] * LAI$$

Specific leaf area

Specific leaf area (SLA) was calculated for green leaves and for leaves from the litter. For the green leaves, the specific leaf area was calculated for each height in the crown. For the litter, the specific leaf area was calculated for each time point. For some trees, the leaf sample size had to be adjusted if the number of samples was < 30 leaves.

$$\text{SLA dry } \left(dm^2 / g\ DW\right) \text{ (sample } n = 30) = \frac{\text{Sum of leaf area of sampled leaves } \left[dm^2\right]}{30 * \text{mean DW of 30 leaves } [g/\ \text{leaf}]}$$

$$\text{SLA moist } \left(dm^2 / g\ WW\right) \text{ (sample } n = 30) = \frac{\text{Sum of leaf area of sampled leaves } \left[dm^2\right]}{30 * \text{mean WW of 30 leaves } [g/\ \text{leaf}]}$$

Dry weight of branch, bark and stem samples

$$\text{DW sample } = 1 - WC\ [g / g \text{ moist}]$$

Average thickness of bark

The average bark thickness for the bark biomass calculation was determined by the average bark thickness of stem disks 1 – 5.

Fine root density

$$\text{Root density } \left[g / cm^3\right] = \frac{\text{Root biomass } [g]}{\text{Volume of the soil sample } \left[cm^3\right]}$$

Total amount of a given nutrient in a given tree compartment

$$\begin{gathered}\text{Total nutrient in tree compartment [kg]} = \\ \text{Total biomass of compartment [kg]} \times \frac{\text{Nutrient concentration [g]}}{1000}\end{gathered}$$

Mass loss correction factor (MLCF) at time point xy

$$MLCF = 1 - \frac{Mean\ SLA\ green\ leaves\ \left[dm^2 / g\ DW\right]\ (top;\ middle;\ bottom)}{SLA\ litter\ time\ point\ xy\ \left[dm^2 / g\ DW\right]}$$

Nutrient stock

For the depth of 25-50 cm in the soil at Arisdorf, the nutrient concentrations from the depth of 0-25 cm were used and the fine earth BD was halved as an approximation for the higher proportion of the soil skeleton. The nutrient stock was calculated for a depth of 50 cm.

$$Fine\ earth\ BD\ \left[g / cm^3\right] = \frac{Fine\ earth\ DW\ [g]}{Sample\ volume\ \left[cm^3\right]}$$

$$Nutrient\ stock\ [kg / ha] = Fine\ earth\ BD\ \left[g / cm^3\right] \times 1'000'000 \times Nutrient\ concentration\ [kg / kg]$$

CEC

$$Equivalent\ mass_{cation}\ [mmol_c / kg] = Relative\ atomic\ mass\ /\ valency_{cation}$$

$$Cation\ equivalent\ [mmol_c / kg] = \frac{Nutrient\ concentration\ [mg / kg]}{Equivalent\ mass\ [mmol_c / 100\ g] \times 10} \times 10$$

H+ [mmol$_c$/kg] data was taken from the soil profile data of Waldlabor and Arisdorf with the assumption that the concentration is similar.

The CEC is calculated as the sum of the cation equivalents of the below listed cations:

$$CEC\ [mmol_c / kg] = Ca^{2+} + Mg^{2+} + K^+ + Na^+ + H^+ + Al^{3+}$$

BS

$$BS\ [\%] = \frac{Ca^{2+} + Mg^{2+} + K^+ + Na^+}{CEC\ \ [mmol_c / kg]} \times 100$$

6.2 Declaration of contribution to the data collection

The data collection of the data used in this thesis was done before this thesis started, meaning that the data for this thesis was mostly obtained.

The exception was the evaluation with the program WINSEEDLE to calculate afterwards the leaf area of the leaf scans for the SLA of the green leaves and the leaves from the litter (see chapter 2.1 for details).

On the other hand, I could contribute to the data collection for the additional sites of the Swiss Biomass project, Apples (Canton of Vaud) and Villigen (Canton of Aargau) in Switzerland. There, I assisted and conducted the following data collections. The data from these two sites was collected in the same way as the data from Waldlabor and Arisdorf. Therefore, details on sampling and processing procedure at the laboratory can be looked up in chapter 2.1 and 2.3.

- Pre-processing of sample of green leaves and leaves from litter of *Fagus sylvatica* and *Quercus* procedure to determine the SLA for Villigen (Weighing, drying, scanning, for details see chapter 2.1)
- Pre-processing of branches with needles and SLA measurements of *Picea abies* for Villigen (sampling and removing of needles from branches, sampling of branches with a diameter of < 5 mm and 5 – 20 mm, drying branches and needles, scanning of needles to determine the SLA, see chapt. 2.1 for details).
- Field work during wood harvesting in Villigen (see 2.1 for details on sampling)
- Assistance in collection of soil samples in a depth of 0 – 25 cm around *Fagus sylvatica* trees in Villigen
- Pre-processing of the soil samples (weighing, sorting roots out of *Picea abies* and *Fagus sylvatica* and *Quercus*, washing and weighing of roots, drying and sieving of soil samples)
- Assistance in pre-processing of stem disks of Villigen (weighing, labelling, bark thickness and circumference measurement of stem disks)
- “Olsen P” measurements of the soil samples of Villigen in the laboratory

6.3 R-Code and statistical test results

6.3.1 R-Code

In the following exemplary R codes for the t-tests, the ANOVA, the Krusal Wallis test, the Eta Square test as well as the sub steps are provided.

```
# hypothesis 1 - t-tests Waldlabor Arisdorf (same procedure for Bülach and Irchel)

# Shapiro-Wilk normality test (example of N concentration in leaves)

capture.output(apply(nutrients_hyp1_v2,2,shapiro.test), file = "ZF_shapiro_beech_v2.csv")


# Levene's Test for Homogeneity of Variance (example of N concentration in leaves)

leveneTest(N_leaves ~ Site, data = nutrients_hyp1_levene)


# Tukey's Ladder of Powers (example for Mg concentration in stem)

# transformation of data to reach normal distribution

# if (lambda >  0){TRANS = x ^ lambda}

# if (lambda == 0){TRANS = log(x)}

# if (lambda <  0){TRANS = -1 * x ^ lambda}

nutrients_hyp1_all$N_stem_tuk = transformTukey(nutrients_hyp1_all$N_stem,

                                               plotit=FALSE)


# Welch Two Sample t-test (example of N concentration in stem, tukey transformed)

# alternative hypothesis: true difference in means between group Arisdorf and group Waldlabor is not equal to 0

# 95 percent confidence interval

t.test(N_stem_tuk ~ Site, data = nutrients_hyp1_all)
```

```
# Wilcoxon rank sum exact test (non-parametric test) (example of organic C concentration in the soil)
# alternative hypothesis: true location shift is not equal to 0
wilcox.test(nutrients_hyp1_all$Corg_soil ~ nutrients_hyp1_all$Site, exact = TRUE, correct = FALSE)

################################ ANOVA / Kruskal-Wallis test #####################################
# 1. Visual assessment of normal distribution of the data
# 1.1 QQPlot of all data: quantile-quantile plot
ggqqplot(nutrients$N_leaves_needles, ylab = "[g/kg]", xlab = "", title = "Normal distribution of N in leaves / needles")

# 1.2 Shapiro-Wilk Normality Test (example of N concentration in leaves and needles)
shapiro.test(nutrients$N_leaves_needles)
# 1.3 Histogram
hist(nutrients$N_leaves_needles, main = "Histogram of N in leaves / needles", ylab = "", xlab = "N [g/kg]")



## 2. Fit an Analysis of Variance Model (one-way)
# = test if there is a significant difference between the means of two independent groups (example of N concentration in leaves
and needles
# factors = grouping variables
# Hypothesis N0: There is no difference in the means of factor
# Alternative hypothesis = means are not equal.
# Model assumptions: normal distribution and equal variances
aov_N_leav_needl <- aov(N_leaves_needles ~  Geological_substrate_group, data = nutrients)
## summarize model output
summary(aov_N_leav_needl)

## 3. Test assumptions of ANOVA
# 3.1 Check for normal distribution (visual) (example of N concentration in leaves and needles)
# QQ-Plot/ Normality plot of the residuals
# quantiles of residuals are plotted vs. quantiles of normal distribution
# The normal probability plot of the residuals should approximately follow a straight line.
plot(aov_N_leav_needl, 2, main = "Residual plot N in leaves & needles*)

# identify outliers (example of geological substrate group carbonaceous loose)
## carbonaceous_loose
identify_outliers(nutrients[2:32,6])

# 3.2 Shapiro-Wilk Normality Test - test normal distribution of residuals of the ANOVA model
```

```
shapiro.test(aov_N_leav_needl$residuals)


# 3.3 Check the homogeneity of variance assumption
# 3.3.1 Residual vs. fitted plot (visual) (example of N concentrations in leaves and needles)
par(mfrow = c(1, 1))
plot(aov_N_leav_needl, 1)
# 3.3.2 Levene's Test of residuals
# p-value > 0.05 means that variances are equal
leveneTest(N_leaves_needles ~ Geological_substrate_group  , data = nutrients)


# 4. Tukey's Ladder of Powers (example of N concentration in leaves and needles) to reach normal distribution
nutrients$N_leav_needl_tuk = transformTukey(nutrients$N_leaves_needles, plotit=FALSE)


# 5. Kruskal Wallis test (non-parametric) (example for N concentration in leaves and needles)
# for independent samples, tests whether the central tendencies of several independent samples differ.
# is used when the requirements for an ANOVA are not met.
kruskal_Nleavneedl <- kruskal.test(N_leaves_needles ~ Geological_substrate_group, data = nutrients)


# 6. If significant difference: conduct a post-hoc test to test which groups are significantly different
# 6.1 ANOVA: Tukey Honest Significant Differences: multiple comparisons of means (example for Ca concentration in branches)
#   95% family-wise confidence level
Ca_branches_tukey <- TukeyHSD(aov_tuk_nutrients_Ca_branches)
# 6.2 Kruskal Wallis: Pairwise Wilcoxon Rank Sum Tests (example for Mg concentration in leaves and needles)
pairwise.wilcox.test(nutrients$Mg_leaves_needles, nutrients$Geological_substrate_group,
                     p.adjust.method = "BH", exact=FALSE)


# 7. Effect size Eta Squared
# measures the proportion of variance associated with each effect in an ANOVA model or Kruskal Wallis test.
# 0.01: Effect size is small.
# 0.06: Effect size is medium.
# Large effect size if the number is 0.14 or above.
# 7.1 code for Eta Squared if ANOVA preceded (example for Ca concentration in leaves and needles)
etaSquared(aov_Ca_leav_needl_tuk)
#                                        eta.sq eta.sq.part
# 7.2 code for Eta Squared if Kruskal Wallis test preceded (example for N concentration in leaves and needles)
nutrients %>%
  kruskal_effsize(N_leaves_needles ~ Geological_substrate_group)
```

6.3.2 Statistical test results

In the following, the test statistics for each conducted test are presented (Table A1-11). Grey filled fields mean that no test statistic of this test type was calculated for this parameter.

Table A 1: Summary table of the Welch Two Sample T-test of the nutrient concentrations by tree compartment at Waldlabor and Arisdorf. T = t-value, Df = degrees of freedom. Data transformations prior to the test are marked in blue. A p-value <0.05 indicates significant difference.

	T	Df	P-value	T	Df	P-value	T	Df	P-value
	Leaves			**Branches**			**Bark**		
N	-1.245	7.995	0.248	2.017	6.567	0.086	-3.188	7.064	0.015
P	-4.104	6.024	0.006	-3.428	5.228	0.017	-2.579	6.240	0.040
S	0.573	7.577	0.583	5.883	6.102	0.001	-0.993	7.996	0.350
K	0.072	7.580	0.945	-1.139	5.764	0.300	-1.030	7.999	0.333
Mg	-4.758	5.754	0.004	-6.278	6.646	< 0.001	-2.514	6.632	0.042
Ca	7.419	5.995	< 0.001	5.105	7.932	< 0.001	5.972	6.790	< 0.001
	Stem			**Fine roots**					
N	-1.598	6.953	0.154	0.356	7.941	0.731			
P	-1.720	7.990	0.124	-3.413	7.854	0.009			
S	-0.551	6.224	0.601	-0.232	5.521	0.825			
K	2.440	7.990	0.041	-6.161	7.343	< 0.001			
Mg	0.214	7.360	0.836						
Ca	-2.374	5.332	0.060	6.023	7.985	< 0.001			

Table A 2: Summary table of the Welch Two Sample T-test of the nutrient concentrations in the soil at Waldlabor and Arisdorf. T = t-value, Df = degrees of freedom. Data transformations prior to the test are marked in blue. A p-value <0.05 indicates significant difference.

	T	Df	P-value
		Soil	
C_{org}			
N_{tot}			
C:N	7.699	4.386	0.001
P_{tot}	3.490	5.148	0.017
P_{inorg}	7.432	4.415	0.001
P_{org}	-0.800	4.471	0.464
K	6.366	7.998	< 0.001
Mg	-10.078	7.620	< 0.001
Ca			

Table A 3: Summary table of the Wilcoxon Rank Sum Test of the nutrient concentrations by tree compartment at Waldlabor and Arisdorf. W = test statistic. A p-value <0.05 indicates significant difference.

	W	P-value	W	P-value	W	P-value
	Leaves		**Branches**		**Bark**	
N						
P						
S						
K						
Mg						
Ca						
	Bark		**Stem**		**Fine roots**	
N						
P						
S						
K						
Mg					25	0.008
Ca						

Table A 4: Summary table of the Wilcoxon Rank Sum Test of the nutrient concentrations in the soil at Waldlabor and Arisdorf. W = test statistic. A p-value <0.05 indicates significant difference.

	W	P-value
	Soil	
C_{org}	25	0.008
N_{tot}	25	0.008
C:N		
K		
Mg		
Ca	25	0.008

Table A 5: Summary table of the Welch Two Sample T-test of the nutrient concentrations by tree compartment at Bülach and Irchel. T = t-value, Df = degrees of freedom. Data transformations prior to the test are marked in blue. A p-value <0.05 indicates significant difference.

	T	Df	P-value	T	Df	P-value	T	Df	P-value
	Branches < 5 mm			**Branches 5-20 mm**			**Branches 20-70 mm**		
N	0.924	7.531	0.384	-0.185	4.332	0.862	0.518	4.578	0.629
P	5.282	6.686	0.001	2.172	7.900	0.062	3.255	7.775	0.012
S	0.417	7.102	0.689	-0.574	5.306	0.590	-0.812	7.928	0.440
K	-0.363	7.331	0.727	-0.261	7.890	0.801	-2.703	8.000	0.027
Mg	2.006	7.997	0.080	0.397	6.813	0.704	-0.638	5.082	0.551
Ca	-0.407	7.661	0.695	-0.628	6.309	0.552	0.493	7.788	0.636
	Bark			**Stem 70 mm - >250 mm**					
N	0.737	5.249	0.493	0.428	4.610	0.688			
P	3.372	5.162	0.019	1.763	6.770	0.123			
S	1.798	5.608	0.126	-1.863	7.986	0.099			
K	-3.375	7.810	0.010	-1.238	7.174	0.255			
Mg	-1.077	6.992	0.317	-0.821	4.652	0.451			
Ca	-0.195	7.885	0.851	-0.255	6.912	0.806			

*Table A 6: Summary table of the ANOVA by nutrient and geological substrate group. Df = degrees of freedom, Sum Sq = sum of squares, Mean Sq = mean squares, Pr(>F) = p-value. Data transformations prior to the test are marked in blue. Significance levels p-values: *** <0.001, ** <0.01, * <0.05.*

	Df	Sum Sq	Mean Sq	F-value	Pr(>F)		Df	Sum Sq	Mean Sq	F-value	Pr(>F)	
Nutrient			**Leaves**						**Branches**			
N							3	13.640	4.546	1.571	0.202	
Residuals							87	251.690	2.893			
P	3	0.172	0.057	2.798	0.045	*	3	0.010	0.003	3.138	0.029	*
Residuals	89	1.822	0.020				87	0.089	0.001			
K							3	10.100	3.366	5.194	0.002	**
Residuals							89	57.680	0.648			
Mg							3	0.013	0.004	1.968	0.125	
Residuals							90	0.205	0.002			
Ca	3	0.213	0.071	7.906	< 0.001	***	3	0.234	0.078	6.269	< 0.001	***
Residuals	92	0.828	0.009				90	1.122	0.012			
Nutrient			**Bark**						**Stem**			
N	3	5.304	1.7682	6.351	< 0.001	***	3	0.065	0.022	1.231	0.303	
Residuals	90	25.056	0.2784				89	1.557	0.017			
P							3	0.063	0.021	3.055	0.032	*
Residuals							108	0.755	0.007			
K												
Residuals												
Mg	3	0.676	0.225	4.995	0.003	**						
Residuals	112	5.051	0.045									
Ca												
Residuals												

*Table A 7: Summary table of the Kruskal Wallis test by nutrient and geological substrate group. Df = degrees of freedom. Data transformations prior to the test are marked in blue. Significance levels p-values: *** <0.001, ** <0.01, * <0.05.*

	Chi-squared	Df	P-value		Chi-squared	Df	P-value
Nutrient		**Leaves**				**Branches**	
N	7.004	3	0.072	(.)			
P							
K	4.815	3	0.186				
Mg	12.860	3	0.005	**			
Ca							
Nutrient		**Bark**				**Stem**	
N							
P	20.934	3	< 0.001	***			
K	35.432	3	< 0.001	***	2.646	3	0.450
Mg					0.852	3	0.837
Ca	8.314	3	0.040	*	0.722	3	0.868

Table A 8: Summary table of the post-hoc Tukey test of the nutrient concentrations with significant differences in the ANOVA. Diff = Mean difference between 2 groups, Lwr = lower end point of interval, Upr = upper end point of interval, p adj = p-value. A P-value <0.05 indicates significant differences.

		Ca				**P**			
		Leaves / needles				**Leaves needles**			
		Diff	Lwr	Upr	P adj	Diff	Lwr	Upr	P adj
Carbonaceous loose	Carbonaceous solidified	0.142	0.061	0.222	< 0.001	-0.119	-0.241	0.002	0.056
	Siliceous loose	0.050	-0.023	0.123	0.283	-0.013	-0.125	0.099	0.990
	Siliceous solidified	0.034	-0.040	0.107	0.631	-0.030	-0.141	0.082	0.896
Carbonaceous solidified	Siliceous loose	-0.092	-0.165	-0.019	0.007	0.106	-0.006	0.218	0.070
	Siliceous solidified	-0.108	-0.182	-0.034	0.001	0.090	-0.022	0.201	0.159
Siliceous loose	Siliceous solidified	-0.016	-0.081	0.049	0.916	-0.017	-0.118	0.084	0.973
		P				**K**			
		Branches				**Branches**			
		Diff	Lwr	Upr	P adj	Diff	Lwr	Upr	P adj
Carbonaceous loose	Carbonaceous solidified	0.017	-0.008	0.042	0.306	0.605	-0.017	1.227	0.060
	Siliceous loose	0.008	-0.015	0.032	0.797	-0.011	-0.590	0.569	1.000
	Siliceous solidified	0.028	0.003	0.053	0.022	0.709	0.087	1.331	0.019
Carbonaceous solidified	Siliceous loose	-0.008	-0.034	0.017	0.813	-0.615	-1.242	0.012	0.056
	Siliceous solidified	0.011	-0.015	0.037	0.687	0.104	-0.562	0.771	0.977
Siliceous loose	Siliceous solidified	0.020	-0.005	0.044	0.174	0.719	0.092	1.346	0.018
		Ca				**N**			
		Branches				**Bark**			
		Diff	Lwr	Upr	P adj	Diff	Lwr	Upr	P adj
Carbonaceous loose	Carbonaceous solidified	0.126	0.040	0.212	0.001	0.483	0.069	0.898	0.015
	Siliceous loose	0.037	-0.044	0.117	0.630	0.601	0.221	0.981	< 0.001
	Siliceous solidified	-0.006	-0.091	0.079	0.998	0.455	0.046	0.864	0.023
Carbonaceous solidified	Siliceous loose	-0.089	-0.176	-0.002	0.042	0.117	-0.287	0.522	0.873
	Siliceous solidified	-0.132	-0.223	-0.041	0.002	-0.029	-0.460	0.403	0.998
Siliceous loose	Siliceous solidified	-0.043	-0.129	0.043	0.562	-0.146	-0.545	0.253	0.774
		Mg				**P**			
		Bark				**Stem**			
		Diff	Lwr	Upr	P adj	Diff	Lwr	Upr	P adj
Carbonaceous loose	Carbonaceous solidified	0.176	0.026	0.325	0.014	-0.027	-0.087	0.033	0.649
	Siliceous loose	0.179	0.038	0.320	0.007	0.014	-0.044	0.071	0.926
	Siliceous solidified	0.188	0.034	0.341	0.010	-0.047	-0.106	0.013	0.175
Carbonaceous solidified	Siliceous loose	0.004	-0.136	0.143	1.000	0.040	-0.017	0.098	0.259
	Siliceous solidified	0.012	-0.140	0.165	0.997	-0.020	-0.079	0.039	0.822
Siliceous loose	Siliceous solidified	0.009	-0.136	0.153	0.999	-0.060	-0.116	-0.004	0.031

Table A 9: Summary table of Pairwise Wilcoxon Rank Sum Tests of the nutrient concentrations with significant differences in the Kruskal-Wallis test. P-value <0.05 indicates significant differences.

	Carbonaceous loose	Carbonaceous solidified	Siliceous loose
Mg in leaves/ needles			
	P-value		
Carbonaceous solidified	0.012	-	-
Siliceous loose	0.806	0.052	-
Siliceous solidified	0.317	0.006	0.317
Ca in bark			
	P-value		
Carbonaceous solidified	0.102	-	-
Siliceous loose	0.677	0.075	-
Siliceous solidified	0.290	0.102	0.404
K in bark			
	P-value		
Carbonaceous solidified	< 0.001	-	-
Siliceous loose	< 0.001	0.910	-
Siliceous solidified	< 0.001	0.260	0.530
P in bark			
	P-value		
Carbonaceous solidified	0.006	-	-
Siliceous loose	0.001	0.172	-
Siliceous solidified	< 0.001	0.138	0.771

Table A 10: Summary table of the Eta Squared effect size of the ANOVA results. The eta-squared value shows the strength or magnitude related to the effect.

	Leaves		**Branches**		**Bark**		**Stem**	
Nutrient	Eta square	Magnitude	Eta square	Magnitude	Eta square	Magnitude	Eta square	Magnitude
N					0.160	large		
P	0.086		0.098	large			0.078	large
K			0.149	large				
Mg					0.118	large		
Ca	0.205	large	0.173	large				

Table A 11: Summary table of the Kruskal-Wallis Effect Size. Effsize = estimate of the effect size, magnitude = magnitude of effect size.

	Leaves		**Branches**		**Bark**		**Stem**	
Nutrient	Effsize	Magnitude	Effsize	Magnitude	Effsize	Magnitude	Effsize	Magnitude
N								
P					0.145	large		
K					0.262	large		
Mg	0.0795	moderate						
Ca					0.043	small		

6.4 Additional figures

In this section, additional figures (Figure A1–4) are presented with the in the data marked points of the four Swiss study sites: Q49 stands for Arisdorf, Q76 for Waldlabor, Q30 for Bülach and Q31 for Irchel.

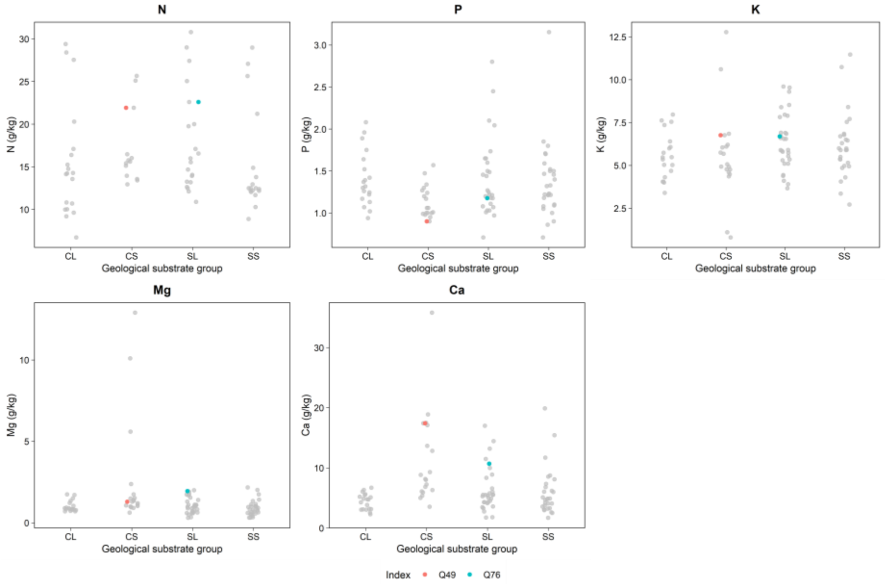

Figure A 1: Boxplots with nutrient concentrations in leaves and needles [g/kg] by geological substrate. The geological substrate groups are CL = carbonaceous loose, CS = carbonaceous solidified, SL = siliceous loose, SS = siliceous solidified. Q49 = Arisdorf, Q76 = Waldlabor.

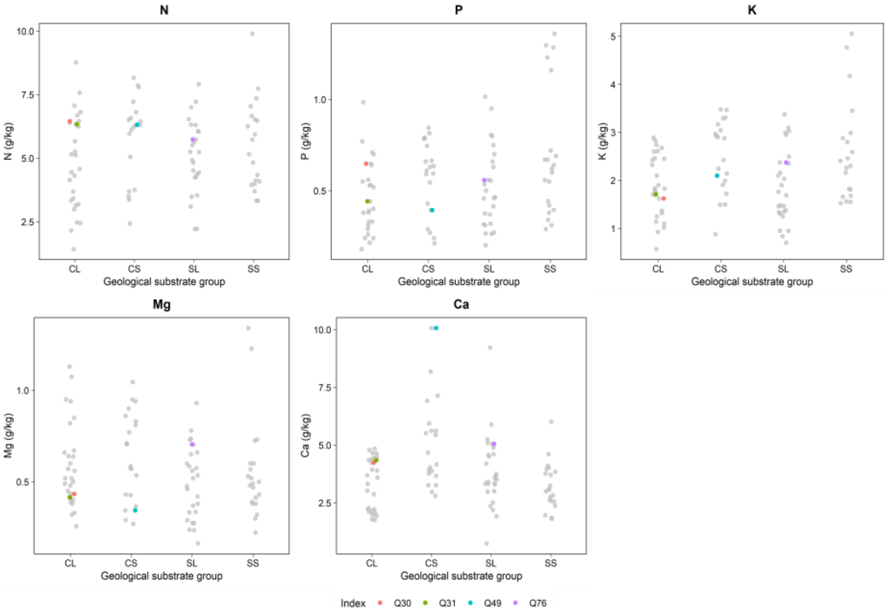

Figure A 2: Boxplots with nutrient concentrations in branches [g/kg] by geological substrate. The geological substrate groups are CL = carbonaceous loose, CS = carbonaceous solidified, SL = siliceous loose, SS = siliceous solidified. Q49 = Arisdorf, Q76 = Waldlabor, Q30 = Bülach, Q31 = Irchel.

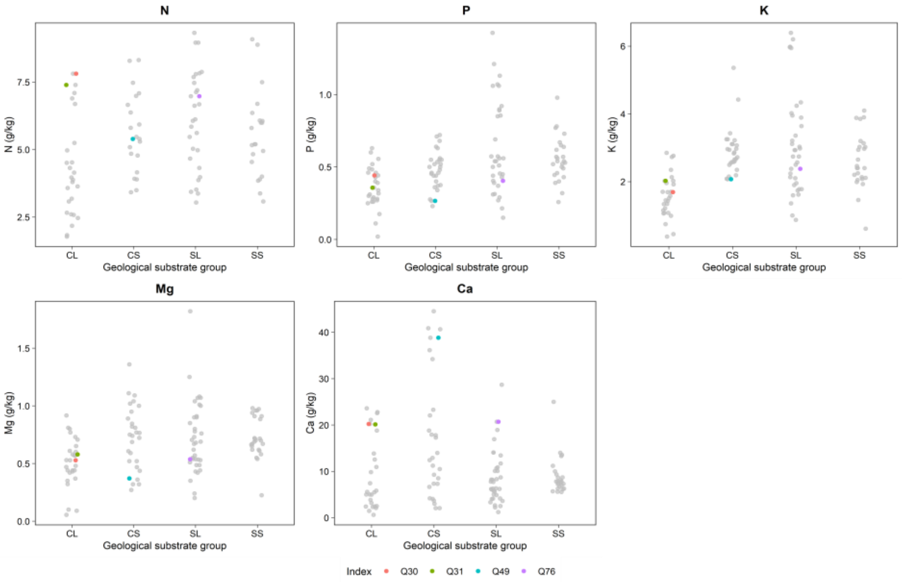

Figure A 3: Boxplots with nutrient concentrations [g/kg] in bark by geological substrate. The geological substrate groups are CL = carbonaceous loose, CS = carbonaceous solidified, SL = siliceous loose, SS = siliceous solidified. Q49 = Arisdorf, Q76 = Waldlabor, Q30 = Bülach, Q31 = Irchel.

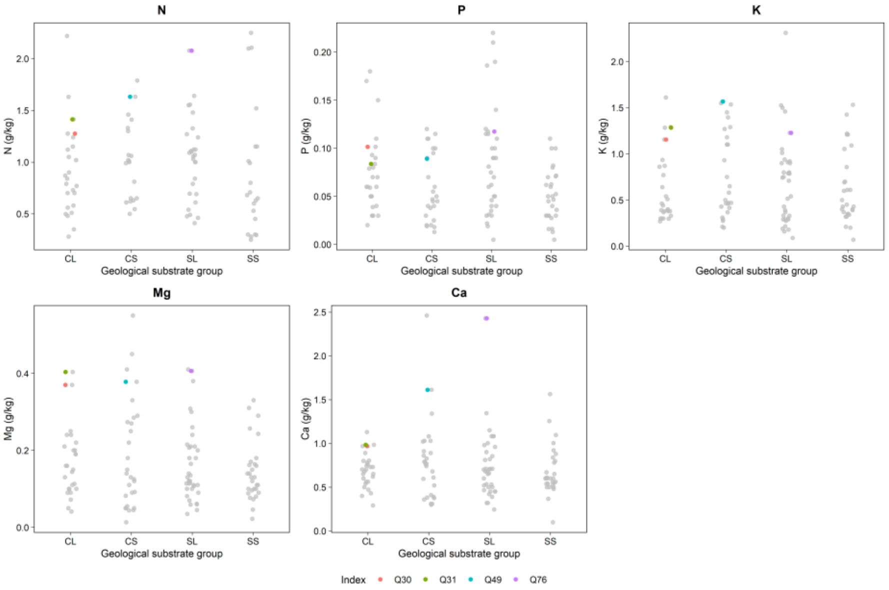

Figure A 4: Boxplots with nutrient concentrations[g/kg] in stem by geological substrate. The geological substrate groups are CL = carbonaceous loose, CS = carbonaceous solidified, SL = siliceous loose, SS = siliceous solidified. Q49 = Arisdorf, Q76 = Waldlabor, Q30 = Bülach, Q31 = Irchel.

6.5 Literature overview ANOVA

Table A 12: Sources, origin country, tree species, geologic substrate and attributed group and soil of the studies investigated in the ANOVA and the Kruskal Wallis tests. Luster et al. (2021) refers to the data of Waldlabor and Arisdorf used in this thesis and is not cited in the references.

Index	Source	Country	Tree species	Geologic substrate	Geological substrate group	Soil classified
Q1	Bredemeier 1987	Germany (Niedersachsen)	*Fagus sylvatica*	Upper Muschelkalk loess	Carbonaceous loose	Parabraunerde
Q2	Bredemeier 1987	Germany (Lüneb. Heide)	*Quercus*	Pleistocene	Carbonaceous loose	Podsol / Braunerde
Q3	Bredemeier 1987	Germany (Lüneb. Heide)	*Pinus sylvestris*	Pleistocene	Carbonaceous loose	Podsol / Braunerde
Q4	Dietrich et al. 2002	Germany (Bayern)	*Picea abies*	Carbonaceous loose sediment	Carbonaceous loose	Parabraunerde
Q5	Eriksson and Rosen 1994	Sweden (south)	*Picea abies*	Pleistocene	Carbonaceous loose	Dystochrept
Q6	Eriksson and Rosen 1994	Sweden (south)	*Larix decidua*	Pleistocene	Carbonaceous loose	Dystochrept
Q7	Eriksson and Rosen 1994	Sweden (south)	*Abies alba*	Pleistocene	Carbonaceous loose	Dystochrept
Q8	Eriksson and Rosen 1994	Sweden (south)	*Abies alba*	Pleistocene	Carbonaceous loose	Dystochrept
Q9	Gehrmann 2002	Germany (NRW)	*Fagus sylvatica*	Pleistocene	Carbonaceous loose	Podsol
Q10	Gehrmann 2002	Germany (NRW)	*Pinus sylvestris*	Sandy loess	Carbonaceous loose	Podsol / Braunerde
Q11	Gehrmann 2002	Germany (NRW)	*Fagus sylvatica*	Lower Muschelkalk loess	Carbonaceous loose	Braunerde / Pseudogley
Q12	Huber et al. 2011	Germany (München)	*Picea abies*	Pleistoceneen loess over tertiary silty sand	Carbonaceous loose	Braunerde / Parabraunerde
Q13	Heinsdorf and Krauß 1990	Germany (Brandenburg)	*Pinus sylvestris*	Pleistocene	Carbonaceous loose	Podsol / Braunerde
Q14	Markan 1993	Germany (Berlin)	*Quercus*	Pleistocene	Carbonaceous loose	Podsol / Braunerde
Q15	Markan 1993	Germany (Berlin)	*Quercus*	Pleistocene	Carbonaceous loose	Podsol / Braunerde
Q16	Miller et al. 1976	Scotland	*Pinus nigra*	Shifting sand	Carbonaceous loose	Unknown
Q17	Rademacher et al. 1999	Germany (Lüneb. Heide)	*Pinus sylvestris*	Pleistocene	Carbonaceous loose	Braunerde / Podsol
Q18	Rademacher et al. 1999	Germany (Lüneb. Heide)	*Pinus sylvestris*	Pleistocene	Carbonaceous loose	Braunerde / Podsol
Q19	Rademacher et al. 1999	Germany (Lüneb. Heide)	*Pinus sylvestris*	Pleistocene	Carbonaceous loose	Braunerde / Podsol
Q20	Rademacher et al. 2001	Germany (Lüneb. Heide)	*Quercus*	Gravel sand	Carbonaceous loose	Braunerde / Podsol
Q21	Steiner et al. 1998	Germany (Brandenburg)	*Pinus sylvestris*	Pleistocene	Carbonaceous loose	Podsol / Braunerde
Q22	Steiner et al. 1998	Germany (Brandenburg)	*Pinus sylvestris*	Pleistocene	Carbonaceous loose	Podsol / Braunerde
Q23	Weis et al. 2009	Germany (Bayern)	*Picea abies*	Pleistocene loess over tertiary silty sand deposits	Carbonaceous loose	Parabraunerde
Q24	Wright and Will 1958	Scotland	*Pinus sylvestris*	Dune sand	Carbonaceous loose	Unknown
Q25	Wright and Will 1958	Scotland	*Pinus sylvestris*	Dune sand	Carbonaceous loose	Unknown
Q26	Wright and Will 1958	Scotland	*Pinus sylvestris*	Dune sand	Carbonaceous loose	Unknown
Q27	Wright and Will 1958	Scotland	*Pinus nigra*	Dune sand	Carbonaceous loose	Unknown
Q28	Wright and Will 1958	Scotland	*Pinus nigra*	Dune sand	Carbonaceous loose	Unknown
Q29	Wright and Will 1958	Scotland	*Pinus nigra*	Dune sand	Carbonaceous loose	Unknown

Index	Source	Country	Tree species	Geologic substrate	Geological substrate group	Soil classified
Q30	Zimmermann et al. 2020	Switzerland (Zurich)	*Fagus sylvatica*	Pleistocene	Carbonaceous loose	Cambisol / Luvisol
Q31	Zimmermann et al. 2020	Switzerland (Zurich)	*Fagus sylvatica*	Pleistocene	Carbonaceous loose	Cambisol / Luvisol
Q32	Block et al. 2016	Germany	*Fagus sylvatica*	Devon I	Carbonaceous solidified	Podsol / Braunerde / Pseudogley
Q33	Block et al. 2016	Germany	*Fagus sylvatica*	Devon II	Carbonaceous solidified	Braunerde / Pseudogley
Q34	Block et al. 2016	Germany	*Fagus sylvatica*	Devon III	Carbonaceous solidified	Braunerde / Pseudogley / Parabraunerde
Q35	Block et al. 2016	Germany	*Quercus*	Devon I	Carbonaceous solidified	Podsol / Braunerde / Pseudogley
Q36	Block et al. 2016	Germany	*Quercus*	Devon II	Carbonaceous solidified	Braunerde / Pseudogley
Q37	Block et al. 2016	Germany	*Quercus*	Devon III	Carbonaceous solidified	Braunerde / Pseudogley / Parabraunerde
Q38	Block et al. 2016	Germany	*Picea abies*	Devon I	Carbonaceous solidified	Podsol / Braunerde
Q39	Block et al. 2016	Germany	*Picea abies*	Devon II	Carbonaceous solidified	Braunerde / Pseudogley
Q40	Block et al. 2016	Germany	*Picea abies*	Devon III	Carbonaceous solidified	Braunerde / Pseudogley / Parabraunerde
Q41	Block et al. 2016	Germany	*Pinus sylvestris*	Devon I	Carbonaceous solidified	Podsol / Braunerde / Pseudogley
Q42	Block et al. 2016	Germany	*Pinus sylvestris*	Devon II	Carbonaceous solidified	Braunerde / Pseudogley
Q43	Block et al. 2016	Germany	*Pseudotsuga menziesii*	Devon I	Carbonaceous solidified	Podsol / Braunerde / Pseudogley
Q44	Block et al. 2016	Germany	*Pseudotsuga menziesii*	Devon II	Carbonaceous solidified	Braunerde / Pseudogley
Q45	Calvaruso et al. 2017	France	*Fagus sylvatica*	Tithonian limestone	Carbonaceous solidified	Leptosol / Braunerde
Q46	Gehrmann 2002	Germany (NRW)	*Quercus*	Terrace gravel	Carbonaceous solidified	Braunerde / Pseudogley
Q47	Gehrmann 2002	Germany (NRW)	*Picea abies*	Flammenmergel	Carbonaceous solidified	Podsol
Q48	Hochbichler et al. 1994	Austria	*Fagus sylvatica*	Flysch	Carbonaceous solidified	Braunerde
Q49	Luster et al. 2021	Switzerland (Basel)	*Fagus sylvatica*	Mergelstein; Kalkoolith	Carbonaceous solidified	Rendzic Leptosol
Q50	Meiwes and Beese 1988	Germany (Nds. Bergland)	*Fagus sylvatica*	Lower Muschelkalk	Carbonaceous solidified	Terrua Fusca / Rendzina
Q51	Ranger et al. 1995	France	*Pseudotsuga menziesii*	Dev.Dinantian	Carbonaceous solidified	Dystochrept
Q52	Ranger et al. 1995	France	*Pseudotsuga menziesii*	Dev.Dinantian	Carbonaceous solidified	Dystochrept
Q53	Ranger et al. 1995	France	*Pseudotsuga menziesii*	Dev.Dinantian	Carbonaceous solidified	Dystochrept
Q54	Trüby 1994	Germany (Nördl.Eifel)	*Fagus sylvatica*	Carbonaceous	Carbonaceous solidified	Unknown
Q55	Trüby 1994	Germany (Nördl.Eifel)	*Fagus sylvatica*	Carbonaceous	Carbonaceous solidified	Unknown
Q56	Trüby 1994	Germany (Nördl.Eifel)	*Quercus*	Carbonaceous	Carbonaceous solidified	Unknown
Q57	Trüby 1994	Germany (Nördl.Eifel)	*Picea abies*	Carbonaceous	Carbonaceous solidified	Unknown
Q58	Trüby 1994	Germany (Nördl.Eifel)	*Picea abies*	Carbonaceous	Carbonaceous solidified	Unknown
Q59	Trüby 1994	Germany (Nördl.Eifel)	*Pinus sylvestris*	Carbonaceous	Carbonaceous solidified	Unknown
Q60	Block et al. 2016	Germany	*Fagus sylvatica*	Rotliegendes	Siliceous loose	Braunerde / Pseudogley

Index	Source	Country	Tree species	Geologic substrate	Geological substrate group	Soil classified
Q61	Block et al. 2016	Germany	*Fagus sylvatica*	Sand of red sandstones	Siliceous loose	Podsol / Braunerde
Q62	Block et al. 2016	Germany	*Quercus*	Rotliegendes	Siliceous loose	Braunerde / Pseudogley
Q63	Block et al. 2016	Germany	*Quercus*	Sand of red sandstones	Siliceous loose	Podsol / Braunerde
Q64	Block et al. 2016	Germany	*Picea abies*	Sand of red sandstones	Siliceous loose	Podsol / Braunerde
Q65	Block et al. 2016	Germany	*Pinus sylvestris*	Alluvial sand	Siliceous loose	Sand
Q66	Block et al. 2016	Germany	*Pinus sylvestris*	Sand of red sandstones	Siliceous loose	Podsol / Braunerde
Q67	Block et al. 2016	Germany	*Pseudotsuga menziesii*	Rotliegendes	Siliceous loose	Braunerde / Pseudogley
Q68	Block et al. 2016	Germany	*Pseudotsuga menziesii*	Sand of red sandstones	Siliceous loose	Podsol / Braunerde
Q69	Block et al. 2016	Germany	*Larix decidua*	Sand of red sandstones	Siliceous loose	Podsol / Braunerde
Q70	Bredemeier 1987	Germany (S. Niedersachsen)	*Picea abies*	Red sandstone loess	Siliceous loose	Podsol / Braunerde
Q71	Dietrich et al. 2002	Germany (Bayern)	*Picea abies*	Loose sediment	Siliceous loose	Braunerde / Pseudogley
Q72	Ellenberg et al. 1986	Germany (Niedersachsen)	*Fagus sylvatica*	Bundsandstein loess	Siliceous loose	Clay loamy silt
Q73	Gehrmann 2002	Germany (NRW)	*Fagus sylvatica*	Phyllit / quarzit loess	Siliceous loose	Podsol / Pseudogley
Q74	Ingerslev and Hallbäcken 1999	Denmark	*Picea abies*	Dune sand	Siliceous loose	Podsol
Q75	Lamersdorf 1988	Germany (Niedersachsen)	*Picea abies*	Shifting sand	Siliceous loose	Podsol
Q76	Luster et al. 2021	Switzerland (Zurich)	*Fagus sylvatica*	Pleistocene	Siliceous loose	Pseudogleyed Luvisol
Q77	Neirynck et al. 1998	Belgium (north-east)	*Pinus nigra*	Pleistocene over tertiary	Siliceous loose	Podsol
Q78	Pavlov 1972	Germany (S. Niedersachsen)	*Fagus sylvatica*	Red sandstone loess	Siliceous loose	Podsol / Braunerde
Q79	Pavlov 1972	Germany (S. Niedersachsen)	*Fagus sylvatica*	Red sandstone loess	Siliceous loose	Podsol / Braunerde
Q80	Pavlov 1972	Germany (S. Niedersachsen)	*Fagus sylvatica*	Red sandstone loess	Siliceous loose	Podsol / Braunerde
Q81	Pavlov 1972	Germany (S. Niedersachsen)	*Picea abies*	Red sandstone loess	Siliceous loose	Podsol / Braunerde
Q82	Pavlov 1972	Germany (S. Niedersachsen)	*Picea abies*	Red sandstone loess	Siliceous loose	Podsol / Braunerde
Q83	Pavlov 1972	Germany (S. Niedersachsen)	*Picea abies*	Red sandstone loess	Siliceous loose	Podsol / Braunerde
Q84	Seibt and Wittich 1965	Germany (Lüneb. Heide)	*Picea abies*	Pleistocene	Siliceous loose	Podsol
Q85	Seibt and Wittich 1965	Germany (Lüneb. Heide)	*Pinus sylvestris*	Pleistocene	Siliceous loose	Podsol
Q86	Seibt and Wittich 1965	Germany (Lüneb. Heide)	*Larix decidua*	Pleistocene	Siliceous loose	Podsol
Q87	Trüby 1994	Germany (Südschwarzwald)	*Pseudotsuga menziesii*	Siliceous/ pile	Siliceous loose	Unknown
Q88	Trüby 1994	Germany (Südschwarzwald)	*Pseudotsuga menziesii*	Siliceous	Siliceous loose	Unknown
Q89	Trüby 1994	Germany (Südschwarzwald)	*Picea abies*	Siliceous/ pile	Siliceous loose	Unknown
Q90	Trüby 1994	Germany (Südschwarzwald)	*Picea abies*	Siliceous	Siliceous loose	Unknown
Q91	Trüby 1994	Germany (Südschwarzwald)	*Abies alba*	Siliceous/ pile	Siliceous loose	Unknown
Q92	Trüby 1994	Germany (Südschwarzwald)	*Abies alba*	Siliceous	Siliceous loose	Unknown
Q93	Trüby 1994	Germany (Südschwarzwald)	*Abies alba*	Siliceous/ pile	Siliceous loose	Unknown
Q94	Trüby 1994	Germany (Südschwarzwald)	*Abies alba*	Pile	Siliceous loose	Unknown

Index	Source	Country	Tree species	Geologic substrate	Geological substrate group	Soil classified
Q95	Trüby 1994	Germany (Südschwarzwald)	*Abies alba*	Siliceous	Siliceous loose	Unknown
Q96	Weis and Göttlein 2002	Germany (Bayern)	*Fagus sylvatica*	Tertiary loess	Siliceous loose	Parabraunerde / Pseudogley
Q97	Weis and Göttlein 2002	Germany (Bayern)	*Picea abies*	Tertiary loess	Siliceous loose	Parabraunerde / Pseudogley
Q98	Block 1993	Germany (Pfälzerwald)	*Quercus*	Red sandstone	Siliceous solidified	Podsol / Braunerde
Q99	Block et al. 2016	Germany	*Fagus sylvatica*	Acidic magmatites	Siliceous solidified	Podsol / Braunerde
Q100	Dietrich et al. 2002	Germany (Oberpfalz)	*Picea abies*	Gneiss	Siliceous solidified	Podsol / Braunerde
Q101	Feger et al. 1991	Germany (Schwarzwald)	*Picea abies*	Upper red sandstone	Siliceous solidified	Podsol / Braunerde / Pseudogley
Q102	Gehrmann 2002	Germany (NRW)	*Picea abies*	Shales	Siliceous solidified	Podsol / Braunerde
Q103	Huber et al. 2011	Germany (Nürnberg)	*Picea abies*	Codierit Sillimanit-Flasergneiss	Siliceous solidified	Braunerde
Q104	Le Goaster et al. 1991	France	*Picea abies*	Granite	Siliceous solidified	Dystochrept
Q105	Nebe and Herrmann 1987	Germany (östl. Erzgebirge)	*Picea abies*	Rhyolith	Siliceous solidified	Podsol / Braunerde
Q106	Nihlgård 1972	Sweden (south)	*Fagus sylvatica*	Shales	Siliceous solidified	Braunerde
Q107	Nihlgård 1972	Sweden (south)	*Picea abies*	Sandstone	Siliceous solidified	Braunerde
Q108	Nihlgård and Lindgren 1977	Sweden	*Fagus sylvatica*	Sandstone	Siliceous solidified	Braunerde / Pseudogley
Q109	Nihlgård and Lindgren 1977	Sweden	*Fagus sylvatica*	Sandstone	Siliceous solidified	Podsol
Q110	Oren et al. 1988	Germany (Fichtelgebirge)	*Picea abies*	Phyllit	Siliceous solidified	Podsol
Q111	Oren et al. 1988	Germany (Fichtelgebirge)	*Picea abies*	Phyllit	Siliceous solidified	Podsol / Braunerde
Q112	Ovington and Madgwick 1959	Scotland (south)	*Pinus sylvestris*	Teritary clay	Siliceous solidified	Unknown
Q113	Rademacher 1994	Germany (Harz)	*Picea abies*	Sandstone	Siliceous solidified	Podsol / Braunerde
Q114	Raisch 1983	Germany (Südschwarzwald)	*Picea abies*	Granite	Siliceous solidified	Braunerde / Podsol
Q115	Raisch 1983	Germany (Südschwarzwald)	*Picea abies*	Granite	Siliceous solidified	Braunerde / Podsol
Q116	Raisch 1983	Germany (Südschwarzwald)	*Picea abies*	Granite	Siliceous solidified	Pseudogley
Q117	Raisch 1983	Germany (Südschwarzwald)	*Picea abies*	Granite	Siliceous solidified	Stagnogley
Q118	Raisch 1983	Germany (Südschwarzwald)	*Picea abies*	Granite	Siliceous solidified	Braunerde
Q119	Ranger et al. 1992	France (Westvogesen)	*Picea abies*	Granite/gneiss	Siliceous solidified	Braunerde
Q120	Trüby 1994	Germany (Nördl. Eifel)	*Picea abies*	Siliceous	Siliceous solidified	Unknown
Q121	Trüby 1994	Germany (Nördl. Eifel)	*Picea abies*	Siliceous	Siliceous solidified	Unknown
Q122	Trüby 1994	Germany (Nördl. Eifel)	*Pinus sylvestris*	Siliceous	Siliceous solidified	Unknown
Q123	Trüby 1994	Germany (Nördl. Eifel)	*Pinus sylvestris*	Siliceous	Siliceous solidified	Unknown
Q124	Trüby 1994	Germany (Nördl. Eifel)	*Pinus sylvestris*	Siliceous	Siliceous solidified	Unknown
Q125	Uhlig and von Blanckenburg 2019	Germany (Baden-Wüttemberg)	*Fagus sylvatica*	Präkambrium	Siliceous solidified	Unknown
Q126	Uhlig and von Blanckenburg 2019	Germany (Bayern)	*Fagus sylvatica*	Neoproterozoikum to Silur	Siliceous solidified	Unknown
Q127	Uhlig and von Blanckenburg 2019	Germany (Baden-Wüttemberg)	*Picea abies*	Präkambrium	Siliceous solidified	Unknown
Q128	Uhlig and von Blanckenburg 2019	Germany (Bayern)	*Picea abies*	Neoproterozoikum to Silur	Siliceous solidified	Unknown

6.6 Primary and calculated data

6.6.1 Waldlabor and Arisdorf

In Table A 13-26, all primary and calculated data of Waldlabor and Arisdorf are presented.

Table A 13: Tree height [m], DBH [cm], fresh biomass measurements [kg] and leaf characteristics of Fagus sylvatica at Waldlabor and Arisdorf. Green = estimated from hemispheric photos or TLS, orange = Calculated values.

Site	Tree nr.	Height	DBHA	DBHB	Mean DBH	Total fresh tree biomass	Biomass stem wood fresh	Biomass branches Ø <7 cm fresh	Comment biomass	LAI	Crown area	Leaf area
		[m]	[cm]	[cm]	[cm]	[kg]	[kg]	[kg]			[m^2]	[m^2]
WL	beech 1	26.60	32.40	31.50	31.95	1375.00	1180.00	195.00	Stem wood	4.30	29.01	124.72
WL	beech 2	27.60	42.50	42.20	42.35	2610.00	2250.00	360.00	Stem wood	4.30	34.82	149.73
WL	beech 3	29.00	40.50	43.40	41.95	2110.00	1790.00	320.00	Stem wood	4.30	34.01	146.25
WL	beech 4	32.50	49.20	50.40	49.80	3660.00	3400.00	260.00	Only 2/3 of the branches	5.16	39.94	206.09
WL	beech 5	31.60	34.10	31.40	32.75	1275.00	1200.00	75.00	Only stem, snow	5.16	29.85	154.05
AD	beech 1	32.60	46.20	44.90	45.55	3185.00	2833.13	351.87	Stem wood	9.50	28.96	275.00
AD	beech 2	31.00	42.70	43.00	42.85	2671.00	2460.24	210.76	Stem wood	4.37	24.46	107.00
AD	beech 3	31.60	47.20	44.30	45.75	3186.00	2990.33	195.67	Stem wood	6.08	31.25	190.00
AD	beech 4	32.20	43.40	43.10	43.25	2999.00	2634.38	364.62	Stem wood	6.54	30.75	201.00
AD	beech 5	30.30	45.00	40.80	42.90	2931.00	2658.61	272.39	Stem wood	4.79	27.56	132.00

Table A 14: Wet weight (WW) [g/leaf], dry weight (DW) [g/leaf], SLA [dm^2/g] and nutrient concentrations [% or mg/kg] in green leaves of Fagus sylvatica at three heights at Waldlabor and Arisdorf.

Site	**Tree nr.**	**Mean WW of 70 leaves** [g/leaf]	**Mean WW of 30 leaves before scan** [g/leaf]	**Mean WW of 30 leaves at scan** [g/leaf]	**Mean DW of 30 leaves** [g/leaf]	**SLA** [dm^2/g WW]	**SLA** [dm^2/g WW]	**N** [%]	**Ca** [mg/kg]	**K** [mg/kg]	**Mg** [mg/kg]	**P** [mg/kg]	**S** [mg/kg]
Leaves green, bottom													
WL	beech 1	0.21	0.23	0.19	0.11	1.13	1.96	2.47	11543.38	5861.78	2382.63	1374.97	1730.19
WL	beech 2	0.14	0.15	0.14	0.07	1.28	2.46	2.44	10959.31	8473.92	2277.32	1196.21	1655.94
WL	beech 3	0.28	0.37	0.32	0.19	0.83	1.37	2.27	9896.17	3948.66	2114.59	1033.81	1665.45
WL	beech 4	0.24	0.27	0.24	0.15	1.26	2.05	2.40	15044.37	5354.07	2728.15	1334.99	1675.43
WL	beech 5	0.25	0.27	0.23	0.13	1.28	2.26	2.38	10170.63	6056.01	2524.32	1252.91	1606.86
AD	beech 1	0.18	0.19	0.17	0.09	1.10	2.14	2.51	21359.32	5827.35	2344.34	889.79	1771.78
AD	beech 2	0.23	0.23	0.21	0.12	0.86	1.55	2.37	16725.49	5747.83	1453.73	1006.44	1719.37
AD	beech 3	0.31	0.33	0.32	0.14	0.71	1.55	2.71	17969.31	10189.60	1596.88	1283.32	1861.81
AD	beech 4	0.25	0.27	0.25	0.13	1.01	1.94	2.38	18173.87	6435.26	1686.21	905.95	1667.85
AD	beech 5	0.26	0.30	0.29	0.14	0.90	1.83	2.16	22943.46	9184.28	1804.30	972.58	1667.87
Leaves green, middle													
WL	beech 1	0.31	0.35	0.31	0.16	1.24	2.35	2.40	8928.79	7854.95	1706.30	1336.58	1665.38
WL	beech 2	0.16	0.17	0.16	0.09	0.97	1.69	2.24	12642.79	5956.68	1986.06	1096.61	1572.88
WL	beech 3	0.30	0.38	0.35	0.19	0.73	1.33	2.62	12190.78	6901.93	2234.34	1197.18	1776.84
WL	beech 4	0.20	0.23	0.21	0.15	1.05	1.47	2.31	12918.55	5126.06	2203.80	1223.74	1645.49
WL	beech 5	0.28	0.35	0.32	0.19	0.69	1.19	2.18	10908.53	6362.93	2102.55	1101.06	1593.46
AD	beech 1	0.17	0.22	0.20	0.11	0.86	1.57	2.30	18391.42	4941.79	1768.45	851.55	1695.57
AD	beech 2	0.23	0.28	0.27	0.15	0.72	1.29	2.32	16246.45	5783.97	1035.63	988.90	1829.47
AD	beech 3	0.26	0.31	0.29	0.15	0.83	1.65	2.33	16206.15	7971.84	1468.23	1067.20	1753.80
AD	beech 4	0.26	0.27	0.26	0.14	0.74	1.36	1.94	18065.63	6404.64	1291.29	692.11	1483.22
AD	beech 5	0.26	0.33	0.33	0.17	0.77	1.52	2.36	17815.86	7827.41	862.05	944.14	1815.98
Leaves green, top													
WL	beech 1	0.46	0.46	0.43	0.26	0.60	1.00	2.01	5452.61	9642.52	1095.88	1081.53	1557.08
WL	beech 2	0.25	0.24	0.23	0.15	0.77	1.23	2.28	9701.17	9567.68	1513.72	1268.44	1768.71
WL	beech 3	0.39	0.43	0.39	0.23	0.50	0.85	2.15	10600.66	5990.06	1739.93	1052.52	1667.07
WL	beech 4	0.25	0.27	0.25	0.15	0.60	0.96	1.93	12172.54	4853.87	1250.82	1098.71	1486.51

Site	Tree nr.	Mean WW of 70 leaves	Mean WW of 30 leaves before scan	Mean WW of 30 leaves at scan	Mean DW of 30 leaves	SLA	SLA	N	Ca	K	Mg	P	S
WL	beech 5	0.41	0.42	0.39	0.23	0.56	0.94	1.85	7534.64	8512.51	1397.84	1009.08	1592.17
AD	beech 1	0.23	0.24	0.22	0.14	0.55	0.90	1.68	14205.60	3374.96	559.12	581.95	1355.82
AD	beech 2	0.18	0.18	0.17	0.10	0.62	1.02	1.67	14952.30	5830.97	329.30	681.57	1333.41
AD	beech 3	0.29	0.29	0.28	0.15	0.68	1.27	1.98	18227.85	8631.59	1506.20	1017.69	1595.23
AD	beech 4	0.29	0.29	0.28	0.15	0.55	1.01	2.10	19077.82	7206.92	1170.44	868.29	1744.33
AD	beech 5	0.36	0.40	0.39	0.22	0.50	0.89	2.09	11148.29	6111.10	510.71	753.45	1640.49

Table A 15: Nutrient ratios in leaves of Fagus sylvatica at Waldlabor and Arisdorf.

Site	Tree nr.	N:Ca	N:K	N:Mg	N:P	N:S
WL	beech 1	2.65	2.94	13.27	18.13	13.89
WL	beech 2	2.09	2.90	12.03	19.52	13.91
WL	beech 3	2.15	4.18	11.55	21.43	13.77
WL	beech 4	1.65	4.33	10.73	18.14	13.80
WL	beech 5	2.24	3.06	10.63	19.05	13.37
AD	beech 1	1.20	4.59	13.89	27.92	13.45
AD	beech 2	1.33	3.66	22.56	23.76	13.03
AD	beech 3	1.34	2.62	15.35	20.84	13.47
AD	beech 4	1.16	3.20	15.47	26.01	13.10
AD	beech 5	1.27	2.85	20.77	24.72	12.88

Table A 16: Wet weight (WW) [g/leaf], dry weight (DW) [g/leaf], SLA [dm²/g] and nutrient concentrations [% or mg/kg] in leaves from litter of Fagus sylvatica at Waldlabor and Arisdorf. At Waldlabor, one litter trap was assigned to beech 1-3 and the second to beech 4 and 5. At Arisdorf, one litter trap was assigned to beech 1 and 2 and the second trap to beech 4 and 5. For beech 3, mean values from litter trap 1 and 2 were used.

Site	**Tree nr.**	**Mean WW leaves at scan**	**Mean DW leaves**	**SLA**	**SLA**	**N**	**Ca**	**K**	**Mg**	**P**	**S**
		[g/leaf]	[g/leaf]	[dm²/g WW]	[dm²/g DW]	[%]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]
Litter, time point 1											
WL	beech 1	0.17	NA	0.71	NA	1.31	10621.70	3776.84	1735.73	674.31	1142.92
WL	beech 2	0.17	NA	0.71	NA	1.31	10621.70	3776.84	1735.73	674.31	1142.92
WL	beech 3	0.17	NA	0.71	NA	1.31	10621.70	3776.84	1735.73	674.31	1142.92
WL	beech 4	0.10	NA	0.93	NA	1.42	10389.64	4435.27	1338.51	835.32	1258.18
WL	beech 5	0.10	NA	0.93	NA	1.42	10389.64	4435.27	1338.51	835.32	1258.18
AD	beech 1	0.08	NA	1.00	NA	1.36	16544.81	4613.80	1188.30	512.43	1333.67
AD	beech 2	0.08	NA	1.00	NA	1.36	16544.81	4613.80	1188.30	512.43	1333.67
AD	beech 3	0.09	NA	1.03	NA	1.45	16567.87	4138.20	1235.10	482.25	1322.50
AD	beech 4	0.10	NA	1.07	NA	1.53	16590.93	3662.60	1281.90	452.07	1311.34
AD	beech 5	0.10	NA	1.07	NA	1.53	16590.93	3662.60	1281.90	452.07	1311.34
Litter, time point 2											
WL	beech 1	0.37	0.37	0.35	0.13	0.80	2.08	0.92	12107.02	4092.81	1894.68
WL	beech 2	0.37	0.37	0.35	0.13	0.80	2.08	0.92	12107.02	4092.81	1894.68
WL	beech 3	0.37	0.37	0.35	0.13	0.80	2.08	0.92	12107.02	4092.81	1894.68
WL	beech 4	0.29	0.26	0.17	0.10	1.00	1.60	0.79	11842.68	4892.18	1641.24
WL	beech 5	0.29	0.26	0.17	0.10	1.00	1.60	0.79	11842.68	4892.18	1641.24
AD	beech 1	0.18	0.21	0.20	0.12	1.06	1.84	0.80	22427.89	3253.63	1140.27
AD	beech 2	0.18	0.21	0.20	0.12	1.06	1.84	0.80	22427.89	3253.63	1140.27
AD	beech 3	0.18	0.21	0.20	0.12	1.08	1.78	0.79	21879.96	3153.87	1062.03
AD	beech 4	0.17	0.21	0.20	0.13	1.09	1.72	0.79	21332.03	3054.12	983.80
AD	beech 5	0.17	0.21	0.20	0.13	1.09	1.72	0.79	21332.03	3054.12	983.80
Litter, time point 3											
WL	beech 1	0.37	0.26	0.23	0.13	1.14	2.01	0.83	13474.32	2589.58	1882.16

Site	Tree nr.	Mean WW leaves at scan	Mean DW leaves	SLA	SLA	N	Ca	K	Mg	P	S
WL	beech 2	0.37	0.26	0.23	0.13	1.14	2.01	0.83	13474.32	2589.58	1882.16
WL	beech 3	0.37	0.26	0.23	0.13	1.14	2.01	0.83	13474.32	2589.58	1882.16
WL	beech 4	0.18	0.23	0.20	0.10	1.33	2.64	0.86	18275.89	2269.36	2478.35
WL	beech 5	0.18	0.23	0.20	0.10	1.33	2.64	0.86	18275.89	2269.36	2478.35
AD	beech 1	0.13	0.14	0.12	0.10	1.53	1.95	0.78	25194.19	2240.80	1418.99
AD	beech 2	0.13	0.14	0.12	0.10	1.53	1.95	0.78	25194.19	2240.80	1418.99
AD	beech 3	0.13	0.14	0.13	0.10	1.61	2.08	1.15	24325.21	2203.27	1379.55
AD	beech 4	0.13	0.14	0.13	0.11	1.70	2.21	1.51	23456.23	2165.74	1340.10
AD	beech 5	0.13	0.14	0.13	0.11	1.70	2.21	1.51	23456.23	2165.74	1340.10

Table A 17: Water content (WC) [g/g moist] and nutrient concentrations [% or mg/kg] in branches of different diameters of Fagus sylvatica at Waldlabor and Arisdorf. At Arisdorf, the WC of the branches <5 mm of beech 3 and 5 were calculated with corrected DW.

Site	Tree nr.	WC	N	Ca	K	Mg	P	S
		[g/g moist]	[%]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]
Branches Ø <5 mm								
WL	beech 1	0.46	1.06	5251.02	4010.41	1008.62	1101.39	673.17
WL	beech 2	0.46	1.07	5116.62	4606.20	1086.07	1067.70	744.33
WL	beech 3	0.44	1.25	11336.36	3528.76	1378.62	1327.60	879.83
WL	beech 4	0.47	1.14	11513.91	3113.08	522.63	1045.53	790.20
WL	beech 5	0.47	1.29	13053.44	2984.30	1023.49	1221.04	803.49
AD	beech 1	0.41	1.23	12188.27	3158.66	406.35	733.21	922.50
AD	beech 2	0.44	1.12	16895.51	3007.76	381.96	720.60	844.47
AD	beech 3	0.46	1.13	11015.79	3204.35	616.28	784.69	829.19
AD	beech 4	0.43	1.14	12716.99	3081.11	481.99	728.33	792.97
AD	beech 5	0.43	1.14	13547.32	3697.77	258.55	834.03	828.13
Branches Ø 5–20 mm								

Site	Tree nr.	WC	N	Ca	K	Mg	P	S
WL	beech 1	0.42	0.66	3190.68	3633.44	823.82	760.00	493.64
WL	beech 2	0.44	0.52	7652.84	2022.53	1064.48	414.03	419.04
WL	beech 3	0.42	0.53	6547.70	2796.04	648.67	530.26	377.85
WL	beech 4	0.41	0.62	7778.14	2143.03	579.66	391.31	480.49
WL	beech 5	0.41	0.57	6324.20	2490.39	1035.62	738.65	449.39
AD	beech 1	0.41	0.45	8262.01	1732.71	186.80	243.76	302.95
AD	beech 2	0.44	0.50	13224.50	1346.95	190.90	234.67	316.49
AD	beech 3	0.44	0.35	8469.90	1775.65	329.04	216.78	315.74
AD	beech 4	0.44	0.45	11221.56	1508.14	316.34	233.85	352.26
AD	beech 5	0.44	0.51	9959.00	1637.20	281.16	301.30	319.56
Branches Ø 20–70 mm								
WL	beech 1	0.42	0.33	1849.98	2348.50	400.76	327.40	212.11
WL	beech 2	0.43	0.30	3493.63	1594.03	554.45	214.85	198.04
WL	beech 3	0.42	0.36	2845.24	1747.08	598.48	345.98	246.15
WL	beech 4	0.42	0.38	5406.52	1286.10	538.85	241.93	235.78
WL	beech 5	0.37	0.30	3965.30	1300.93	428.71	231.81	195.36
AD	beech 1	0.42	0.31	5054.10	1427.54	265.75	164.90	199.66
AD	beech 2	0.46	0.35	7399.27	1167.11	316.67	140.46	196.21
AD	beech 3	0.43	0.14	6518.54	1590.33	324.25	192.30	235.75
AD	beech 4	0.43	0.28	6976.27	1208.39	433.97	127.47	212.78
AD	beech 5	0.44	0.40	7610.99	1963.06	366.37	243.56	275.90
Branches Ø 70–120 mm								
WL	beech 1	0.42	0.26	925.75	2264.80	387.62	272.13	171.48
WL	beech 2	0.43	0.19	1459.55	1339.81	597.52	153.19	173.60
WL	beech 3	0.40	0.29	1520.11	2124.44	547.52	542.64	229.54
WL	beech 4	0.41	0.21	1291.72	811.00	574.28	138.44	129.30
WL	beech 5	0.40	0.15	746.82	1294.18	282.24	93.69	99.96
AD	beech 1	NA	NA	NA	NA	NA	NA	NA

Site	Tree nr.	WC	N	Ca	K	Mg	P	S
AD	beech 2	NA	NA	NA	NA	NA	NA	NA
AD	beech 3	NA	NA	NA	NA	NA	NA	NA
AD	beech 4	NA	NA	NA	NA	NA	NA	NA
AD	beech 5	NA	NA	NA	NA	NA	NA	NA

Table A 18: Water content (WC) [g/g moist], bark thickness [cm] and nutrient concentrations [% or mg/kg] in bark and stem disks of Fagus sylvatica at Waldlabor and Arisdorf.

Site	Tree nr.	WC	Thickness bark	N	Ca	K	Mg	P	S
		[g/g moist]	[cm]	[%]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]
Bark									
WL	beech 1	0.38	4.60	0.81	20269.68	1932.25	554.15	392.27	404.52
WL	beech 2	0.40	5.00	0.71	20350.15	3413.24	645.83	568.61	443.10
WL	beech 3	0.39	4.60	0.76	21413.28	2346.07	448.21	415.27	437.11
WL	beech 4	0.37	5.80	0.59	28783.74	1907.51	478.86	278.11	334.77
WL	beech 5	0.45	3.60	0.62	12636.38	2283.98	557.33	368.65	387.98
AD	beech 1	0.37	5.20	0.63	41486.59	2180.98	370.57	364.34	445.15
AD	beech 2	0.37	4.20	0.55	37923.26	1846.83	219.14	240.02	335.61
AD	beech 3	0.38	4.60	0.45	39002.04	1850.23	354.84	213.12	342.94
AD	beech 4	0.36	5.90	0.55	33201.68	1843.52	569.03	244.24	387.98
AD	beech 5	0.37	4.90	0.52	42533.98	2640.22	340.54	266.47	357.07
Stem disk 1									
WL	beech 1	0.31	5.00	0.25	2750.32	1336.07	140.93	107.00	161.44
WL	beech 2	0.30	6.00	0.14	884.36	940.07	199.72	65.07	107.44
WL	beech 3	0.31	6.00	0.27	2970.65	1177.70	356.48	119.18	173.17
WL	beech 4	0.15	6.00	0.23	7225.51	1086.97	432.59	120.07	169.84
WL	beech 5	0.13	4.00	0.13	1040.94	1064.25	178.95	67.54	104.12
AD	beech 1	0.36	7.00	0.24	1479.68	735.34	186.72	83.76	124.60

Site	Tree nr.	WC	Thickness bark	N	Ca	K	Mg	P	S
AD	beech 2	0.41	6.00	0.17	1157.66	1326.87	696.90	124.59	149.57
AD	beech 3	0.42	6.00	0.19	2609.47	1338.98	332.26	98.66	155.36
AD	beech 4	0.38	7.00	0.18	1269.56	1820.22	656.76	101.48	209.66
AD	beech 5	0.40	7.00	0.15	1436.88	2470.29	693.38	134.82	159.74
Stem disk 2									
WL	beech 1	0.43	5.00	0.26	4985.85	1373.47	294.07	123.16	165.25
WL	beech 2	0.39	3.00	0.13	899.22	761.74	267.42	48.84	91.56
WL	beech 3	0.39	4.00	0.37	3992.84	1646.10	279.91	202.72	263.39
WL	beech 4	0.11	8.00	0.13	996.83	937.45	747.04	69.98	109.25
WL	beech 5	0.14	4.00	0.16	2291.55	1072.19	207.99	64.86	108.05
AD	beech 1	0.39	5.50	0.17	1449.89	1606.79	513.23	91.63	122.66
AD	beech 2	0.44	5.00	0.16	1209.66	1012.60	656.77	102.46	133.13
AD	beech 3	0.43	5.00	0.17	1110.89	1652.17	319.74	103.10	164.75
AD	beech 4	0.39	9.00	0.19	3760.09	2163.30	469.27	78.30	161.40
AD	beech 5	0.43	5.00	0.22	3664.79	1609.29	303.24	139.67	180.14
Stem disk 3									
WL	beech 1	0.32	4.00	0.27	3348.54	1383.87	298.02	136.07	176.18
WL	beech 2	0.38	5.00	0.24	5795.89	1062.71	314.68	120.03	169.20
WL	beech 3	0.38	4.00	0.12	1137.49	1039.89	599.45	76.36	105.93
WL	beech 4	0.13	6.50	0.19	4508.45	1279.66	622.98	99.62	136.29
WL	beech 5	0.14	3.50	0.13	1134.63	1222.40	282.71	57.89	109.18
AD	beech 1	0.38	6.00	0.21	3426.24	1388.52	324.95	94.13	141.60
AD	beech 2	0.44	4.00	0.15	1230.60	1284.33	605.01	91.33	128.25
AD	beech 3	0.45	5.00	0.14	1078.47	1628.93	245.47	77.57	120.39
AD	beech 4	0.36	5.00	0.20	1041.86	1281.45	292.76	89.98	180.49
AD	beech 5	0.44	4.50	0.20	1138.47	1622.79	282.28	129.00	143.69
Stem disk 4									

Site	Tree nr.	WC	Thickness bark	N	Ca	K	Mg	P	S
WL	beech 1	0.36	4.00	0.24	1599.04	1848.19	362.63	148.53	165.74
WL	beech 2	0.31	6.00	0.16	1803.22	1068.71	325.11	91.37	123.30
WL	beech 3	0.32	5.00	0.21	963.07	1271.21	398.27	138.59	147.13
WL	beech 4	0.17	5.50	0.17	2763.94	1249.79	859.72	98.47	124.03
WL	beech 5	0.18	3.50	0.15	1185.41	1018.39	358.51	73.51	109.87
AD	beech 1	0.44	4.50	0.15	1163.66	1891.99	360.89	50.84	104.77
AD	beech 2	0.44	3.00	0.18	1118.62	1359.44	424.30	92.32	121.54
AD	beech 3	0.44	4.00	0.12	935.02	1874.39	228.74	97.95	117.61
AD	beech 4	0.42	5.00	0.14	1224.02	1261.05	271.30	49.20	125.82
AD	beech 5	0.46	5.00	0.11	1445.07	1468.20	284.90	46.90	93.55
Stem disk 5									
WL	beech 1	0.40	5.00	0.27	1205.12	1800.22	250.67	215.59	164.37
WL	beech 2	0.40	5.00	0.25	2072.68	1074.33	401.44	127.70	140.52
WL	beech 3	0.36	4.00	0.38	2882.61	1402.47	534.29	273.55	212.70
WL	beech 4	0.24	3.00	0.17	1053.90	959.24	945.97	125.89	128.89
WL	beech 5	0.17	3.00	0.19	1230.13	1611.58	498.70	165.31	141.42
AD	beech 1	0.43	3.00	0.14	1283.27	1527.37	201.07	82.22	116.04
AD	beech 2	0.44	3.00	0.15	1514.64	1271.20	232.61	55.09	85.07
AD	beech 3	0.43	3.00	0.13	1170.05	2123.10	264.93	91.31	125.09
AD	beech 4	0.45	3.50	0.12	1173.35	1637.76	264.39	61.09	122.80
AD	beech 5	0.44	3.00	0.13	2186.44	1811.19	335.87	62.33	124.12

Table A 19: Root density [mg/cm^3] and nutrient concentrations [% or mg/kg] in fine roots in a depth of 0-25 cm, 25-50 cm and in average of 0-50 cm depth of Fagus sylvatica at Waldlabor and Arisdorf.

Site	**Tree nr.**	**Root density** [mg/cm^3]	**N** [%]	**Ca** [mg/kg]	**K** [mg/kg]	**Mg** [mg/kg]	**P** [mg/kg]	**S** [mg/kg]
Fine roots 0–25 cm								
WL	beech 1	0.62	1.04	5538.22	3840.80	1173.69	619.55	840.24
WL	beech 2	0.76	1.04	9092.37	3515.32	1234.33	552.14	885.84
WL	beech 3	1.24	1.05	6832.45	3060.14	1104.64	667.55	720.41
WL	beech 4	0.56	1.14	6906.76	3849.90	1775.08	740.56	1010.92
WL	beech 5	0.91	0.93	7260.58	3698.44	1170.95	527.53	906.63
AD	beech 1	2.31	1.09	17835.27	2246.53	939.56	502.97	879.81
AD	beech 2	1.79	0.94	35879.57	2006.36	862.14	446.51	842.56
AD	beech 3	1.73	0.93	14642.86	2144.41	800.05	426.88	781.23
AD	beech 4	1.62	0.89	17523.17	2265.40	904.94	392.15	739.19
AD	beech 5	1.44	0.97	13732.69	2826.81	737.56	445.96	888.59
Fine roots 25–50 cm								
WL	beech 1	0.18	0.83	5320.61	4378.65	1406.05	461.97	672.25
WL	beech 2	0.11	0.82	NA	NA	NA	NA	NA
WL	beech 3	0.48	0.79	5787.18	3227.80	1558.89	355.12	561.87
WL	beech 4	0.11	1.02	NA	NA	NA	NA	NA
WL	beech 5	0.24	0.80	7873.18	4613.87	1710.03	467.86	932.40
AD	beech 1	NA	NA	NA	NA	NA	NA	NA
AD	beech 2	NA	NA	NA	NA	NA	NA	NA
AD	beech 3	NA	NA	NA	NA	NA	NA	NA
AD	beech 4	NA	NA	NA	NA	NA	NA	NA
AD	beech 5	NA	NA	NA	NA	NA	NA	NA
Fine roots 0-50 cm								
WL	beech 1	0.40	0.93	5429.42	4109.72	1289.87	540.76	756.24
WL	beech 2	0.44	0.93	9092.37	3515.32	1234.33	552.14	885.84

Site	Tree nr.	Root density	N	Ca	K	Mg	P	S
WL	beech 3	0.86	0.92	6309.82	3143.97	1331.77	511.33	641.14
WL	beech 4	0.34	1.08	6906.76	3849.90	1775.08	740.56	1010.92
WL	beech 5	0.58	0.86	7566.88	4156.16	1440.49	497.69	919.52
AD	beech 1	2.31	1.09	17835.27	2246.53	939.56	502.97	879.81
AD	beech 2	1.79	0.94	35879.57	2006.36	862.14	446.51	842.56
AD	beech 3	1.73	0.93	14642.86	2144.41	800.05	426.88	781.23
AD	beech 4	1.62	0.89	17523.17	2265.40	904.94	392.15	739.19
AD	beech 5	1.44	0.97	13732.69	2826.81	737.56	445.96	888.59

Table A 20: pH, grain size distribution [%] and nutrient concentrations [% or mg/kg] in two depths 0 – 25 cm and 25 – 50 cm and in average in the soil next to Fagus sylvatica at Waldlabor and Arisdorf.

Site	Tree nr.	pH $CaCl_2$	Sand	Silt	Clay	C_{org}	N_{tot}	P_{tot}	P_i	P_{org}	Ca	K	Mg
			[%]	[%]	[%]	[%]	[%]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]
Soil 0–25 cm													
WL	beech 1	4.60	35.30	41.55	23.15	2.11	0.17	20.76	6.98	13.78	1240.63	70.42	185.31
WL	beech 2	4.89	33.80	39.35	26.85	2.52	0.23	16.86	6.79	10.07	1990.79	83.01	282.18
WL	beech 3	4.43	33.90	42.45	23.65	2.44	0.20	24.89	9.45	15.45	1174.26	72.97	180.13
WL	beech 4	4.50	34.65	38.75	26.60	2.43	0.19	24.94	8.74	16.20	1536.27	91.12	281.32
WL	beech 5	4.62	33.15	39.80	27.05	2.00	0.18	22.78	8.17	14.61	1499.74	85.75	274.08
AD	beech 1	6.87	25.65	27.25	47.10	9.58	0.66	23.46	18.58	4.88	8584.57	125.84	121.46
AD	beech 2	6.97	58.10	25.45	16.45	9.49	0.68	26.90	20.42	6.48	8583.31	132.33	98.78
AD	beech 3	7.00	46.10	18.45	35.45	6.84	0.48	17.82	13.88	3.95	7859.95	127.35	80.03
AD	beech 4	6.93	44.85	17.80	37.35	6.34	0.43	31.95	13.00	18.95	7691.46	117.13	99.54
AD	beech 5	6.77	50.15	16.05	33.80	6.43	0.44	22.68	14.27	9.08	8240.58	144.72	80.57
Soil 25–50 cm													
WL	beech 1	4.97	32.10	37.25	30.65	0.79	0.08	8.59	1.41	7.18	1812.75	88.37	344.40
WL	beech 2	5.79	32.25	36.30	31.45	0.84	0.09	8.74	1.39	7.35	2431.95	97.54	390.38
WL	beech 3	4.61	32.75	39.55	27.70	0.71	0.07	8.96	1.70	7.25	1490.49	83.89	303.08
WL	beech 4	4.86	30.50	33.90	35.60	0.81	0.08	8.87	2.62	6.24	2179.60	111.59	475.54

Site	Tree nr.	pH $CaCl_2$	Sand	Silt	Clay	C_{org}	N_{tot}	P_{tot}	P_i	P_{org}	Ca	K	Mg
WL	beech 5	5.11	31.10	35.70	33.20	0.81	0.08	12.51	1.62	10.89	2254.53	105.02	435.56
AD	beech 1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD	beech 2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD	beech 3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD	beech 4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD	beech 5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Soil 0–50 cm													
WL	beech 1	4.79	33.70	39.40	26.90	1.45	0.13	14.68	4.20	10.48	1526.69	79.40	264.86
WL	beech 2	5.34	33.03	37.83	29.15	1.68	0.16	12.80	4.09	8.71	2211.37	90.27	336.28
WL	beech 3	4.52	33.33	41.00	25.68	1.58	0.14	16.93	5.57	11.35	1332.37	78.43	241.61
WL	beech 4	4.68	32.58	36.33	31.10	1.62	0.14	16.90	5.68	11.22	1857.93	101.36	378.43
WL	beech 5	4.87	32.13	37.75	30.13	1.40	0.13	17.64	4.89	12.75	1877.13	95.39	354.82
AD	beech 1	6.87	25.65	27.25	47.10	9.58	0.66	23.46	18.58	4.88	8584.57	125.84	121.46
AD	beech 2	6.97	58.10	25.45	16.45	9.49	0.68	26.90	20.42	6.48	8583.31	132.33	98.78
AD	beech 3	7.00	46.10	18.45	35.45	6.84	0.48	17.82	13.88	3.95	7859.95	127.35	80.03
AD	beech 4	6.93	44.85	17.80	37.35	6.34	0.43	31.95	13.00	18.95	7691.46	117.13	99.54
AD	beech 5	6.77	50.15	16.05	33.80	6.43	0.44	22.68	14.27	9.08	8240.58	144.72	80.57

Table A 21: Cation concentrations [mmol$_c$/kg], cation exchange capacity (CEC) [mmol$_c$/kg] and base saturation (BS) [%] in the soil next to Fagus sylvatica at Waldlabor and Arisdorf.

Site	Tree nr.	H	Na	Al	Ca	K	Mg	CEC	BS
		[mmol$_c$ / kg]	[mmol$_c$ / kg]	[mmol$_c$ / kg]	[mmol$_c$ / kg]	[mmol$_c$ / kg]	[mmol$_c$ / kg]	[mmol$_c$ / kg]	[%]
0-25 cm soil									
WL	beech 1	4.20	0.31	4.95	61.91	0.18	2.49	74.03	87.65
WL	beech 2	4.20	0.32	1.28	99.35	0.21	3.79	109.14	94.98
WL	beech 3	4.20	0.29	8.28	58.60	0.19	2.42	73.97	83.13
WL	beech 4	4.20	0.41	8.70	76.66	0.23	3.78	93.98	86.27
WL	beech 5	4.20	0.42	5.13	74.84	0.22	3.68	88.49	89.46
AD	beech 1	0.00	0.53	0.13	428.39	0.32	1.63	431.01	99.97
AD	beech 2	0.00	0.48	0.13	428.33	0.34	1.33	430.60	99.97

Site	Tree nr.	H	Na	Al	Ca	K	Mg	CEC	BS
AD	beech 3	0.00	0.47	0.15	392.23	0.33	1.07	394.25	99.96
AD	beech 4	0.00	0.52	NA	383.82	0.30	1.34	385.98	100.00
AD	beech 5	0.00	0.53	NA	411.23	0.37	1.08	413.21	100.00
25-50 cm soil									
WL	beech 1	4.20	0.38	3.02	90.46	0.23	4.63	102.90	92.99
WL	beech 2	4.20	0.35	0.14	121.36	0.25	5.24	131.54	96.70
WL	beech 3	4.20	0.38	7.68	74.38	0.21	4.07	90.92	86.94
WL	beech 4	4.20	0.55	4.62	108.77	0.29	6.39	124.81	92.93
WL	beech 5	4.20	0.56	1.32	112.51	0.27	5.85	124.70	95.57
AD	beech 1	0	NA	NA	NA	NA	NA	NA	NA
AD	beech 2	0	NA	NA	NA	NA	NA	NA	NA
AD	beech 3	0	NA	NA	NA	NA	NA	NA	NA
AD	beech 4	0	NA	NA	NA	NA	NA	NA	NA
AD	beech 5	0	NA	NA	NA	NA	NA	NA	NA

Table A 22: Soil samples from 1, 3 and 5 m around Fagus sylvatica with sample volume [cm^3], fine earth dry weight (DW) [g] and fine earth bulk density (BD) [g/cm^3] at Waldlabor and Arisdorf.

Sample number	Soil depth	Thickness sample	V sample	Fine earth DW	Fine earth BD
	[cm]	[cm]	[cm^3]	[g]	[g/cm^3]
SB_WL_Bu1_3_11	0–25	25	490.87	535.2	1.09
SB_WL_Bu1_3_11	25–50	26	510.51	675.1	1.32
SB_WL_Bu1_3_21	0–25	25	490.87	481.8	0.98
SB_WL_Bu1_3_21	25–50	25	490.87	640.3	1.30
SB_WL_Bu1_3_70	0–25	25	490.87	458	0.93
SB_WL_Bu1_3_70	25–50	25	490.87	635.7	1.30
SB_WL_Bu1_3_83	0–25	24	471.24	535.2	1.14
SB_WL_Bu1_3_83	25–50	26	510.51	675.1	1.32
SB_WL_Bu1_3_95	0–25	25	490.87	481.8	0.98
SB_WL_Bu1_3_95	25–50	24.5	481.06	640.3	1.33

Sample number	Soil depth	Thickness sample	V sample	Fine earth DW	Fine earth BD
SB_WL_Bu1_3_102	0–25	25	490.87	458	0.93
SB_WL_Bu1_3_102	25–50	27.5	539.96	635.7	1.18
SB_WL_Bu1_3_200	0–25	23	451.60	422.7	0.94
SB_WL_Bu1_3_200	25–50	25	490.87	631.1	1.29
SB_WL_Bu1_3_211	0–25	25	490.87	482.8	0.98
SB_WL_Bu1_3_211	25–50	25	490.87	601.8	1.23
SB_WL_Bu1_3_262	0–25	25	490.87	520.4	1.06
SB_WL_Bu1_3_262	25–50	25	490.87	604.4	1.23
SB_WL_Bu4_5_18	0–25	25	490.87	525.8	1.07
SB_WL_Bu4_5_18	25–50	22	431.97	525.9	1.22
SB_WL_Bu4_5_55	0–25	25	490.87	526.3	1.07
SB_WL_Bu4_5_55	25–50	23	451.60	583.4	1.29
SB_WL_Bu4_5_68	0–25	24	471.24	469.4	1.00
SB_WL_Bu4_5_68	25–50	24	471.24	553.1	1.17
SB_WL_Bu4_5_76	0–25	25.5	500.69	521.1	1.04
SB_WL_Bu4_5_76	25–50	22	431.97	519.5	1.20
SB_WL_Bu4_5_90	0–25	24.5	481.06	394.8	0.82
SB_WL_Bu4_5_90	25–50	25	490.87	582.8	1.19
SB_WL_Bu4_5_106	0–25	25.5	500.69	454.7	0.91
SB_WL_Bu4_5_106	25–50	25	490.87	629.6	1.28
SB_AD_Bu1_5_5	0–25	24.5	481.06	139.9	0.29
SB_AD_Bu1_5_5	25–50	NA	NA	NA	0.15
SB_AD_Bu1_5_122	0–25	23	451.60	96.7	0.21
SB_AD_Bu1_5_122	25–50	NA	NA	NA	0.11
SB_AD_Bu1_5_141	0–25	17	333.79	49.9	0.15
SB_AD_Bu1_5_141	25–50	NA	NA	NA	0.07
SB_AD_Bu1_5_16	0–25	25.5	500.69	112.6	0.22
SB_AD_Bu1_5_16	25–50	NA	NA	NA	0.11
SB_AD_Bu1_5_88	0–25	23	451.60	87.6	0.19

Sample number	Soil depth	Thickness sample	V sample	Fine earth DW	Fine earth BD
SB_AD_Bu1_5_88	25–50	NA	NA	NA	0.10
SB_AD_Bu1_5_107	0–25	25	490.87	96.1	0.20
SB_AD_Bu1_5_107	25–50	NA	NA	NA	0.10
SB_AD_Bu1_5_190	0–25	21	412.33	43	0.10
SB_AD_Bu1_5_190	25–50	NA	NA	NA	0.05
SB_AD_Bu1_5_260	0–25	23	451.60	90.6	0.20
SB_AD_Bu1_5_260	25–50	NA	NA	NA	0.10
SB_AD_Bu1_5_277	0–25	22	431.97	40	0.09
SB_AD_Bu1_5_277	25–50	NA	NA	NA	0.05
SB_AD_Bu1_5_174	0–25	21.5	422.15	64.9	0.15
SB_AD_Bu1_5_174	25–50	NA	NA	NA	0.08
SB_AD_Bu1_5_218	0–25	24	471.24	81.5	0.17
SB_AD_Bu1_5_218	25–50	NA	NA	NA	0.09
SB_AD_Bu1_5_288	0–25	22.5	441.79	92.4	0.21
SB_AD_Bu1_5_288	25–50	NA	NA	NA	0.10
SB_AD_Bu1_5_202	0–25	20	392.70	104.1	0.27
SB_AD_Bu1_5_202	25–50	NA	NA	NA	0.13
SB_AD_Bu1_5_274	0–25	23	451.60	115.1	0.25
SB_AD_Bu1_5_274	25–50	NA	NA	NA	0.13
SB_AD_Bu1_5_316	0–25	23.5	461.42	121.6	0.26
SB_AD_Bu1_5_316	25–50	NA	NA	NA	0.13

Table A 23: Bulk densities (BD) [g/cm^3] of soil samples in two depths 0-25 and 25-50 cm and nutrient stocks [kg/ha] in the soil around Fagus sylvatica at Waldlabor and Arisdorf.

			Sample labels from each distance around tree			**BD from each sampled distance**				**Stock per depth 0–25 and 25–50 cm**			**Stock in a depth of 0–50 cm**		
Site	**Tree nr.**	**Soil depth** [cm]	**Sample 1 m distance**	**Sample 3 m distance**	**Sample 5 m distance**	**BD Sample 1 m distance** [g/cm^3]	**BD sample 2 m distance** [g/cm^3]	**BD sample 5 m distance** [g/cm^3]	**Mean BD** [g/cm^3]	**Ca** [kg/ha]	**K** [kg/ha]	**Mg** [kg/ha]	**Ca** [kg/ha]	**K** [kg/ha]	**Mg** [kg/ha]
WL	be1	0–25	SB_WL_Bu1_3_11	SB_WL_Bu1_3_70	SB_WL_Bu1_3_102	1.09	0.93	0.93	0.99	1222.59	69.40	182.61	3515.57	181.18	618.25
WL	be2	25–50	SB_WL_Bu1_3_11	SB_WL_Bu1_3_70	SB_WL_Bu1_3_102	1.32	1.30	1.18	1.26	2292.98	111.78	435.64			
WL	be3	0–25	SB_WL_Bu1_3_200	SB_WL_Bu1_3_211	SB_WL_Bu1_3_262	0.94	0.98	1.06	0.99	1977.32	82.45	280.27	5011.52	204.14	767.32
WL	be4	25–50	SB_WL_Bu1_3_200	SB_WL_Bu1_3_211	SB_WL_Bu1_3_262	1.29	1.23	1.23	1.25	3034.20	121.69	487.05			
WL	be5	0–25	SB_WL_Bu1_3_21	SB_WL_Bu1_3_83	SB_WL_Bu1_3_95	0.98	1.14	0.98	1.03	1212.91	75.38	186.06	3179.29	186.05	585.91
WL	be1	25–50	SB_WL_Bu1_3_21	SB_WL_Bu1_3_83	SB_WL_Bu1_3_95	1.30	1.32	1.33	1.32	1966.38	110.67	399.85			
WL	be2	0–25	SB_WL_Bu4_5_76	SB_WL_Bu4_5_90	SB_WL_Bu4_5_106	1.04	0.82	0.91	0.92	1418.28	84.12	259.71	4086.48	220.73	841.85
WL	be3	25–50	SB_WL_Bu4_5_76	SB_WL_Bu4_5_90	SB_WL_Bu4_5_106	1.20	1.19	1.28	1.22	2668.20	136.61	582.14			
WL	be4	0–25	SB_WL_Bu4_5_18	SB_WL_Bu4_5_55	SB_WL_Bu4_5_68	1.07	1.07	1.00	1.05	1569.44	89.74	286.82	4337.25	218.67	821.53
WL	be5	25–50	SB_WL_Bu4_5_18	SB_WL_Bu4_5_55	SB_WL_Bu4_5_68	1.22	1.29	1.17	1.23	2767.81	128.93	534.72			
AD	be1	0–25	SB_AD_Bu1_5_5	SB_AD_Bu1_5_122	SB_AD_Bu1_5_141	0.29	0.21	0.15	0.22	1872.69	27.45	26.50	2809.03	41.18	39.74
AD	be2	25–50	SB_AD_Bu1_5_5	SB_AD_Bu1_5_122	SB_AD_Bu1_5_141	0.15	0.11	0.07	0.11	936.34	13.73	13.25			
AD	be3	0–25	SB_AD_Bu1_5_190	SB_AD_Bu1_5_260	SB_AD_Bu1_5_277	0.10	0.20	0.09	0.13	1137.29	17.53	13.09	1705.94	26.30	19.63
AD	be4	25–50	SB_AD_Bu1_5_190	SB_AD_Bu1_5_260	SB_AD_Bu1_5_277	0.05	0.10	0.05	0.07	568.65	8.77	6.54			
AD	be5	0–25	SB_AD_Bu1_5_174	SB_AD_Bu1_5_218	SB_AD_Bu1_5_288	0.15	0.17	0.21	0.18	1403.88	22.75	14.29	2105.82	34.12	21.44
AD	be1	25–50	SB_AD_Bu1_5_174	SB_AD_Bu1_5_218	SB_AD_Bu1_5_288	0.08	0.09	0.10	0.09	701.94	11.37	7.15			
AD	be2	0–25	SB_AD_Bu1_5_16	SB_AD_Bu1_5_88	SB_AD_Bu1_5_107	0.22	0.19	0.20	0.20	1575.82	24.00	20.39	2363.73	35.99	30.59
AD	be3	25–50	SB_AD_Bu1_5_16	SB_AD_Bu1_5_88	SB_AD_Bu1_5_107	0.11	0.10	0.10	0.10	787.91	12.00	10.20			
AD	be4	0–25	SB_AD_Bu1_5_202	SB_AD_Bu1_5_274	SB_AD_Bu1_5_316	0.27	0.25	0.26	0.26	2152.14	37.80	21.04	3228.21	56.69	31.56
AD	be5	25–50	SB_AD_Bu1_5_202	SB_AD_Bu1_5_274	SB_AD_Bu1_5_316	0.13	0.13	0.13	0.13	1076.07	18.90	10.52			

Table A 24: Dry weight (DW) [kg] and total nutrient amounts [g] of tree compartments of Fagus sylvatica at Waldlabor and Arisdorf.

Site	**Tree nr.**	**Biomass DW** [kg]	**N** [g]	**Ca** [g]	**K** [g]	**Mg** [g]	**P** [g]	**S** [g]
Total biomass leaves (leaf characteristica from mean of 3 heights)								
WL	beech 1	7.06	16.18	61.00	54.96	12.20	8.93	11.65
WL	beech 2	8.34	193.31	92.63	66.75	16.07	9.91	13.90
WL	beech 3	12.36	289.86	134.68	69.39	25.09	13.53	21.05
WL	beech 4	13.81	305.48	184.79	70.60	28.47	16.84	22.13
WL	beech 5	10.52	224.69	100.35	73.40	21.13	11.79	16.81
AD	beech 1	17.92	387.55	322.35	84.50	27.91	13.88	28.81
AD	beech 2	8.30	175.99	132.61	48.04	7.80	7.41	13.51
AD	beech 3	12.75	298.31	222.72	113.87	19.43	14.32	22.15
AD	beech 4	14.00	299.44	258.21	93.58	19.36	11.51	22.85
AD	beech 5	9.34	205.51	161.63	72.00	9.89	8.31	15.96
Total biomass branches Ø ≤70mm (Branch characteristica from mean of Ø <5mm, Ø 5–20 mm, Ø 20–70 mm)								
WL	beech 1	110.67	756.14	379.68	368.63	82.39	80.75	50.87
WL	beech 2	199.89	1256.37	1083.62	547.89	180.24	113.04	90.71
WL	beech 3	184.33	1314.20	1273.69	495.97	161.34	135.41	92.40
WL	beech 4	146.59	1047.60	1206.85	319.67	80.19	82.03	73.61
WL	beech 5	43.83	315.79	341.02	98.99	36.34	32.02	21.16
AD	beech 1	205.78	1356.76	1749.41	433.43	58.91	78.32	97.75
AD	beech 2	116.62	764.22	1458.45	214.64	34.58	42.59	52.76
AD	beech 3	108.96	590.54	944.44	238.62	46.11	43.36	50.14
AD	beech 4	206.38	1278.90	2126.78	398.85	84.78	74.96	93.42
AD	beech 5	153.36	1046.42	1590.71	373.07	46.32	70.49	72.77
Total biomass bark								
WL	beech 1	4.84	39.08	98.07	9.35	2.68	1.90	1.96
WL	beech 2	6.96	49.05	141.58	23.75	4.49	3.96	3.08
WL	beech 3	6.45	49.25	138.15	15.14	2.89	2.68	2.82

Site	Tree nr.	Biomass DW	N	Ca	K	Mg	P	S
WL	beech 4	12.22	71.96	351.74	23.31	5.85	3.40	4.09
WL	beech 5	4.10	25.62	51.83	9.37	2.29	1.51	1.59
AD	beech 1	1.03	6.47	42.71	2.25	0.38	0.38	0.46
AD	beech 2	1.01	5.54	38.41	1.87	0.22	0.24	0.34
AD	beech 3	0.81	3.66	31.47	1.49	0.29	0.17	0.28
AD	beech 4	0.92	5.03	30.66	1.70	0.53	0.23	0.36
AD	beech 5	0.81	4.24	34.52	2.14	0.28	0.22	0.29
Total biomass stem (characteristica from mean of 5 stem disks)								
WL	beech 1	749.15	1917.82	2080.97	1159.95	201.72	109.43	124.80
WL	beech 2	1449.04	2669.14	3319.87	1422.25	437.14	131.29	183.16
WL	beech 3	1159.41	3142.00	2770.21	1515.90	502.81	187.92	209.23
WL	beech 4	2854.40	5035.17	9447.30	3147.33	2059.91	293.45	381.52
WL	beech 5	1016.78	1535.33	1399.63	1217.86	310.49	87.26	116.45
AD	beech 1	1693.66	3068.91	2981.77	2421.93	537.52	136.37	206.51
AD	beech 2	1392.41	2238.99	1735.27	1741.75	728.39	129.71	171.98
AD	beech 3	1696.51	2510.84	2342.51	2923.96	472.02	158.99	231.81
AD	beech 4	1576.37	2597.86	2670.02	2573.83	616.19	119.82	252.27
AD	beech 5	1503.05	2419.91	2967.51	2700.00	571.06	154.13	210.79
Total biomass fine roots 0–50 cm (Characteristica from mean of 0–25 and 25–50cm; respecitvely only 0–25cm)								
WL	beech 1	2.91	27.24	15.83	11.98	3.76	1.58	2.20
WL	beech 2	3.79	35.38	34.50	13.34	4.68	2.10	3.36
WL	beech 3	7.35	67.68	46.37	23.10	9.79	3.76	4.71
WL	beech 4	3.36	36.35	23.20	12.93	5.96	2.49	3.40
WL	beech 5	4.32	37.20	32.65	17.93	6.22	2.15	3.97
AD	beech 1	16.73	182.01	298.36	37.58	15.72	8.41	14.72
AD	beech 2	10.96	103.13	393.24	21.99	9.45	4.89	9.23
AD	beech 3	13.50	126.10	197.69	28.95	10.80	5.76	10.55
AD	beech 4	12.46	110.92	218.38	28.23	11.28	4.89	9.21

Site	Tree nr.	Biomass DW	N	Ca	K	Mg	P	S
AD	beech 5	9.92	95.93	136.23	28.04	7.32	4.42	8.81
Total biomass of all tree compartments (leaves, branches, bark, stem, fine roots)								
WL	beech 1	874.64	2756.46	2635.54	1693.60	309.41	203.36	191.43
WL	beech 2	1668.03	4203.26	4672.21	2191.82	661.88	260.83	295.09
WL	beech 3	1369.90	4862.99	4363.11	2242.51	714.16	343.51	330.08
WL	beech 4	3030.39	6496.57	11213.89	3902.28	2197.84	400.65	484.06
WL	beech 5	1079.54	2138.62	1925.47	1460.01	383.55	135.50	159.89
AD	beech 1	1935.12	5001.70	5394.59	3020.15	642.31	237.37	348.17
AD	beech 2	1529.30	3287.88	3757.98	2064.84	782.09	184.83	247.72
AD	beech 3	1832.53	3529.45	3738.83	3336.88	549.85	222.71	314.82
AD	beech 4	1810.15	4292.15	5304.06	3125.15	733.31	211.71	377.99
AD	beech 5	1676.48	3772.01	4890.60	3207.64	636.73	237.63	308.55

Table A 25: Biomass and nutrient allocation [%] to tree compartments of Fagus sylvatica at Waldlabor and Arisdorf.

Site	Tree nr.	Biomass DW	N	Ca	K	Mg	P	S
		[%]	[%]	[%]	[%]	[%]	[%]	[%]
Relative allocation of leaves								
WL	beech 1	0.81	0.59	2.31	3.25	3.94	4.39	6.09
WL	beech 2	0.50	4.60	1.98	3.05	2.43	3.80	4.71
WL	beech 3	0.90	5.96	3.09	3.09	3.51	3.94	6.38
WL	beech 4	0.46	4.70	1.65	1.81	1.30	4.20	4.57
WL	beech 5	0.97	10.51	5.21	5.03	5.51	8.70	10.51
AD	beech 1	0.93	7.75	5.98	2.80	4.35	5.85	8.28
AD	beech 2	0.54	5.35	3.53	2.33	1.00	4.01	5.45
AD	beech 3	0.70	8.45	5.96	3.41	3.53	6.43	7.03
AD	beech 4	0.77	6.98	4.87	2.99	2.64	5.44	6.05
AD	beech 5	0.56	5.45	3.30	2.24	1.55	3.50	5.17

Site	Tree nr.	Biomass DW	N	Ca	K	Mg	P	S
Relative allocation of branches								
WL	beech 1	12.65	27.43	14.41	21.77	26.63	39.71	26.57
WL	beech 2	11.98	29.89	23.19	25.00	27.23	43.34	30.74
WL	beech 3	13.46	27.02	29.19	22.12	22.59	39.42	27.99
WL	beech 4	4.84	16.13	10.76	8.19	3.65	20.47	15.21
WL	beech 5	4.06	14.77	17.71	6.78	9.48	23.63	13.23
AD	beech 1	10.63	27.13	32.43	14.35	9.17	33.00	28.08
AD	beech 2	7.63	23.24	38.81	10.40	4.42	23.04	21.30
AD	beech 3	5.95	16.73	25.26	7.15	8.39	19.47	15.93
AD	beech 4	11.40	29.80	40.10	12.76	11.56	35.41	24.72
AD	beech 5	9.15	27.74	32.53	11.63	7.27	29.66	23.59
Relative allocation of bark								
WL	beech 1	0.55	0.17	1.48	5.79	3.02	1.32	0.99
WL	beech 2	0.42	0.12	1.05	6.46	3.59	1.72	1.34
WL	beech 3	0.47	0.09	1.13	6.16	2.12	0.84	0.81
WL	beech 4	0.40	0.09	0.64	9.01	1.06	1.46	0.70
WL	beech 5	0.38	0.17	1.33	3.55	2.44	1.69	0.95
AD	beech 1	0.05	0.10	0.12	1.41	0.35	0.16	0.11
AD	beech 2	0.07	0.13	0.15	1.86	0.24	0.12	0.10
AD	beech 3	0.04	0.13	0.10	0.94	0.27	0.13	0.05
AD	beech 4	0.05	0.14	0.09	0.98	0.23	0.25	0.06
AD	beech 5	0.05	0.13	0.09	1.08	0.34	0.12	0.07
Relative allocation of stem								
WL	beech 1	85.65	69.58	78.96	68.49	65.19	53.81	65.20
WL	beech 2	86.87	63.50	71.06	64.89	66.05	50.34	62.07
WL	beech 3	84.63	64.61	63.49	67.60	70.41	54.71	63.39
WL	beech 4	94.19	77.51	84.25	80.65	93.72	73.24	78.82
WL	beech 5	94.19	71.79	72.69	83.41	80.95	64.40	72.83
AD	beech 1	87.52	61.36	55.27	80.19	83.69	57.45	59.31

Site	Tree nr.	Biomass DW	N	Ca	K	Mg	P	S
AD	beech 2	91.05	68.10	46.18	84.35	93.13	70.18	69.42
AD	beech 3	92.58	71.14	62.65	87.63	85.84	71.39	73.63
AD	beech 4	87.09	60.53	50.34	82.36	84.03	56.60	66.74
AD	beech 5	89.65	64.15	60.68	84.17	89.69	64.86	68.32
Relative allocation of fine roots								
WL	beech 1	0.33	0.99	0.60	0.71	1.22	0.78	1.15
WL	beech 2	0.23	0.84	0.74	0.61	0.71	0.80	1.14
WL	beech 3	0.54	1.39	1.06	1.03	1.37	1.09	1.43
WL	beech 4	0.11	0.56	0.21	0.33	0.27	0.62	0.70
WL	beech 5	0.40	1.74	1.70	1.23	1.62	1.58	2.48
AD	beech 1	0.86	3.64	5.53	1.24	2.45	3.54	4.23
AD	beech 2	0.72	3.14	10.46	1.06	1.21	2.65	3.73
AD	beech 3	0.74	3.57	5.29	0.87	1.96	2.59	3.35
AD	beech 4	0.69	2.58	4.12	0.90	1.54	2.31	2.44
AD	beech 5	0.59	2.54	2.79	0.87	1.15	1.86	2.86

Table A 26: Mass loss correction factor (MLCF) and nutrient remobilisation rates [%] at three time points in litter from Fagus sylvatica at Waldlabor and Arisdorf.

Site	Tree nr.	MLCF	N	Ca	K	Mg	P	S
			[%]	[%]	[%]	[%]	[%]	[%]
Remobilisation rates 09.10.22								
WL	beech 1	0.15	51.53	-4.50	58.76	14.61	54.66	41.14
WL	beech 2	0.14	51.28	17.38	59.23	22.17	50.95	40.76
WL	beech 3	0.43	68.27	44.50	61.69	51.31	64.92	61.79
WL	beech 4	0.07	39.99	27.41	18.90	39.30	35.96	26.61
WL	beech 5	0.08	39.01	0.08	41.69	38.86	31.65	27.76
AD	beech 1	0.17	47.69	23.49	18.60	36.53	44.96	31.00
AD	beech 2	0.30	55.18	27.63	44.30	11.63	59.87	42.74

Site	Tree nr.	MLCF	N [%]	Ca [%]	K [%]	Mg [%]	P [%]	S [%]
AD	beech 3	0.16	48.25	20.63	61.23	32.17	64.06	36.29
AD	beech 4	0.16	40.03	24.78	54.18	22.49	54.03	32.82
AD	beech 5	0.18	42.61	21.08	60.89	0.38	58.20	36.82
Remobilisation rates 30.10.22								
WL	beech 1	0.15	65.73	-19.12	55.31	6.79	74.20	51.65
WL	beech 2	0.14	65.56	5.83	55.82	15.04	72.09	51.34
WL	beech 3	0.43	77.57	36.74	58.49	46.85	80.04	68.62
WL	beech 4	0.07	66.70	17.26	10.54	25.57	69.91	45.69
WL	beech 5	0.08	66.16	-13.89	35.69	25.04	67.89	46.54
AD	beech 1	0.17	69.19	-3.72	42.60	39.10	70.86	50.55
AD	beech 2	0.30	73.60	1.90	60.72	15.20	78.76	58.96
AD	beech 3	0.16	71.62	-4.82	70.45	41.68	79.86	53.74
AD	beech 4	0.16	69.27	3.29	61.79	40.52	72.63	50.58
AD	beech 5	0.18	70.60	-1.47	67.39	23.54	75.11	53.52
Remobilisation rates 23.11.12 WL / 24.11.22 AD								
WL	beech 1	0.12	68.03	-37.19	70.74	4.18	76.31	52.01
WL	beech 2	0.11	67.87	-8.46	71.07	12.66	74.38	51.70
WL	beech 3	0.41	79.07	27.14	72.82	45.36	81.68	68.85
WL	beech 4	0.43	77.92	22.79	74.90	32.03	80.78	70.48
WL	beech 5	0.45	77.56	-6.29	81.96	31.55	79.49	70.94
AD	beech 1	0.21	71.51	-10.22	62.60	28.30	77.76	55.23
AD	beech 2	0.34	75.59	-4.25	74.41	0.17	83.78	62.84
AD	beech 3	0.28	64.85	0.25	82.33	35.15	86.75	61.49
AD	beech 4	0.35	54.06	17.41	78.96	37.07	84.48	62.08
AD	beech 5	0.36	56.04	13.35	82.04	19.12	85.89	64.34

6.6.2 Bülach and Irchel

In Table 27, nutrient concentrations of the tree compartments at Bülach and Ichel are presented.

Table A 27: Nutrient concentrations [g/kg] in tree compartments of Fagus sylvatica per location at Bülach and Irchel.

Site	**Location nr.**	**Location name**	**Tree compartment**	**N**	**P**	**S**	**K**	**Mg**	**Ca**
				[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]
Buelach	Site 1	5702: Lärchenischlag	Branches Ø <5 mm	1.32	1.29	0.82	2.88	0.66	10.29
Buelach	Site 2	5704: Chengelboden		1.24	1.46	0.76	3.42	0.75	4.32
Buelach	Site 3	5708: Brengspel		1.28	1.58	0.80	3.55	0.75	5.34
Buelach	Site 4	5710: Marterloch		1.48	1.44	0.98	3.19	0.67	5.83
Buelach	Site 5	5711: Lindi		1.26	1.57	0.79	3.02	0.81	5.24
Irchel	Site 1	Schaffhuser	Branches Ø <5 mm	1.14	0.91	0.81	3.12	0.64	10.84
Irchel	Site 2	Steig		1.24	0.77	0.84	3.42	0.55	5.58
Irchel	Site 3	Obermeser		1.12	1.15	0.74	3.43	0.68	3.13
Irchel	Site 4	Schartenflue		1.38	0.76	0.89	2.99	0.66	6.48
Irchel	Site 5	Hörnli		1.38	1.14	0.78	3.39	0.71	8.38
Buelach	Site 1	5702: Lärchenischlag	Branches Ø 5–20 mm	0.67	0.52	0.39	1.37	0.45	6.64
Buelach	Site 2	5704: Chengelboden		0.73	0.71	0.45	1.62	0.42	3.42
Buelach	Site 3	5708: Brengspel		0.68	0.80	0.42	1.67	0.39	3.45
Buelach	Site 4	5710: Marterloch		0.69	0.53	0.46	1.30	0.35	4.38
Buelach	Site 5	5711: Lindi		0.66	0.64	0.40	1.42	0.44	3.14
Irchel	Site 1	Schaffhuser	Branches Ø 5–20 mm	0.60	0.40	0.43	1.42	0.41	8.68
Irchel	Site 2	Steig		0.55	0.28	0.35	1.39	0.27	3.34
Irchel	Site 3	Obermeser		0.69	0.61	0.43	1.39	0.27	2.06
Irchel	Site 4	Schartenflue		0.90	0.43	0.56	1.70	0.47	5.02
Irchel	Site 5	Hörnli		0.76	0.59	0.47	1.61	0.43	6.04
Buelach	Site 1	5702: Lärchenischlag		0.30	0.24	0.18	0.89	0.34	5.74

Site	Location nr.	Location name		N	P	S	K	Mg	Ca
Buelach	Site 2	5704: Chengelboden	Branches Ø 20–70 mm	0.28	0.21	0.18	0.94	0.31	2.49
Buelach	Site 3	5708: Brengspel		0.31	0.28	0.20	1.01	0.32	3.53
Buelach	Site 4	5710: Marterloch		0.29	0.20	0.19	0.78	0.25	2.92
Buelach	Site 5	5711: Lindi		0.27	0.25	0.16	0.85	0.27	2.26
Irchel	Site 1	Schaffhuser	Branches Ø 20–70 mm	0.23	0.14	0.19	1.03	0.47	4.36
Irchel	Site 2	Steig		0.28	0.13	0.19	1.00	0.28	2.20
Irchel	Site 3	Obermeser		0.26	0.20	0.17	0.92	0.19	1.37
Irchel	Site 4	Schartenflue		0.43	0.17	0.21	1.10	0.32	3.51
Irchel	Site 5	Hörnli		0.28	0.21	0.18	1.14	0.38	3.48
Buelach	Site 1	5702: Lärchenischlag	Bark	0.82	0.50	0.50	1.74	0.54	31.20
Buelach	Site 2	5704: Chengelboden		0.78	0.44	0.46	1.78	0.56	13.10
Buelach	Site 3	5708: Brengspel		0.73	0.39	0.44	1.82	0.49	22.08
Buelach	Site 4	5710: Marterloch		0.75	0.39	0.46	1.40	0.43	20.07
Buelach	Site 5	5711: Lindi		0.84	0.49	0.49	1.71	0.61	14.72
Irchel	Site 1	Schaffhuser	Bark	0.60	0.35	0.44	2.06	0.59	31.06
Irchel	Site 2	Steig		0.75	0.34	0.45	2.11	0.70	16.59
Irchel	Site 3	Obermeser		0.72	0.37	0.46	2.07	0.43	10.12
Irchel	Site 4	Schartenflue		0.92	0.33	0.45	1.77	0.58	25.45
Irchel	Site 5	Hörnli		0.72	0.38	0.42	2.10	0.64	22.66
Buelach	Site 1	5702: Lärchenischlag	Stem Ø >70 mm	0.13	0.10	0.10	1.12	0.36	1.14
Buelach	Site 2	5704: Chengelboden		0.12	0.07	0.09	0.94	0.33	0.80
Buelach	Site 3	5708: Brengspel		0.13	0.13	0.12	1.49	0.39	1.02
Buelach	Site 4	5710: Marterloch		0.14	0.10	0.13	1.13	0.41	1.07
Buelach	Site 5	5711: Lindi		0.13	0.11	0.11	1.10	0.36	0.81
Irchel	Site 1	Schaffhuser	Stem Ø >70 mm	0.11	0.08	0.13	1.28	0.51	1.32
Irchel	Site 2	Steig		0.12	0.07	0.14	1.25	0.37	1.00
Irchel	Site 3	Obermeser		0.11	0.08	0.11	1.10	0.24	0.66
Irchel	Site 4	Schartenflue		0.24	0.08	0.13	1.48	0.48	1.00

Irchel	Site 5	Hörnli	0.13	0.10	0.12	1.36	0.47	1.01

6.6.3 ANOVA / Kruskal Wallis

In Table 28 and 29, the nutrient concentrations of the tree compartments from studies in European temperate forests are presented.

Table A 28: Tree species, to the study attributed geological substrate group and nutrient concentrations [g/kg] in leaves/ needles and branches in trees of European temperate forests.

Index	**Tree species**	**Geological substrate group**	**Leaves / needles**					**Branches**					
			N	**Ca**	**K**	**Mg**	**P**	**N**	**Ca**	**K**	**Mg**	**P**	**S**
			[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]
Q1	*Fagus sylvatica*	Carbonaceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q2	*Quercus*	Carbonaceous loose	NA	NA	NA	NA	NA	7.58	4.44	1.83	0.60	0.52	NA
Q3	*Pinus sylvestris*	Carbonaceous loose	NA	NA	NA	NA	NA	2.48	1.93	1.10	0.32	0.18	NA
Q4	*Picea abies*	Carbonaceous loose	13.58	5.51	4.05	0.83	1.22	3.33	3.03	1.37	0.49	0.31	NA
Q5	*Picea abies*	Carbonaceous loose	NA	NA	NA	NA	NA	6.40	3.94	2.83	0.95	0.77	NA
Q6	*Larix decidua*	Carbonaceous loose	NA	NA	NA	NA	NA	7.07	2.27	2.32	0.67	0.71	NA
Q7	*Abies alba*	Carbonaceous loose	NA	NA	NA	NA	NA	8.77	3.90	2.45	0.94	0.70	NA
Q8	*Abies alba*	Carbonaceous loose	NA	NA	NA	NA	NA	6.69	3.69	2.61	1.13	0.53	NA
Q9	*Fagus sylvatica*	Carbonaceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q10	*Pinus sylvestris*	Carbonaceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q11	*Fagus sylvatica*	Carbonaceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q12	*Picea abies*	Carbonaceous loose	10.03	3.20	3.40	0.90	0.94	4.15	2.88	2.43	1.08	0.99	NA
Q13	*Pinus sylvestris*	Carbonaceous loose	14.24	4.28	5.03	0.82	1.32	2.45	2.07	0.93	0.26	0.22	NA
Q14	*Quercus*	Carbonaceous loose	27.54	6.72	7.62	1.50	2.08	6.82	4.66	2.89	0.57	0.39	NA
Q15	*Quercus*	Carbonaceous loose	29.40	6.34	7.36	1.75	1.96	5.15	4.79	1.90	0.39	0.24	NA
Q16	*Pinus nigra*	Carbonaceous loose	10.70	5.21	7.55	1.35	1.75	1.43	3.33	1.14	0.56	0.26	NA
Q17	*Pinus sylvestris*	Carbonaceous loose	14.14	2.30	4.68	0.73	1.39	4.58	3.60	1.70	0.52	0.38	NA
Q18	*Pinus sylvestris*	Carbonaceous loose	15.26	3.07	5.47	0.84	1.37	3.69	1.99	1.02	0.33	0.24	NA
Q19	*Pinus sylvestris*	Carbonaceous loose	17.11	3.15	4.31	0.71	1.13	6.25	4.85	1.83	0.50	0.53	NA

Index	**Tree species**	**Geological substrate group**	**Leaves / needles**					**Branches**					
			N	**Ca**	**K**	**Mg**	**P**	**N**	**Ca**	**K**	**Mg**	**P**	**S**
Q20	*Quercus*	Carbonaceous loose	28.41	5.12	7.97	1.71	1.89	5.12	2.22	2.10	0.38	0.56	NA
Q21	*Pinus sylvestris*	Carbonaceous loose	20.31	3.84	5.02	0.71	1.30	5.26	2.11	1.25	0.40	0.33	NA
Q22	*Pinus sylvestris*	Carbonaceous loose	16.39	3.05	5.74	0.78	1.42	4.45	2.23	1.32	0.45	0.33	NA
Q23	*Picea abies*	Carbonaceous loose	14.77	5.65	4.00	0.84	1.24	5.67	4.32	0.57	0.64	0.64	0.45
Q24	*Pinus sylvestris*	Carbonaceous loose	9.64	2.55	6.00	0.93	1.02	2.99	1.79	2.74	0.52	0.38	NA
Q25	*Pinus sylvestris*	Carbonaceous loose	14.29	3.10	5.48	0.90	1.52	4.32	1.76	2.68	0.64	0.55	NA
Q26	*Pinus sylvestris*	Carbonaceous loose	10.83	4.76	4.05	0.81	1.17	3.19	2.15	1.74	0.48	0.40	NA
Q27	*Pinus nigra*	Carbonaceous loose	10.00	6.07	6.07	1.04	1.64	3.42	4.39	2.46	0.82	NA	NA
Q28	*Pinus nigra*	Carbonaceous loose	6.74	4.88	5.35	0.81	1.07	2.16	4.64	1.80	0.66	0.29	NA
Q29	*Pinus nigra*	Carbonaceous loose	9.20	4.80	6.40	1.22	1.26	3.15	4.50	2.60	0.85	NA	NA
Q30	*Fagus sylvatica*	Carbonaceous loose	NA	NA	NA	NA	NA	6.46	4.24	1.62	0.43	0.65	0.40
Q31	*Fagus sylvatica*	Carbonaceous loose	NA	NA	NA	NA	NA	6.33	4.35	1.71	0.41	0.44	0.41
Q32	*Fagus sylvatica*	Carbonaceous solidified	NA	NA	NA	NA	NA	6.13	3.27	1.91	0.57	0.59	0.49
Q33	*Fagus sylvatica*	Carbonaceous solidified	NA	NA	NA	NA	NA	6.51	3.93	2.25	0.58	0.61	0.45
Q34	*Fagus sylvatica*	Carbonaceous solidified	NA	NA	NA	NA	NA	6.82	5.52	2.88	0.71	0.67	0.47
Q35	*Quercus*	Carbonaceous solidified	NA	NA	NA	NA	NA	7.87	5.45	2.91	0.95	0.82	0.53
Q36	*Quercus*	Carbonaceous solidified	NA	NA	NA	NA	NA	8.17	5.94	2.97	0.81	0.64	0.58
Q37	*Quercus*	Carbonaceous solidified	NA	NA	NA	NA	NA	7.80	8.19	3.29	0.94	0.63	0.59
Q38	*Picea abies*	Carbonaceous solidified	13.42	3.55	4.76	0.62	1.06	5.06	2.98	2.42	0.54	0.55	0.55
Q39	*Picea abies*	Carbonaceous solidified	12.96	6.86	4.36	1.20	1.17	6.45	4.17	3.17	0.90	0.79	0.55
Q40	*Picea abies*	Carbonaceous solidified	13.58	7.25	4.92	1.35	1.24	5.98	4.68	3.48	1.05	0.75	0.52
Q41	*Pinus sylvestris*	Carbonaceous solidified	15.77	5.03	5.07	1.03	1.20	6.31	3.67	3.04	0.86	0.66	0.65
Q42	*Pinus sylvestris*	Carbonaceous solidified	16.03	6.10	5.68	0.91	1.57	7.22	3.77	2.93	0.71	0.79	0.67
Q43	*Pseudotsuga menziesii*	Carbonaceous solidified	15.62	6.32	6.05	1.39	1.06	6.26	5.63	3.31	0.83	0.79	0.58
Q44	*Pseudotsuga menziesii*	Carbonaceous solidified	15.13	8.17	5.75	1.49	1.27	6.58	5.63	3.47	0.77	0.85	0.63
Q45	*Fagus sylvatica*	Carbonaceous solidified	NA	NA	NA	NA	NA	NA	4.03	1.99	0.43	0.59	NA
Q46	*Quercus*	Carbonaceous solidified	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q47	*Picea abies*	Carbonaceous solidified	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q48	*Fagus sylvatica*	Carbonaceous solidified	25.66	13.67	12.78	2.38	1.47	3.70	6.91	1.49	0.59	0.21	NA

Index	**Tree species**	**Geological substrate group**	**Leaves / needles**					**Branches**					
			N	**Ca**	**K**	**Mg**	**P**	**N**	**Ca**	**K**	**Mg**	**P**	**S**
Q49	*Fagus sylvatica*	Carbonaceous solidified	21.92	17.43	6.76	1.29	0.90	6.32	10.07	2.10	0.34	0.39	0.46
Q50	*Fagus sylvatica*	Carbonaceous solidified	25.11	17.50	10.61	1.52	1.34	3.38	7.14	1.50	0.37	0.24	NA
Q51	*Pseudotsuga menziesii*	Carbonaceous solidified	16.49	9.31	4.77	1.11	0.98	3.76	3.88	2.14	0.43	0.43	NA
Q52	*Pseudotsuga menziesii*	Carbonaceous solidified	15.43	5.93	4.48	1.07	0.99	3.51	2.80	1.72	0.29	0.29	NA
Q53	*Pseudotsuga menziesii*	Carbonaceous solidified	13.95	8.01	4.93	0.99	1.01	2.43	3.27	0.88	0.27	0.27	NA
Q54	*Fagus sylvatica*	Carbonaceous solidified	NA	17.10	1.10	12.90	1.00	NA	NA	NA	NA	NA	NA
Q55	*Fagus sylvatica*	Carbonaceous solidified	NA	18.90	0.80	10.10	1.00	NA	NA	NA	NA	NA	NA
Q56	*Quercus*	Carbonaceous solidified	NA	35.80	6.10	5.60	0.90	NA	NA	NA	NA	NA	NA
Q57	*Picea abies*	Carbonaceous solidified	NA	12.85	6.20	0.95	1.00	NA	NA	NA	NA	NA	NA
Q58	*Picea abies*	Carbonaceous solidified	NA	8.85	6.85	1.75	0.95	NA	NA	NA	NA	NA	NA
Q59	*Pinus sylvestris*	Carbonaceous solidified	NA	5.40	4.60	1.00	1.30	NA	NA	NA	NA	NA	NA
Q60	*Fagus sylvatica*	Siliceous loose	NA	NA	NA	NA	NA	7.23	5.25	3.10	0.66	1.02	0.50
Q61	*Fagus sylvatica*	Siliceous loose	NA	NA	NA	NA	NA	6.07	3.36	2.04	0.52	0.42	0.45
Q62	*Quercus*	Siliceous loose	NA	NA	NA	NA	NA	7.92	9.23	3.38	0.93	0.95	0.59
Q63	*Quercus*	Siliceous loose	NA	NA	NA	NA	NA	7.00	4.90	2.10	0.73	0.56	0.54
Q64	*Picea abies*	Siliceous loose	13.27	6.58	4.39	1.08	1.03	5.53	5.09	3.00	0.78	0.63	0.50
Q65	*Pinus sylvestris*	Siliceous loose	14.68	4.15	5.80	0.97	1.44	6.54	3.33	2.95	0.74	0.75	0.63
Q66	*Pinus sylvestris*	Siliceous loose	16.56	3.48	5.10	0.82	1.01	4.38	2.99	2.35	0.58	0.38	0.62
Q67	*Pseudotsuga menziesii*	Siliceous loose	15.54	8.90	5.54	1.10	1.08	6.32	5.90	3.03	0.54	0.70	0.56
Q68	*Pseudotsuga menziesii*	Siliceous loose	17.11	5.53	5.30	1.02	0.71	4.82	3.01	2.50	0.48	0.47	NA
Q69	*Larix decidua*	Siliceous loose	NA	NA	NA	NA	NA	6.31	3.65	2.16	0.59	0.54	NA
Q70	*Picea abies*	Siliceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q71	*Picea abies*	Siliceous loose	13.94	5.43	3.66	0.63	1.07	3.54	2.51	1.46	0.38	0.31	NA
Q72	*Fagus sylvatica*	Siliceous loose	25.05	4.30	9.30	0.88	1.65	5.65	4.51	1.35	0.29	0.80	0.40
Q73	*Fagus sylvatica*	Siliceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q74	*Picea abies*	Siliceous loose	12.65	5.56	5.90	1.74	1.27	6.05	3.74	1.69	0.65	0.66	NA
Q75	*Picea abies*	Siliceous loose	NA	5.50	5.10	0.59	NA	NA	0.75	1.31	0.16	NA	NA
Q76	*Fagus sylvatica*	Siliceous loose	22.60	10.71	6.70	1.95	1.18	5.74	5.06	2.37	0.70	0.56	0.40
Q77	*Pinus nigra*	Siliceous loose	13.19	1.75	5.74	0.51	0.97	4.25	1.92	1.25	0.46	0.27	NA

Index	Tree species	Geological substrate group	Leaves / needles					Branches					
			N	**Ca**	**K**	**Mg**	**P**	**N**	**Ca**	**K**	**Mg**	**P**	**S**
Q78	*Fagus sylvatica*	Siliceous loose	30.79	4.53	8.52	0.66	2.04	2.23	2.35	0.70	0.24	0.32	NA
Q79	*Fagus sylvatica*	Siliceous loose	28.99	5.29	9.54	0.75	1.74	4.27	3.30	1.47	0.24	0.46	NA
Q80	*Fagus sylvatica*	Siliceous loose	27.43	3.61	7.82	0.71	1.49	4.92	3.58	1.33	0.27	0.81	NA
Q81	*Picea abies*	Siliceous loose	10.89	4.31	7.96	0.34	1.21	5.26	4.61	0.95	0.34	0.27	NA
Q82	*Picea abies*	Siliceous loose	12.13	2.76	6.91	0.98	1.46	4.52	3.41	0.84	0.27	0.20	NA
Q83	*Picea abies*	Siliceous loose	12.49	4.31	5.90	0.30	1.03	5.24	4.59	0.95	0.33	0.26	NA
Q84	*Picea abies*	Siliceous loose	16.00	13.20	8.40	2.00	2.80	3.10	4.20	1.90	0.60	0.50	NA
Q85	*Pinus sylvestris*	Siliceous loose	20.00	10.00	4.44	1.11	1.11	2.22	3.33	1.48	0.37	0.37	NA
Q86	*Larix decidua*	Siliceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q87	*Pseudotsuga menziesii*	Siliceous loose	NA	5.50	7.90	1.55	2.10	NA	NA	NA	NA	NA	NA
Q88	*Pseudotsuga menziesii*	Siliceous loose	NA	5.05	6.90	1.05	1.25	NA	NA	NA	NA	NA	NA
Q89	*Picea abies*	Siliceous loose	NA	1.80	6.60	0.60	1.65	NA	NA	NA	NA	NA	NA
Q90	*Picea abies*	Siliceous loose	NA	3.30	6.55	0.60	1.50	NA	NA	NA	NA	NA	NA
Q91	*Abies alba*	Siliceous loose	NA	17.00	3.90	1.75	1.20	NA	NA	NA	NA	NA	NA
Q92	*Abies alba*	Siliceous loose	NA	8.35	5.85	1.90	1.60	NA	NA	NA	NA	NA	NA
Q93	*Abies alba*	Siliceous loose	NA	14.45	6.85	1.30	NA	NA	NA	NA	NA	NA	NA
Q94	*Abies alba*	Siliceous loose	NA	11.50	6.55	1.40	NA	NA	NA	NA	NA	NA	NA
Q95	*Abies alba*	Siliceous loose	NA	6.00	9.60	1.10	2.45	NA	NA	NA	NA	NA	NA
Q96	*Fagus sylvatica*	Siliceous loose	19.77	5.79	5.35	1.69	1.22	3.49	2.19	1.38	0.42	0.32	NA
Q97	*Picea abies*	Siliceous loose	14.07	4.89	4.10	0.89	1.18	4.44	3.52	1.76	0.56	0.46	NA
Q98	*Quercus*	Siliceous solidified	NA	NA	NA	NA	NA	6.47	3.12	1.52	0.22	0.39	NA
Q99	*Fagus sylvatica*	Siliceous solidified	NA	NA	NA	NA	NA	7.05	4.04	2.41	0.52	0.67	0.46
Q100	*Picea abies*	Siliceous solidified	13.80	2.62	5.37	0.61	1.22	3.98	2.38	1.56	0.43	0.34	NA
Q101	*Picea abies*	Siliceous solidified	8.90	3.58	2.72	0.32	0.71	3.33	2.56	1.55	0.32	0.29	NA
Q102	*Picea abies*	Siliceous solidified	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q103	*Picea abies*	Siliceous solidified	10.30	3.30	3.35	0.83	0.86	3.70	2.75	1.83	0.57	0.44	NA
Q104	*Picea abies*	Siliceous solidified	12.50	3.77	5.50	0.43	1.50	7.73	2.83	4.77	0.60	1.23	NA
Q105	*Picea abies*	Siliceous solidified	14.90	6.00	6.00	0.50	1.05	5.94	3.97	2.88	0.39	0.60	NA
Q106	*Fagus sylvatica*	Siliceous solidified	25.64	5.13	5.90	1.74	1.59	6.67	3.85	2.30	0.41	0.56	NA

Index	Tree species	Geological substrate group	Leaves / needles					Branches					
			N	Ca	K	Mg	P	N	Ca	K	Mg	P	S
Q107	*Picea abies*	Siliceous solidified	12.22	4.67	6.78	0.53	1.21	9.89	3.25	5.05	0.73	1.30	NA
Q108	*Fagus sylvatica*	Siliceous solidified	27.08	8.75	7.71	2.02	1.08	5.16	6.02	2.16	0.53	0.42	NA
Q109	*Fagus sylvatica*	Siliceous solidified	21.21	6.06	4.85	1.42	1.85	6.25	4.61	1.68	0.48	0.64	NA
Q110	*Picea abies*	Siliceous solidified	NA	11.72	NA	0.97	1.70	NA	3.06	NA	1.23	1.29	NA
Q111	*Picea abies*	Siliceous solidified	28.98	19.91	11.47	2.17	3.15	7.35	4.11	4.17	0.72	1.16	NA
Q112	*Pinus sylvestris*	Siliceous solidified	12.19	4.93	5.89	0.82	1.23	3.33	1.81	1.81	0.38	0.38	NA
Q113	*Picea abies*	Siliceous solidified	12.95	2.53	4.97	0.32	1.10	4.83	1.85	1.66	0.47	0.31	NA
Q114	*Picea abies*	Siliceous solidified	12.20	1.70	5.90	0.34	1.18	6.53	1.96	2.26	0.30	0.67	NA
Q115	*Picea abies*	Siliceous solidified	12.40	4.20	6.45	0.91	1.32	3.96	2.63	2.46	0.50	0.62	NA
Q116	*Picea abies*	Siliceous solidified	12.50	6.20	6.85	0.57	1.09	4.12	2.59	2.99	0.38	0.55	NA
Q117	*Picea abies*	Siliceous solidified	11.70	8.10	5.15	0.64	1.33	4.09	3.78	2.80	0.49	0.69	NA
Q118	*Picea abies*	Siliceous solidified	12.50	4.10	5.35	0.68	1.22	4.34	3.00	3.45	0.60	0.72	NA
Q119	*Picea abies*	Siliceous solidified	12.06	3.09	4.06	1.01	1.71	5.73	3.71	2.59	1.34	1.36	NA
Q120	*Picea abies*	Siliceous solidified	NA	7.35	6.50	0.65	0.90	NA	NA	NA	NA	NA	NA
Q121	*Picea abies*	Siliceous solidified	NA	4.80	6.30	1.00	1.00	NA	NA	NA	NA	NA	NA
Q122	*Pinus sylvestris*	Siliceous solidified	NA	4.90	6.70	0.80	1.80	NA	NA	NA	NA	NA	NA
Q123	*Pinus sylvestris*	Siliceous solidified	NA	6.80	4.95	1.15	1.50	NA	NA	NA	NA	NA	NA
Q124	*Pinus sylvestris*	Siliceous solidified	NA	4.10	4.30	1.00	1.40	NA	NA	NA	NA	NA	NA
Q125	*Fagus sylvatica*	Siliceous solidified	NA	8.55	10.74	1.34	1.46	NA	NA	NA	NA	NA	NA
Q126	*Fagus sylvatica*	Siliceous solidified	NA	2.98	8.40	0.76	1.52	NA	NA	NA	NA	NA	NA
Q127	*Picea abies*	Siliceous solidified	NA	15.45	7.54	1.13	1.47	NA	NA	NA	NA	NA	NA
Q128	*Picea abies*	Siliceous solidified	NA	3.22	5.99	1.02	1.21	NA	NA	NA	NA	NA	NA

Table A 29: Tree species, to the study attributed geological substrate group and nutrient concentrations [g/kg] in bark and stem in trees of European temperate forests.

Index	**Tree species**	**Geological substrate group**	**Bark**						**Stem**					
			N [g/kg]	**Ca** [g/kg]	**K** [g/kg]	**Mg** [g/kg]	**P** [g/kg]	**S** [g/kg]	**N** [g/kg]	**Ca** [g/kg]	**K** [g/kg]	**Mg** [g/kg]	**P** [g/kg]	**S** [g/kg]
Q1	*Fagus sylvatica*	Carbonaceous loose	3.97	23.60	1.08	0.48	0.63	NA	1.02	0.78	0.38	0.25	0.18	NA
Q2	*Quercus*	Carbonaceous loose	6.69	21.10	1.51	0.73	0.27	NA	1.15	0.43	0.87	0.05	0.05	NA
Q3	*Pinus sylvestris*	Carbonaceous loose	2.58	2.50	0.45	0.09	0.11	NA	1.12	0.68	0.30	0.09	0.03	NA
Q4	*Picea abies*	Carbonaceous loose	4.32	9.83	1.96	0.81	0.43	NA	0.58	0.70	0.33	0.10	0.03	NA
Q5	*Picea abies*	Carbonaceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q6	*Larix decidua*	Carbonaceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q7	*Abies alba*	Carbonaceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q8	*Abies alba*	Carbonaceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q9	*Fagus sylvatica*	Carbonaceous loose	NA	13.86	2.35	0.65	0.48	NA	NA	0.80	0.93	0.07	0.09	NA
Q10	*Pinus sylvestris*	Carbonaceous loose	NA	3.85	0.74	0.05	0.18	NA	NA	0.56	0.46	0.04	0.08	NA
Q11	*Fagus sylvatica*	Carbonaceous loose	7.10	22.56	2.76	0.71	0.46	NA	NA	NA	NA	NA	NA	NA
Q12	*Picea abies*	Carbonaceous loose	3.80	0.60	0.38	0.10	0.02	NA	0.28	0.60	0.38	0.10	0.02	NA
Q13	*Pinus sylvestris*	Carbonaceous loose	2.47	5.57	1.34	0.32	0.32	NA	0.50	0.70	0.30	0.14	0.04	NA
Q14	*Quercus*	Carbonaceous loose	5.25	12.54	1.58	0.57	0.30	NA	2.22	1.13	1.61	0.22	0.17	NA
Q15	*Quercus*	Carbonaceous loose	3.18	22.78	2.02	0.43	0.26	NA	1.63	0.29	1.29	0.11	0.11	NA
Q16	*Pinus nigra*	Carbonaceous loose	1.78	2.44	0.99	0.53	0.34	NA	0.35	0.54	0.30	0.13	0.05	NA
Q17	*Pinus sylvestris*	Carbonaceous loose	3.08	5.02	1.70	0.61	0.49	NA	1.05	0.62	0.40	0.15	0.06	NA
Q18	*Pinus sylvestris*	Carbonaceous loose	2.66	5.48	1.15	0.44	0.26	NA	0.90	0.76	0.30	0.19	0.03	NA
Q19	*Pinus sylvestris*	Carbonaceous loose	3.58	7.45	1.21	0.44	0.28	NA	0.48	0.73	0.27	0.16	0.03	NA
Q20	*Quercus*	Carbonaceous loose	6.90	18.81	1.92	0.57	0.39	NA	1.24	0.50	0.86	0.09	0.15	NA
Q21	*Pinus sylvestris*	Carbonaceous loose	4.97	4.99	1.06	0.37	0.25	NA	0.70	0.65	0.44	0.20	0.05	NA
Q22	*Pinus sylvestris*	Carbonaceous loose	3.88	4.98	1.08	0.35	0.28	NA	0.73	0.80	0.38	0.24	0.07	NA
Q23	*Picea abies*	Carbonaceous loose	4.51	10.96	2.13	0.92	0.56	0.41	0.51	0.74	0.37	0.11	0.06	0.05
Q24	*Pinus sylvestris*	Carbonaceous loose	4.15	2.31	2.85	0.60	0.46	NA	0.79	0.47	0.77	0.21	0.07	NA
Q25	*Pinus sylvestris*	Carbonaceous loose	4.53	2.40	2.73	0.77	0.60	NA	0.87	0.40	0.64	0.24	0.08	NA
Q26	*Pinus sylvestris*	Carbonaceous loose	2.60	5.83	1.34	0.44	0.40	NA	0.77	0.73	0.39	0.20	0.06	NA
Q27	*Pinus nigra*	Carbonaceous loose	3.64	3.18	1.70	0.80	0.52	NA	0.84	0.89	0.54	0.19	0.09	NA

Index	**Tree species**	**Geological substrate group**	**Bark**						**Stem**					
			N	**Ca**	**K**	**Mg**	**P**	**S**	**N**	**Ca**	**K**	**Mg**	**P**	**S**
Q28	*Pinus nigra*	Carbonaceous loose	1.83	2.09	1.43	0.42	0.29	NA	0.56	0.56	0.39	0.10	0.04	NA
Q29	*Pinus nigra*	Carbonaceous loose	2.18	1.47	1.45	0.47	0.31	NA	0.70	0.65	0.51	0.16	0.06	NA
Q30	*Fagus sylvatica*	Carbonaceous loose	7.81	20.23	1.69	0.53	0.44	0.47	1.28	0.97	1.16	0.37	0.10	0.11
Q31	*Fagus sylvatica*	Carbonaceous loose	7.40	20.13	2.02	0.58	0.36	0.45	1.41	0.98	1.28	0.40	0.08	0.12
Q32	*Fagus sylvatica*	Carbonaceous solidified	7.48	12.90	2.15	0.74	0.44	0.49	1.00	0.79	1.10	0.33	0.10	0.11
Q33	*Fagus sylvatica*	Carbonaceous solidified	8.29	13.97	2.94	0.82	0.55	0.57	1.02	0.86	1.27	0.27	0.11	0.11
Q34	*Fagus sylvatica*	Carbonaceous solidified	7.09	17.29	3.43	0.81	0.55	0.50	0.99	1.03	1.55	0.55	0.11	0.12
Q35	*Quercus*	Carbonaceous solidified	5.81	17.78	2.96	1.11	0.52	0.49	1.41	0.60	1.45	0.18	0.12	0.14
Q36	*Quercus*	Carbonaceous solidified	6.99	12.42	3.22	0.95	0.50	0.62	1.33	0.61	1.54	0.13	0.10	0.13
Q37	*Quercus*	Carbonaceous solidified	5.93	22.05	3.25	1.02	0.37	0.56	1.30	0.68	1.40	0.12	0.10	0.15
Q38	*Picea abies*	Carbonaceous solidified	4.78	7.34	2.67	0.75	0.52	0.42	0.50	0.74	0.50	0.13	0.04	0.07
Q39	*Picea abies*	Carbonaceous solidified	5.09	8.52	3.07	1.04	0.63	0.45	0.81	0.89	0.46	0.14	0.05	0.06
Q40	*Picea abies*	Carbonaceous solidified	5.47	10.49	3.11	1.09	0.68	0.43	1.01	1.02	0.47	0.15	0.06	0.06
Q41	*Pinus sylvestris*	Carbonaceous solidified	3.50	4.18	2.09	0.85	0.38	0.39	0.61	1.03	0.47	0.25	0.05	0.07
Q42	*Pinus sylvestris*	Carbonaceous solidified	4.85	6.66	2.09	0.77	0.50	0.48	1.06	1.08	0.47	0.29	0.07	0.09
Q43	*Pseudotsuga menziesii*	Carbonaceous solidified	3.92	3.68	2.97	0.52	0.55	0.44	0.65	0.39	0.28	0.05	0.05	0.07
Q44	*Pseudotsuga menziesii*	Carbonaceous solidified	4.16	4.05	3.25	0.52	0.64	0.45	0.55	0.38	0.29	0.06	0.04	0.06
Q45	*Fagus sylvatica*	Carbonaceous solidified	NA	23.28	2.66	0.44	0.45	NA	NA	0.83	1.10	0.27	0.12	NA
Q46	*Quercus*	Carbonaceous solidified	8.32	18.82	2.86	0.69	0.28	NA	1.46	0.36	0.42	0.01	NA	NA
Q47	*Picea abies*	Carbonaceous solidified	NA	11.21	2.35	0.61	0.54	NA	NA	0.76	0.37	0.05	NA	NA
Q48	*Fagus sylvatica*	Carbonaceous solidified	5.30	34.21	2.50	0.72	0.23	NA	1.07	2.46	0.93	0.45	0.06	NA
Q49	*Fagus sylvatica*	Carbonaceous solidified	5.40	38.83	2.07	0.37	0.27	0.37	1.63	1.61	1.57	0.38	0.09	0.14
Q50	*Fagus sylvatica*	Carbonaceous solidified	6.38	40.88	2.58	0.47	0.36	NA	1.79	1.34	1.10	0.29	0.09	NA
Q51	*Pseudotsuga menziesii*	Carbonaceous solidified	6.66	2.06	5.36	0.59	0.72	NA	0.65	0.30	1.29	0.09	0.02	NA
Q52	*Pseudotsuga menziesii*	Carbonaceous solidified	3.90	2.06	2.83	0.36	0.48	NA	0.62	0.31	0.75	0.05	0.02	NA
Q53	*Pseudotsuga menziesii*	Carbonaceous solidified	3.42	3.00	2.19	0.32	0.44	NA	0.63	0.31	0.21	0.05	0.03	NA
Q54	*Fagus sylvatica*	Carbonaceous solidified	NA	44.53	2.55	0.32	0.56	NA	NA	0.52	1.18	0.41	0.04	NA
Q55	*Fagus sylvatica*	Carbonaceous solidified	NA	36.15	2.60	0.27	0.40	NA	NA	0.79	0.65	0.22	0.05	NA

Index	**Tree species**	**Geological substrate group**	**Bark**						**Stem**					
			N	**Ca**	**K**	**Mg**	**P**	**S**	**N**	**Ca**	**K**	**Mg**	**P**	**S**
Q56	*Quercus*	Carbonaceous solidified	NA	40.65	2.72	0.77	0.34	NA	NA	0.41	0.58	0.04	0.03	NA
Q57	*Picea abies*	Carbonaceous solidified	NA	7.31	4.42	1.00	0.71	NA	NA	0.91	0.43	0.08	0.02	NA
Q58	*Picea abies*	Carbonaceous solidified	NA	17.92	2.58	0.89	0.46	NA	NA	0.77	0.20	0.09	0.02	NA
Q59	*Pinus sylvestris*	Carbonaceous solidified	NA	9.27	3.11	1.36	0.46	NA	NA	0.38	0.31	0.11	0.01	NA
Q60	*Fagus sylvatica*	Siliceous loose	7.20	18.93	2.98	0.57	0.54	0.48	1.48	0.96	1.46	0.38	0.10	0.11
Q61	*Fagus sylvatica*	Siliceous loose	7.69	13.44	2.57	0.69	0.39	0.60	1.09	0.82	0.94	0.26	0.12	0.13
Q62	*Quercus*	Siliceous loose	6.12	28.69	3.36	0.91	0.50	0.55	1.55	0.71	1.50	0.14	0.14	0.15
Q63	*Quercus*	Siliceous loose	5.85	16.93	2.13	0.76	0.31	0.50	1.33	0.50	0.91	0.10	0.08	0.12
Q64	*Picea abies*	Siliceous loose	4.98	10.87	2.74	0.85	0.56	0.45	0.69	0.98	0.43	0.12	0.04	0.05
Q65	*Pinus sylvestris*	Siliceous loose	3.87	7.77	2.24	0.73	0.46	0.44	0.70	1.15	0.52	0.24	0.06	0.07
Q66	*Pinus sylvestris*	Siliceous loose	3.44	6.28	1.60	0.62	0.27	0.44	0.46	0.86	0.37	0.22	0.03	0.08
Q67	*Pseudotsuga menziesii*	Siliceous loose	3.98	4.11	3.03	0.35	0.54	0.43	0.54	0.39	0.33	0.05	0.05	0.07
Q68	*Pseudotsuga menziesii*	Siliceous loose	3.04	2.23	1.78	0.24	0.29	NA	0.41	0.25	0.22	0.04	0.04	NA
Q69	*Larix decidua*	Siliceous loose	4.67	4.16	1.74	0.54	0.37	NA	1.06	0.47	0.29	0.12	0.04	NA
Q70	*Picea abies*	Siliceous loose	3.37	8.32	1.00	0.42	0.89	NA	1.03	0.71	0.09	0.06	0.09	NA
Q71	*Picea abies*	Siliceous loose	5.47	7.71	2.10	0.80	0.51	NA	0.49	0.65	0.30	0.07	0.03	NA
Q72	*Fagus sylvatica*	Siliceous loose	7.80	6.20	1.90	1.07	0.85	0.52	1.10	0.53	0.80	0.18	0.19	0.15
Q73	*Fagus sylvatica*	Siliceous loose	9.33	14.07	1.78	0.90	0.31	NA	1.64	1.35	1.01	0.31	0.06	NA
Q74	*Picea abies*	Siliceous loose	5.62	8.22	2.74	1.08	0.56	NA	1.07	0.70	0.54	0.14	0.09	NA
Q75	*Picea abies*	Siliceous loose	NA	3.60	6.20	1.00	NA	NA	NA	0.45	0.92	0.09	NA	NA
Q76	*Fagus sylvatica*	Siliceous loose	6.98	20.69	2.38	0.54	0.40	0.40	2.08	2.43	1.23	0.41	0.12	0.14
Q77	*Pinus nigra*	Siliceous loose	3.52	1.20	0.87	0.20	0.15	NA	1.24	0.52	0.29	0.11	0.07	NA
Q78	*Fagus sylvatica*	Siliceous loose	8.96	10.10	2.93	0.49	0.57	NA	1.12	1.08	0.90	0.11	0.12	NA
Q79	*Fagus sylvatica*	Siliceous loose	8.96	10.10	2.93	0.49	0.57	NA	1.12	1.08	0.90	0.11	0.12	NA
Q80	*Fagus sylvatica*	Siliceous loose	7.83	6.21	1.96	1.07	0.86	NA	1.11	0.53	0.79	0.18	0.19	NA
Q81	*Picea abies*	Siliceous loose	7.13	6.33	5.94	0.54	0.90	NA	1.56	1.08	1.53	0.21	0.22	NA
Q82	*Picea abies*	Siliceous loose	6.68	11.70	3.95	0.78	0.21	NA	0.48	1.00	0.74	0.17	0.05	NA
Q83	*Picea abies*	Siliceous loose	6.63	8.70	3.11	0.71	1.43	NA	0.84	0.71	0.27	0.11	0.08	NA

Index	Tree species	Geological substrate group	Bark						Stem					
			N	Ca	K	Mg	P	S	N	Ca	K	Mg	P	S
Q84	*Picea abies*	Siliceous loose	7.88	8.18	4.24	1.82	1.21	NA	1.00	0.71	0.79	0.21	0.21	NA
Q85	*Pinus sylvestris*	Siliceous loose	6.07	6.07	3.21	1.25	1.07	NA	0.79	0.90	0.79	0.41	0.10	NA
Q86	*Larix decidua*	Siliceous loose	4.32	2.50	1.36	0.68	0.45	NA	0.61	0.50	0.39	0.21	0.11	NA
Q87	*Pseudotsuga menziesii*	Siliceous loose	NA	3.34	6.39	0.53	1.06	NA	NA	0.32	0.16	0.06	NA	NA
Q88	*Pseudotsuga menziesii*	Siliceous loose	NA	2.67	5.97	0.43	NA	NA	NA	0.32	0.18	0.06	NA	NA
Q89	*Picea abies*	Siliceous loose	NA	4.03	3.64	1.01	0.92	NA	NA	0.68	0.33	0.13	0.02	NA
Q90	*Picea abies*	Siliceous loose	NA	5.03	3.89	1.04	1.13	NA	NA	0.66	0.19	0.20	0.01	NA
Q91	*Abies alba*	Siliceous loose	NA	5.78	4.34	0.44	NA	NA	NA	0.45	0.71	0.08	0.03	NA
Q92	*Abies alba*	Siliceous loose	NA	5.61	4.02	0.55	1.06	NA	NA	0.60	0.75	0.12	NA	NA
Q93	*Abies alba*	Siliceous loose	NA	NA	NA	NA	NA	NA	NA	0.45	2.31	0.12	NA	NA
Q94	*Abies alba*	Siliceous loose	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q95	*Abies alba*	Siliceous loose	NA	4.87	5.98	0.51	0.69	NA	NA	0.42	0.80	0.10	0.02	NA
Q96	*Fagus sylvatica*	Siliceous loose	7.47	14.06	2.50	0.67	0.43	NA	1.27	0.81	1.05	0.30	0.09	NA
Q97	*Picea abies*	Siliceous loose	5.03	10.65	1.62	0.90	0.44	NA	1.00	0.68	0.29	0.11	0.05	NA
Q98	*Quercus*	Siliceous solidified	6.70	13.33	1.46	0.23	0.26	NA	2.25	0.37	1.05	0.05	0.07	NA
Q99	*Fagus sylvatica*	Siliceous solidified	9.09	13.55	2.94	0.70	0.54	0.47	1.52	0.92	1.21	0.33	0.10	0.11
Q100	*Picea abies*	Siliceous solidified	5.17	7.81	0.61	0.98	0.56	NA	0.63	0.61	0.35	0.10	0.04	NA
Q101	*Picea abies*	Siliceous solidified	3.08	7.43	1.99	0.62	0.32	NA	0.28	0.56	0.32	0.08	0.03	NA
Q102	*Picea abies*	Siliceous solidified	6.00	9.33	1.93	0.66	0.46	NA	1.15	0.80	0.39	0.10	0.05	NA
Q103	*Picea abies*	Siliceous solidified	3.85	7.30	2.05	0.89	0.45	NA	0.30	0.55	0.37	0.11	0.03	NA
Q104	*Picea abies*	Siliceous solidified	5.20	6.70	4.10	0.70	0.77	NA	0.80	0.60	0.60	0.10	0.10	NA
Q105	*Picea abies*	Siliceous solidified	3.38	11.20	2.20	0.54	0.39	NA	0.53	0.84	0.20	0.09	0.03	NA
Q106	*Fagus sylvatica*	Siliceous solidified	8.89	10.00	2.11	0.61	0.52	NA	0.99	0.52	0.86	0.24	0.08	NA
Q107	*Picea abies*	Siliceous solidified	4.55	7.64	3.14	0.97	0.62	NA	0.71	0.48	0.43	0.07	0.06	NA
Q108	*Fagus sylvatica*	Siliceous solidified	6.36	25.00	2.46	0.55	0.40	NA	1.15	0.88	1.09	0.29	0.07	NA
Q109	*Fagus sylvatica*	Siliceous solidified	7.50	14.00	2.08	0.65	0.43	NA	1.01	0.56	1.21	0.31	0.11	NA
Q110	*Picea abies*	Siliceous solidified	6.06	7.82	3.03	0.72	0.98	NA	2.10	NA	NA	NA	NA	NA
Q111	*Picea abies*	Siliceous solidified	6.08	7.83	3.02	0.72	0.64	NA	2.11	1.26	1.22	0.16	NA	NA

Index	**Tree species**	**Geological substrate group**	**Bark**						**Stem**					
			N	**Ca**	**K**	**Mg**	**P**	**S**	**N**	**Ca**	**K**	**Mg**	**P**	**S**
Q112	*Pinus sylvestris*	Siliceous solidified	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Q113	*Picea abies*	Siliceous solidified	4.95	5.60	2.65	0.58	0.57	NA	0.68	0.65	0.61	0.10	0.06	NA
Q114	*Picea abies*	Siliceous solidified	4.00	8.70	2.25	0.67	0.52	NA	0.25	0.50	0.45	0.12	0.03	NA
Q115	*Picea abies*	Siliceous solidified	3.90	7.00	2.40	0.91	0.53	NA	0.30	0.50	0.40	0.14	0.03	NA
Q116	*Picea abies*	Siliceous solidified	5.20	6.10	3.20	0.72	0.65	NA	0.30	0.60	0.40	0.11	0.03	NA
Q117	*Picea abies*	Siliceous solidified	6.00	8.10	2.40	0.67	0.78	NA	0.45	0.60	0.50	0.13	0.05	NA
Q118	*Picea abies*	Siliceous solidified	5.80	5.70	2.40	0.62	0.73	NA	0.60	0.60	0.70	0.16	0.08	NA
Q119	*Picea abies*	Siliceous solidified	4.83	8.66	2.13	0.96	0.57	NA	0.65	0.67	0.32	0.13	0.05	NA
Q120	*Picea abies*	Siliceous solidified	NA	7.24	3.90	0.69	0.54	NA	NA	0.78	0.35	0.09	0.01	NA
Q121	*Picea abies*	Siliceous solidified	NA	NA	NA	NA	NA	NA	NA	0.10	0.07	0.02	0.02	NA
Q122	*Pinus sylvestris*	Siliceous solidified	NA	6.26	3.85	0.94	0.50	NA	NA	0.60	0.43	0.15	0.02	NA
Q123	*Pinus sylvestris*	Siliceous solidified	NA	5.53	3.88	0.91	0.67	NA	NA	0.50	0.34	0.18	0.04	NA
Q124	*Pinus sylvestris*	Siliceous solidified	NA	6.28	2.97	0.96	0.49	NA	NA	0.54	0.21	0.14	0.01	NA
Q125	*Fagus sylvatica*	Siliceous solidified	NA	NA	NA	NA	NA	NA	NA	1.10	1.43	0.16	0.05	0.09
Q126	*Fagus sylvatica*	Siliceous solidified	NA	NA	NA	NA	NA	NA	NA	1.56	0.69	0.26	0.06	0.10
Q127	*Picea abies*	Siliceous solidified	NA	NA	NA	NA	NA	NA	NA	0.54	1.53	0.08	0.05	0.06
Q128	*Picea abies*	Siliceous solidified	NA	NA	NA	NA	NA	NA	NA	1.00	0.61	0.17	0.07	0.11

Declaration of independence

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

Muri, 30.09.2022

Place, date

Jana Berrocoso